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QUANTUM HEGEMONY?

**China's Ambitions and the Challenge
to U.S. Innovation Leadership**

Elsa B. Kania & John K. Costello



Center for a
New American
Security

About the Author



ELSA B. KANIA is an Adjunct Fellow with the Technology and National Security Program at the Center for a New American Security (CNAS). She focuses on Chinese defense innovation in emerging technologies in support of the Artificial Intelligence and Global Security Initiative

at CNAS, while also acting as a member of the research team for the new Task Force on Artificial Intelligence and National Security. Her research interests include Chinese military modernization, information warfare, and defense science and technology. Kania is an independent analyst, consultant, and co-founder of the China Cyber and Intelligence Studies Institute. She also was a 2018 Fulbright Specialist and is a Non-Resident Fellow with the Australian Strategic Policy Institute's International Cyber Policy Centre. Kania works in support of the China Aerospace Studies Institute through its Associates Program, and she is a consulting analyst with Pointe Bello, as well as a policy advisor for the nonprofit Technology for Global Security. She has been named an official "Mad Scientist" by the U.S. Army's Training and Doctrine Command. Kania is a graduate of Harvard College (summa cum laude, Phi Beta Kappa), where her thesis on the evolution of the Chinese military's strategic thinking on information warfare was awarded the James Gordon Bennett Prize. She was a Boren Scholar in Beijing and is fluent in Mandarin Chinese.



JOHN K. COSTELLO is a co-founder and director emeritus for the China Cyber and Intelligence Studies Institute, as well as a cybersecurity fellow at New America. He was formerly a Senior Analyst for cyber and East Asia at Flashpoint, where he engaged in analysis of Chinese cyber

crime and the deep and dark web. Previously, he was a Congressional Innovation Fellow for the majority staff in the U.S. House of Representatives Committee on Oversight and Government Reform. During his time on the Hill, Costello helped investigate the 2015 breach into the Office of Personnel Management and helped oversee federal IT management. He also worked as a research analyst at Defense Group Inc., where he concentrated on Chinese cyber espionage, information warfare, and intellectual property theft. A U.S. Navy veteran and former NSA analyst, Costello is fluent in Mandarin Chinese, having graduated with honors from the Defense Language Institute.

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Objectives and Methodology

This report draws upon an extensive review of the available open-source Chinese language resources relevant to understanding Chinese advances in quantum science and technology. These include, but are not limited to, media reporting, official plans and policies, academic articles, technical publications, and other online resources. There is a full listing of references included, but certain sources are only available upon request. While not fully comprehensive, this initial analysis seeks to establish a baseline understanding of these issues and to raise questions for future research, while proposing an initial series of policy considerations and recommendations. The authors welcome any questions and comments on the paper.

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About the Technology & National Security Program

Technology is changing our lives. Rapid developments in artificial intelligence, autonomy, cyber-physical systems, networking and social media, and disinformation are profoundly altering the national security landscape. Nation-states have new tools at their disposal for political influence as well as new vulnerabilities to attacks. Non-state groups and individuals are empowered by social media and radical transparency. Artificial intelligence and automation raise profound questions about the role of humans in conflict and war.

CNAS' Technology and National Security program explores the policy challenges associated with these and other emerging technologies. A key focus of the program is bringing together the technology and policy communities to better understand these challenges and together develop solutions.

Note

The title of this report, "Quantum Hegemony," is inspired by the typical Chinese choice of phrasing for the concept of "quantum supremacy," which indicates the point at which a quantum computer will surpass a classical computer. Literally, "量子霸权" might also be translated "quantum hegemony," and the word in question (霸权) is often used, for instance, in Chinese criticisms of "American hegemony."

QUANTUM HEGEMONY?

China's Ambitions and the Challenge to U.S. Innovation Leadership

01	Executive Summary
02	Introduction
03	The Second Quantum Revolution
06	China's Quantum Ambitions
13	China's Advances in Quantum Technologies
21	The Strategic Implications of China's Quantum Leaps
27	Conclusions and Recommendations
31	Endnotes

Executive Summary

China is positioning itself as a powerhouse in quantum science. Within the past several years, Chinese researchers have achieved a track record of consistent advances in basic research and in the development of quantum technologies, including quantum cryptography, communications, and computing, as well as reports of progress in quantum radar, sensing, imaging, metrology, and navigation. Their breakthroughs demonstrate the successes of a long-term research agenda that has dedicated extensive funding to this domain while actively cultivating top talent. China's rise as a powerhouse in quantum science was displayed to the world with the August 2016 launch of the world's first quantum satellite, Micius (or Mozi, 墨子). Since then, China's launch of new national "megaprojects" in quantum communications and computing reflect the continued prioritization of these technologies.

China's leaders recognize the strategic potential of quantum science and technology to enhance economic and military dimensions of national power.

At the highest levels, China's leaders recognize the strategic potential of quantum science and technology to enhance economic and military dimensions of national power. These quantum ambitions are intertwined with China's national strategic objective to become a science and technology superpower (科技强国). Rather than relying primarily on the "absorption" of foreign technologies in its pursuit of indigenous innovation, China instead intends to achieve truly disruptive, even "radical" innovation (源头创新) in strategic emerging technologies, including biotechnology and artificial intelligence. As China advances a national strategy for military-civil fusion (or "civil-military integration," 军民融合), these critical technologies also will be leveraged for a range of defense applications. While international collaborations can be integral to advancing global scientific progress, the sensitivity and strategic objectives associated with these technologies in China could, at worst, undermine such engagements, perhaps resulting in such future "made in China" innovation being restricted to China.

China clearly aspires to lead the "second quantum revolution" that is occurring with the advent of these new technologies. China's widespread employment of provably secure quantum cryptography and quantum

communications is intended to create new networks that will be, at least in theory, "unhackable." In the decades to come, the realization of quantum computing will create unparalleled computing capabilities, with impactful applications that include cracking prevalent types of encryption. Although China is a relative latecomer to the race, this competition will be a marathon, not a sprint, taking place over decades to come, and Chinese scientists – who are receiving nearly unlimited resources and recently have established a new world record for entangled quantum bits (qubits) – could catch up in the long term. Meanwhile, Chinese researchers claim to have achieved notable advances in quantum radar, sensing, imaging, metrology, and navigation, which enable greater precision and sensitivity. In addition, early research in quantum materials, such as topological insulators, may enable new paradigms of information processing, have applications in clean energy, and even be used in one pathway to quantum computing.

China's advances in quantum science could impact the future military and strategic balance, perhaps even leapfrogging traditional U.S. military-technological advantages. Although it is difficult to predict the trajectories and timeframes for their realization, these dual-use quantum technologies could "offset" key pillars of U.S. military power, potentially undermining critical technological advantages associated with today's information-centric ways of war, epitomized by the U.S. model. As China shifts its most sensitive military, governmental, and commercial communications to quantum networks, this transition could enhance information security, perhaps frustrating U.S. cyber espionage and signals intelligence capabilities, though these systems will likely remain susceptible to exploitation nonetheless. At the same time, this national transition to quantum cryptography could ensure that China will be more secure against the more distant threat that a future quantum computer might be able to break prevalent kinds of cryptography using Shor's algorithm. By contrast, the United States has yet to progress toward implementing such solutions, or alternatives from post-quantum cryptography, at scale. Going forward, if China succeeds in becoming a pioneer in quantum computing, then the leveraging of such immense computing capabilities could convey strategic advantage, placing sensitive information systems at risk. Meanwhile, the introduction of quantum navigation may allow greater independence from space-based systems, and the realization of quantum radar, imaging, and sensing would enhance domain awareness and targeting, potentially undermining U.S. investments in stealth technologies or even

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allowing for the tracking of submarines. In the aggregate, these advances could support the continued emergence of the Chinese People's Liberation Army (PLA) as a true peer competitor in these new technological frontiers of military power.

The United States must recognize the trajectory of China's advances in these technologies and the promise of their potential military and commercial applications. In response, the United States should build upon and redouble existing efforts to remain a leader, or at least a major contender, in the development of quantum technologies through enhancing the vitality of its innovation ecosystem. The United States must ensure that basic and applied research and development in quantum science and technology receive adequate, sustained funding, while seeking to attract and retain top talent. In the process, the exploration of new paradigms for public-private partnership will also be critical. While continuing to explore options for post-quantum encryption, the U.S. government should start to evaluate the costs and timeframes associated with a military- and government-wide transition from today's prevalent forms of encryption to a new regime, which might require considerable changes to the underlying information infrastructure. The Department of Defense (DoD) also should undertake further analysis of the utility of available forms of quantum cryptography and communications to secure military information systems. As developments in quantum radar, sensing, imaging, metrology, and navigation become more mature, the DoD also should consider further prototyping of and experimentation with these technologies. Going forward, although the full impact of this second quantum revolution remains to be seen – and some skepticism is warranted – the United States must mitigate the long-term risks of technological surprise in this domain through leveraging its existing advantages in innovation.

Introduction

*"If it is correct, it signifies the end of science."*¹
—Albert Einstein

Today, technologies that harness the “spooky” properties of quantum physics are rapidly becoming a reality. Although the United States has been an early leader and a pioneer in this domain of science, China is rapidly advancing, with aspirations to take the lead in a new generation of quantum technologies.² Backed by national leadership at the highest levels, Chinese researchers are achieving notable progress in a variety of disciplines of quantum science. To date, China already has emerged as a world leader in research and applications of “uncrackable” quantum cryptography, which can enhance the security of communications. The launch of the world's first quantum satellite, Micius (or Mozi, 墨子) in August 2016 first prominently showcased China's progress and ambitions to the world. Since then, Micius, the start of a future Chinese constellation of quantum satellites, has been used for groundbreaking experiments under the Quantum Experiments in Space Science (QUESS) program. Chinese competitors are starting to catch up in quantum computing, which will create immense computing power that could overcome prevalent types of encryption. Concurrently, Chinese research and development in quantum radar, sensing, imaging, metrology, and navigation could have direct military applications. Chinese scientists also are starting to focus on the potential of new quantum materials, known as topological insulators, which will have utility in energy, semiconductors, and quantum computing. Potentially, each of these technologies could rewrite the rules of how information can be used and processed. Looking forward, China's advances in quantum technologies have the potential to alter the military and strategic balance.

Chinese research and development in quantum radar, sensing, imaging, metrology, and navigation could have direct military applications.

The Second Quantum Revolution

“Those who are not shocked when they first come across quantum theory cannot possibly have understood it.”³

—Niels Bohr

At present, we are in the midst of a “second quantum revolution” in which continued advances in quantum physics are giving rise to disruptive new technologies, just as the first quantum revolution unlocked secrets about the nature of reality.⁴ Although the future trajectory of these new quantum technologies is difficult to predict, the growing recognition of their potential revolutionary ramifications has intensified international competition. In recent history, U.S. researchers have been at the forefront of global progress in quantum science and technology. Today, however, the U.S. lead is increasingly challenged as other nations – particularly China, as well as top teams in Canada, Australia, and Europe – are rapidly advancing.⁵ It is worth noting that for the most part, the latter teams have built upon a foundation of U.S. funding and engagement, often involving close collaboration with the U.S. military and intelligence community, whereas Chinese efforts reflect more fully indigenous innovation.⁶

Overview of Quantum Technologies

At a basic level, quantum science harnesses the strange, often counterintuitive properties of quantum physics. Once realized and employed at scale, the resulting technologies could establish exciting new paradigms in just about every context in which information is used, stored, collected, or processed, providing vastly more powerful instruments for security, computation, and measurement. Beyond their lucrative and impactful commercial applications, these quantum technologies also will have a range of applications in and implications for national security and defense.⁷

GENERAL PRINCIPLES

To date, advances in quantum science have enabled the development of a range of technologies that include quantum computing, cryptography, and metrology, among others. Although these technologies reflect distinct disciplines with disparate applications, all leverage several fundamental properties of quantum phenomena. The concept of “superposition” refers to the ability of a particle, like a photon, to exist across all possible states at the same time. Another, entanglement, involves linkage among two or more particles such that

their properties are interrelated. Einstein famously – and quite derisively – characterized entanglement as “spooky action at a distance.” The observation of a particle or entangled pair will “collapse” the system, resulting in de-coherence and the return of the system to a classical (non-quantum) state.⁸ Such strange properties give these technologies their unique power and potential.

QUANTUM CRYPTOGRAPHY

The inherent qualities of quantum states enable quantum cryptography to be “uncrackable,” at least in theory. The most prevalent approach is known as quantum key distribution (QKD), through which cryptographic keys are exchanged in quantum states through entanglement. In accordance with the “no cloning” theorem, quantum information cannot be copied, and any attempted interference or eavesdropping within a quantum system can be readily detected.⁹ As such, this secure mechanism for key exchange can be used to encrypt communications through classical techniques, often over existing fiber-optic cables. Theoretically, quantum key distribution ensures “perfect,” or rather “provable,” security, including against future quantum computers, which will have the power to break prevalent types of classical encryption.¹⁰ If executed correctly, this form of quantum cryptography can enhance the security of networks used for quantum communications. To date, concerns over information security have been a major impetus for significant national and growing commercial investments in this field. A major advantage of using quantum cryptography to secure information and communications is that the recipient and sender can determine if the message has been intercepted. At present, there are two primary forms of quantum communications networks: the use of QKD across nodes connected by fiber and “free space” quantum communications (i.e., over open air).

At present, transmitting information through fiber-optic networks tends to limit the range of QKD, whereas free space quantum communications, such as between a ground station and satellite, can allow the scaling up of quantum communications to a greater distances. However, free space introduces potential forms of interference. Only recently was the “nocturnal problem,” which initially limited the use of quantum communications to nighttime due to interference from daylight, at least partly resolved.¹¹ To at least a limited extent, quantum communication also is feasible underwater, including in seawater.¹² There also have been advances in quantum secure direct communication, a technique that involves the transmission of information itself, rather than only the key, in quantum form.¹³

A major advantage of using quantum cryptography to secure information and communications is that the recipient and sender can determine if the message has been intercepted.

In practice, the perfect security that quantum cryptography promises may not be achievable. The substitution of QKD for conventional encryption does not eliminate other weak links and vulnerabilities in the security of a system. Thus far, QKD has confronted a range of practical challenges in implementation beyond the laboratory.¹⁴ Given the considerable logistical and technological difficulties, QKD, according to the initial assessment of a report from the U.S. Air Force Scientific Advisory Board, did not appear to confer enough of a security advantage to warrant the added complexity necessary for its use, relative to the best classical alternatives available.¹⁵ There have even been several demonstrations of techniques to hack, spoof, or otherwise interfere with commercial quantum cryptographic systems, such as through side-channel attacks and means of interception that remain below the expected error threshold or replicate data surreptitiously.¹⁶ The detection of these potential loopholes has since enabled measures to mitigate those vulnerabilities and better verify the security of quantum systems. But it remains to be seen whether this promise of “perfect” security will ever be more fully realized.

QUANTUM COMPUTING

While traditional “classical” computers perform calculations using standard “bits” that exist in states of 0 or 1, quantum computing employs “qubits.” These quantum analogues of the “bit” exist in a superposition of all possible states, thus enabling an extreme, even exponential advantage in computing capabilities.¹⁷ At present, recognition of the power and potential of a full-scale, generalizable quantum computer has been the primary impetus for high levels of private sector and national funding for research and development. The potential military and commercial applications of quantum computing could be nearly endless, applicable wherever speed and processing power are at a premium. Those suggested to date include large-scale simulations for complex systems, new frontiers of research in biology and chemistry, and the acceleration of machine learning.¹⁸

Presently, a general-purpose, full-scale quantum computer does not yet exist, and there are several potential pathways that could enable future quantum computing. D-Wave, a Canada-based company, has developed what is sometimes characterized as a quantum computer. However, this computer uses “quantum annealing,” a form of computation that does not clearly demonstrate the “quantum speedup” that would arise with “true” quantum computing.¹⁹ To date, most industry teams, including IBM and Google, have focused primarily on the use of superconducting circuits that are cooled to extreme temperatures.²⁰ Some research teams also have started to explore the use of trapped ions to create quantum simulators of over 50 qubits.²¹ New techniques for optical quantum computing involving interactions between photons also are believed to be promising.²² In addition, recent advances in topological quantum computing, which leverage the topological properties of certain particles, could prove fairly robust against error and disturbance relative to other approaches,²³ and Microsoft, among others, is starting to explore this approach.²⁴ Given these disparate approaches to its development, quantum computing will not be a singular phenomenon.

At present, the quest for “quantum supremacy,” the point at which a quantum computer is capable of outperforming a traditional, classical computer, is commanding headlines.²⁵ Notably, in March 2018, Google introduced the Bristlecone, a new quantum computing chip that has 72 qubits.²⁶ However, researchers at Alibaba’s quantum computing laboratory have challenged Google’s claims that it is on the verge of achieving quantum supremacy through this chip,²⁷ based on a classical simulation that suggested that error rates would still be too high to allow for true quantum supremacy.²⁸ Chinese researchers have also claimed to be on track to achieve quantum supremacy (量子霸权), perhaps as soon as 2018 or 2019.²⁹

The path to quantum computing may be long and tortuous, and considerable challenges will remain beyond the achievement of quantum supremacy.

Beyond this symbolic, often over-hyped milestone, there will continue to be significant technological barriers that need to be overcome to develop a fully capable quantum computer that is useful practically. Critically, the correction of errors remains a major challenge, though there are known and promising techniques

to enhance control over qubits.³⁰ In addition, it will be challenging to design new algorithms and software appropriate for quantum computers.³¹ The path to quantum computing may be long and tortuous, and considerable challenges will remain beyond the achievement of quantum supremacy.

Despite these remaining obstacles, there are reasons for concern that the advent of quantum computing could undermine prevalent encryption standards. Using Shor's algorithm, a quantum computer of sufficient capability – though estimates on the number of qubits and likely timeframes required vary – would be able to crack types of encryption that are based on the difficulty of prime factorization, which would be impossible to achieve in a feasible time frame with a classical computer.³² In 2015, likely in response to progress in quantum computing, the National Security Agency (NSA) updated its “Suite B” encryption methods to ones that focused on “quantum resistant” encryption, or encryption standards that would be beyond a quantum computer's ability to break.³³ The National Institute of Standards and Technology (NIST) also has sought to advance the development of a set of such quantum-resistant encryption standards.³⁴ While certain types of cryptography, including lattice-based encryption, are less efficient but could be quantum-resistant, the use of quantum cryptography, such as QKD, also can serve as a shield against future quantum computers.³⁵

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For the military, as the information age ends, and a new age based on artificial intelligence and automation starts to emerge, powerful quantum computers, along with other forms of advanced computing, such as neuromorphic computing, promise to play a critical role.³⁶ The imperative for computing capabilities will only intensify as data and information emerge as a new strategic resource, requiring more advanced analytics.³⁷ The future computing landscape seems likely to be

fairly heterogeneous, with advanced forms of classical computing coexisting and sometimes integrated with quantum computing, depending on specific use cases and applications.³⁸

QUANTUM RADAR, TIMING, IMAGING, SENSING, METROLOGY, AND NAVIGATION

The employment of quantum phenomena to achieve highly precise and accurate detection and measurement can be leveraged for a range of applications. The realization of quantum radar, such as via entangled photons, could overcome stealth technologies and might be resistant to advanced forms of radar jamming. Several

Several variants of quantum sensors might enable militaries to detect stealthy, hidden, or underground targets.

variants of quantum sensors might enable militaries to detect stealthy, hidden, or underground targets. The techniques for “ghost” imaging (i.e., “two-photon imaging”), which typically involve non-quantum (or “classical”) properties at present but could leverage quantum properties further in the future, may have key applications as sensors in space-based intelligence, surveillance, and reconnaissance systems.³⁹ The use of quantum “clocks” for timing could enhance greater precision, critical in modern military operations. In navigation, a “quantum compass” could serve as a more accurate substitute for GPS, particularly in denied environments.

QUANTUM MATERIALS

The recent advances in research on ‘quantum materials,’ which have unique properties linked to quantum effects, are believed to have great promise. According to Professor Zhang Shoucheng of Stanford University, these materials could lead to “a new paradigm of information processing, in which electrons moving in opposing directions are separated into well-ordered lanes,” mitigating dissipation of energy as heat.⁴⁰ Potentially, the development of topological insulators, or quantum spin Hall (QSH) states, could make this a reality. QSH states have “gapless edge or surface states that are topologically protected and immune to impurities or geometric perturbations,” thus displaying “exotic physical properties.”⁴¹

China's Quantum Ambitions

“If we want to win the struggle for quantum supremacy, we must not be ‘guerrillas;’ necessarily, we must organize a ‘group army.’”⁴²

—Guo Guangcan, Key Laboratory of Quantum Information, University of Science and Technology of China

Chinese leaders at the highest levels believe that quantum technologies could become integral to future national competitiveness. Chinese President Xi Jinping himself has highlighted the criticality of quantum technologies to national security and strategic competition. Beyond the history of state support for basic research and China's current strategy for innovation-driven development, this agenda has taken on increased importance since the leaks of former NSA contractor Edward Snowden in June 2013. It appears that Snowden's revelations, which allegedly revealed the extent of U.S. intelligence capabilities and activities in China, intensified anxieties over domestic information security and vulnerabilities to cyber espionage and influence, provoking a search for new cyber security solutions developed indigenously.

Indeed, this incident has been so fundamental to Chinese motivations that Snowden has even been characterized as one of two individuals with a primary role in the scientific “drama” of China's quantum advances, along with Pan Jianwei (潘建伟), considered the father of Chinese quantum science.⁴³ Pan Jianwei also has noted that the Snowden affair reinforced his own sense of the urgency and importance of his work.⁴⁴ Against the backdrop of a broader campaign to enhance national cyber security, Chinese leaders seem to hope that shifting sensitive information and communications to quantum networks could allow the “shield” of quantum cryptography to mitigate vulnerability to adversary cyber espionage and signals intelligence capabilities.⁴⁵ In some cases, the resulting enthusiasm that China may possess about the “absolute security” of quantum communications could be excessive or unwarranted, since the promise of any unhackable system can be chimeric, due to perhaps inevitable systemic and human weaknesses that may remain, despite ongoing research dedicated to mitigating those vulnerabilities.⁴⁶

Regardless, the result of these security concerns has included an intensified focus on quantum communications, considered more secure against cyber espionage, and on quantum computing, which has the



Xi Jinping visited the University of Science and Technology of China in April 2016, and he is pictured here standing next to Pan Jianwei, China's most prominent quantum scientist. Xi's personal attention to quantum technologies is a strong indicator of the high-level importance of this domain. (Xinhua/Li Xueren)

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potential to reset the military and intelligence balance in China's favor. In September 2013, Xi Jinping and other Politburo members listened to remarks from Pan Jianwei on quantum communications and observed demonstrations of quantum communication technologies during a collective study session.⁴⁷ In November 2015, at 5th Plenum of the 18th Party Congress, Xi included quantum communications in the list of major science and technology projects (重大科技项目) prioritized for major breakthroughs by 2030, given their importance to China's long-term strategic requirements.⁴⁸ In April 2016, Xi visited and inspected the University of Science and Technology of China, where he listened to an update from Pan Jianwei on his progress in quantum communications and reaffirmed the importance of his research.⁴⁹ During the 36th Politburo study session on cyber security

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in October 2016, Xi also emphasized the importance of advancing indigenous innovation in quantum communications and other critical cyber and information technologies.⁵⁰ During his work report to the 19th Party Congress in October 2017, Xi emphasized the strategic imperative of innovation, highlighting the new technological revolution that is emerging, including rapid breakthroughs in artificial intelligence and quantum technologies.⁵¹

As China aspires to lead the second quantum revolution, Chinese leaders seek competitive advantage but also may be motivated in part by national pride. In recent history, the United States has been the epicenter of the information technology revolution, reaping the full commercial and military benefits. However, the current, though eroding, U.S. preeminence in this information technology will not necessarily confer substantial advantages in the pursuit of quantum science and technology. Rather, the United States and China are now competing on more equal footing. If its plans to advance quantum science are successful, China could even achieve a first-mover advantage and attain future market and military dominance in these new technologies. There are likely also considerations of national prestige, against the backdrop of Xi's call for rejuvenation and national narrative of the "China Dream" (中国梦), which have motivated efforts to maximize the publicity and attention for milestones like the launch of Micius, including through official propaganda.⁵² Indeed, in his January 2018 New Year's address, Xi highlighted successes in research and development of quantum computers as a major achievement for China.⁵³

China's Plan for Primacy in Quantum Science

China's increasing prioritization of quantum science is best reflected by its inclusion in and promotion through a series of national science and technology (S&T) plans and programs. Although state support for basic research dates back decades, the focus and amount of funding have intensified considerably in recent years. Of course, such initiatives have a mixed track record of success, and it remains to be seen whether or not China will emerge as a clear leader in quantum technologies. Nonetheless, at the very least, these plans reflect current priorities and act as an impetus for greater funding in this domain, along with a focus on recruitment of top talent through state plans. It remains to be seen whether China's traditional approach of pursuing national "megaprojects" that devote massive amounts of funding and resources to drive advances will prove effective in this case.

The initial foundation of basic research in quantum control and information in China was supported through funding sources that include China's National High-Technology Research and Development Plan or "863 Plan" and the former National Key Basic Research and Development Plan or "973 Plan."⁶¹ In 1999, Guo Guangcan (郭光灿), an early pioneer in Chinese quantum physics, who had started research in quantum optics as early as 1983, founded the Key Laboratory of Quantum Information (量子信息重点实验室), under the aegis of the Chinese Academy of Sciences.⁶² In 2001, Pan Jianwei, at the age of 31, returned to China after receiving a PhD from the University of Vienna, where he had worked closely with leading quantum physicist Anton Zeilinger, establishing the Quantum Physics and Quantum Information Laboratory (量子物理与量子信息实验室) at the University of Science and Technology of China (USTC).⁶³ The notable experimental advances achieved through their work in quantum communications evidently intensified interest in and funding for an ambitious long-term research agenda. As early as 2003, Pan Jianwei's team articulated the vision of an integrated world quantum communications network, formulating plans for future experimental quantum science satellites.⁶⁴

At present, these objectives seem to be within reach, and the levels of interest in and funding for quantum

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Quantum Science and Technology in China's S&T Plans and Policies

1986	National High Technology Research and Development Plan/Program (国家高技术研究发展计划, "863 Plan")	Supported dual-use research in quantum science and technology
1997	National Key Basic Research and Development Plan/Program (国家重点基础研究发展计划, "973 Plan")	Provided early support for basic research in quantum control, communication, and information technology
Jan. 2006	National Medium- and Long- Term Science and Technology Development Plan Outline (2006-2020) (国家中长期科学和技术发展规划纲要) ⁵⁴	Highlighted quantum control research to explore quantum phenomena, the development of related electronics, quantum communications, limited small quantum system, and artificial band gap systems, also emphasizing quantum computing
May 2015	Made in China 2025 (中国制造2025) ⁵⁵	Called for actively advancing quantum computing
Feb. 2016	National Key Research and Development Plan (国家重点研发计划) ⁵⁶	Replaced the 863 and 973 plans to support research and development in quantum control and quantum science
Mar. 2016	Thirteenth Five-Year Plan Outline (国民经济和社会发展第十三个五年规划纲) ⁵⁷	Mentioned quantum communications among priorities for strategic emerging industries
Aug. 2016	Thirteenth Five-Year National Science and Technology Innovation Plan (国家科技创新规划) ⁵⁸	Called for results in innovation on the quantum anomalous Hall effect and quantum communications Included quantum communications and computing among major S&T projects prioritized for advances by 2030, including R&D on a universal quantum computing prototype and practical quantum simulator Mentioned quantum navigation among technologies to advance aerospace sensing Prioritized quantum control and quantum information among major strategic forward-looking scientific questions
Dec. 2016	Thirteenth Five-Year National Strategic Emerging Industries Development Plan (国家战略性新兴产业发展规划)	Called for increased capability in ultra-high-definition quantum dot liquid crystal displays Focused on the continued development of quantum cryptography technologies and applications Highlighted the importance of an overall layout that included quantum chips, quantum programming, quantum software, and related materials and devices, promoting the realization of the physics for quantum computing and applications for quantum simulations
Aug. 2017	Thirteenth Five-Year Science and Technology Military-Civil Fusion Special Projects Plan (科技军民融合发展专项规划) ⁵⁹	Included quantum communications and quantum computing as priorities, while also highlighting quantum satellites among a series of new military civil-fusion S&T development projects
Jan. 2018	The State Council's Several Opinions Regarding Comprehensively Strengthening Basic Research (国务院关于全面加强基础科学研究的若干意见) ⁶⁰	Calls for strengthening basic research in quantum science Urges the quickening of the implementation of the "S&T Innovation 2030 Megaproject" in quantum communications and quantum computing

Although there is only limited authoritative information available on total levels of funding, it appears that the recent and current levels of funding will amount to billions of dollars, likely at least tens of billions of RMB.

science have progressively increased within the past several years. As of 2016, the large-scale reorganization of China's national-level research and development planning appears to have strengthened support for quantum science through the new National Key Research and Development Plan.⁶⁵ China has committed to a new "innovation-driven" development strategy, seeking to advance indigenous innovation (自主创新) and even become a leader in radical, disruptive innovation (源头创新).⁶⁶ For the Thirteenth Five-Year Plan time-frame (2016-2020), there is a clear focus on quantum technologies. Notably, the new National Science and Technology Innovation Program (国家科技创新规划) designated quantum communications and quantum computing as a prioritized "S&T Innovation 2030 Major Project."⁶⁷ By 2030, this project calls for the achievement of major advances in metropolitan and inter-city free space quantum communications technology, the development and manufacture of common-use quantum computing prototypes, and the development and manufacture of actual-use quantum simulators.⁶⁸

Although there is only limited authoritative information available on total levels of funding, it appears that the recent and current levels of funding will amount to billions of dollars, likely at least tens of billions of RMB. According to official media, China spent about 1.9 billion RMB (over \$302 million) in quantum science between 2013 and 2015.⁶⁹ In both 2016 and 2017, yearly levels of funding for the project on quantum control and quantum information under the National Key Research and Development Plan alone amounted to 1 billion RMB (\$159 million) across 18 research directions and up to 36 projects.⁷⁰ There also may be up to billions of RMB in funding provided to different projects through China's National Natural Sciences Foundation.⁷¹ In collaboration with the Chinese Academy of Sciences, funding for cooperation in space science and technology for the 2017-2020 time frame, which includes experimental quantum satellites, totals 160 million RMB (\$2.5 million).⁷² Notably, Alibaba will invest \$15

billion into disruptive technologies, including artificial intelligence and quantum technologies, through its new DAMO (Discovery, Adventure, Momentum, and Outlook) Academy.⁷³ Also of note, the PLA's Equipment Development Department is supporting research in quantum technologies, including through the National Defense S&T Key Laboratories Fund (国防科技重点实验室基金), which has provided funding for several projects involving quantum radar and sensing.⁷⁴ Given the increased prioritization of basic research, funding likely will continue to increase in the years to come.⁷⁵

Beyond national programs and funding, there also are a growing number of provincial initiatives emerging. The new Anhui Quantum Science Industry Development Fund (安徽省量子科学产业发展基金), created in December 2017, announced plans to devote 10 billion RMB (nearly \$1.6 billion) in funding to quantum computing, communications, and metrology.⁷⁶ As of March 2018, Shandong Province issued the Shandong Province Quantum Technology Innovation and Development Program (2018-2025) (山东省量子技术创新发展规划 (2018-2025年)).⁷⁷ This plan sets the objective for Jinan to be at the center of a new quantum technology industrial ecosystem with revenues reaching the scale of tens of billions of RMB claiming over 70% of the national defense market. To advance that objective, the Jinan Hi-tech Zone's "Quantum Valley" (量子谷) is intended to advance the creation of a quantum technology industry.⁷⁸ Going forward, other cities and provinces, potentially including Anhui, also may issue their own plans, and these local efforts could prove effective in enabling innovation ecosystems or, alternatively, might result in the misallocation of resources characteristic of state planning.

China has established a number of new institutions to pursue cutting-edge research and development. In July 2017, the Chinese Academy of Sciences established the Quantum Information and Quantum Science and Technology Innovation Research Institute (量子信息与量子科技创新研究院).⁷⁹ As of September 2017, the Chinese government also is building the National Laboratory for Quantum Information Science (量子信息科学国家实验室), which will become the world's largest quantum research facility, in Anhui Province.⁸⁰ This new national laboratory, scheduled to be completed by 2020, will pursue advances in quantum computing and reportedly engage in research "of immediate use" to China's armed forces.⁸¹ This centralization of resources and researchers is intended to create synergies among the expertise and experience of interrelated disciplines to overcome technical and engineering obstacles. The

National Laboratory of Quantum Information Science has received 7 billion RMB (\$1.06 billion) in funding to start,⁸² and there are plans to invest a further 100 billion RMB (or about \$14.76 billion) in this laboratory over the next five years.⁸³

MILITARY-CIVIL FUSION IN QUANTUM SCIENCE AND TECHNOLOGY

It is clear that quantum technologies are prioritized within China's national strategy for military-civil fusion (军民融合).⁸⁴ China's national advances in quantum communications and computing, including its first and future quantum satellites, will be leveraged to support military purposes.⁸⁵ The Thirteenth Five-Year S&T Military-Civil Fusion Special Projects Plan (科技军民融合发展专项规划) included quantum communications, including satellites, and computing among the projects highlighted.⁸⁶ Within the Shandong Province Quantum Technology Innovation and Development Plan (2018-2025), there also is a focus on military-civil fusion, with a call to "promote the two-way transformation of military and civilian S&T achievements in quantum information technologies."⁸⁷

Beyond a wide range of academic laboratories and research institutes, Chinese state-owned defense conglomerates have started to engage in research and development regarding the military applications of quantum technology, including in partnership with academic institutions.

Beyond a wide range of academic laboratories and research institutes, Chinese state-owned defense conglomerates have started to engage in research and development regarding the military applications of quantum technology, including in partnership with academic institutions. For instance, as of 2015, the USTC established the Quantum Technologies Research and Development Center (中航科量子技术联合研发中心) in partnership with the Aviation Industry Corporation of China (AVIC).⁸⁸ In late 2017, USTC and the China Shipbuilding Industry Corporation established three joint laboratories.⁸⁹ The Beijing Academy of Information Science (北京量子信息科学研究院) was established in

The PLA's Academy of Military Science also has elevated its focus on quantum science and technology, against the backdrop of an intensified focus on defense innovation.

December 2017 as a collaboration among the Beijing Municipal Government, Chinese Academy of Sciences, Academy of Military Sciences, Peking University, and Tsinghua University, and Beijing University of Aeronautics and Astronautics, among others, under the leadership of Xue Qikun of the Chinese Academy of Sciences.⁹⁰ Future research collaborations among academic, industry, and defense institutions may contribute to the future development of these dual-use technologies.

At the same time, the PLA's Academy of Military Science (AMS) also has elevated its focus on quantum science and technology, against the backdrop of an intensified focus on defense innovation. In July 2017, AMS completed a reform and reorganization that included the establishment of the National Defense S&T Innovation Research Institute (国防科技创新研究院), which has sought to recruit "first-class scientific talents" for the construction of a "world-class" institution.⁹¹ Its new Front-line Cross-Disciplinary Technologies Research Center (前沿交叉技术研究中心) will pursue research in neuro-cognition, quantum technologies, and flexible electronics, among other fields.⁹² In early 2018, AMS reportedly introduced a contingent of 120 researchers, a significant proportion of whom had PhDs, to pursue research including military applications of intelligent unmanned systems and quantum technologies.⁹³

The PLA is likely to be involved in the relevant research and guidance even for projects that are framed as primarily scientific. In particular, the new PLA Strategic Support Force (战略支援部队, PLASSF) Space Systems Department (航天系统部) has consolidated control over a critical mass of space-based and -related capabilities, including related research and development. After the launch of Micius from the Jiuquan Satellite Launch Center, the PLASSF Political Work Department reportedly was involved in supporting publicity about this world's first quantum satellite.⁹⁴ In official meetings on such space science special research projects, researchers from the Space Systems Department's Jiuquan Satellite Launch Center and the Aerospace Engineering Research Institute (航天工程研究所) often

have participated.⁹⁵ Further exploration of applications of quantum communications in the PLA's space systems – and the expansion of this architecture – likely will occur under the PLASSF's guidance.⁹⁶ There also are researchers at the PLASSF's Information Engineering University who are actively engaged in research on quantum cryptography and communications,⁹⁷ including techniques for measurement-device-independent (MDI) QKD that could be less vulnerable to hackers.⁹⁸ The Information Engineering University also is supporting the creation of the Key Laboratory of Quantum Information and Quantum Cryptography of Henan Province,⁹⁹ and it plans to create a future Quantum Cryptography Laboratory that will build upon its current research, while perhaps also leveraging its academics' engagements with the academic and technical communities.¹⁰⁰

STANDARDIZATION

Beyond current research and development, China also is looking to reinforce a foundation for progress and even primacy in these technologies through setting the standards for their future development. In June 2017, the China Communications Standardization Association (中国通信标准化协会) established a Special Task Group on Quantum Communications and Information Technologies (量子通信与信息技术特设任务组), also known as ST7, with a Quantum Communications Working Group and a Quantum Information Processing Working Group.¹⁰¹ To date, this task force already has initiated several projects and pursued research on the creation of two national standards and one industry standard.¹⁰² The early development of these standards is intended to “support the healthy development of quantum communication technology and its industrial applications in China.”¹⁰³

China's Pursuit of Quantum Talent

Beyond questions of funding, the most critical resource in this case may be talent, which can be attracted and retained through the ability to fund research and provide incentives. The government's concerted attempts to recruit top talent through state plans will be a key factor, such as the Thousand Talents Plan (千人计划), which has incentivized the return of over 7,000 scientists in total as of January 2018, including among its number Pan Jianwei himself.¹⁰⁴ Many leading Chinese quantum physicists have become key figures in Chinese quantum science and technology after receiving PhDs from and pursuing research at top U.S. and international institutions.¹⁰⁵

The future education and recruitment of world-class talent in quantum science will be a critical determinant of China's future trajectory in this domain.

The future education and recruitment of world-class talent in quantum science will be a critical determinant of China's future trajectory in this domain. Indeed, since the early 2000s, under Pan's leadership, a number of students have been sent to study at some of the world's top university programs, with their commitment to return back to China and contribute to building up a leading indigenous research program.¹⁰⁶ Pan initially studied under Anton Zeilinger, a leading expert in quantum communications, at the University of Vienna, and a number of his team members have undertaken a similar trajectory with his support and encouragement. From 2003 to 2008, Pan worked on research on at the University of Heidelberg in Germany with a focus on developing quantum storage technologies, before leaving the lab and returning to China along with a number of his colleagues.¹⁰⁷ Chen Yu'ao (陈宇翱) pursued his PhD and contributed to research on quantum cryptography at the University of Heidelberg.¹⁰⁸ Lu Chaoyang (陆朝阳) undertook his PhD research on quantum dot and optics at the University of Cambridge.¹⁰⁹ Zhang Qiang (张强) studied single-photon detection technology at Stanford.¹¹⁰ Xu Feihu (徐飞虎), recruited through the “Young Thousand Talents” plan, pursued post-doctoral research that included a focus on photon-efficient communication and single-photon imaging at MIT.¹¹¹ Notably, Wang Haohua (王浩华), who has since emerged as a key player in China's pursuit of quantum computing, completed his PhD at Penn State and then was a postdoc at the University of California, Santa Barbara,¹¹² where he collaborated with John Martinis' team (which has since been recruited to Google) on quantum computing, including on the use of superconducting qubits.¹¹³ Wang has contributed to the success of a Chinese team in entangling ten superconducting qubits as of April 2017, reportedly beating Google's record.¹¹⁴ There even have been several foreign quantum physicists who have been attracted to set up labs and pursue research in China due to the resources and opportunities available.¹¹⁵ Of note, Alibaba's DAMO Academy has recruited Hungarian-American scientist Mario Szegedy, formerly a professor at Rutgers, to join its new quantum computing laboratory, where he will pursue research on quantum algorithms, especially their applications in machine learning and optimization.¹¹⁶

In some cases, the tech and/or knowledge transfer associated with this active poaching and recruitment of top talent and their engagements in research abroad can raise questions. Pan Jianwei has highlighted that his time working as a researcher abroad was aimed at contributing to the future development of quantum science in China. In particular, based on agreement with his university, as well as support and permission from the Chinese Academy of Sciences and China's Ministry of Education, during his time engaged in study and research abroad, he has said, "we had a basic commitment, to bring this technology back to [China] when the moment comes. If not, ... how did about a dozen of us on this team all return around almost the same time in 2008? We had a very serious agreement, or say promise, that we must return and do things for the final major objective..."¹¹⁷ In some cases, these overseas engagements aimed at advancing China's indigenous technological developments may even pose a "dual-use dilemma." For instance, at the PLA National University of Defense Technology (NUDT) Center for Interdisciplinary Quantum Information Science (量子信息学科交叉中心), one researcher returned to "devote all his energy to the military,"¹¹⁸ after pursuing post-doctoral research at Stanford University.¹¹⁹

Beyond these talent plans, China's agenda in quantum science also has been enabled through a range of research collaborations and partnerships.¹²⁰ Of course, it is worth noting that Micius, the world's first quantum satellite, was developed and launched through collaboration between Chinese and Austrian researchers – who had hoped but failed to receive money for a European quantum satellite – with a partnership between the Chinese and Austrian Academy of Sciences.¹²¹ There also are a number of further partnerships being established, including the Tsinghua-Michigan Quantum Information Joint Center,¹²² the Tsinghua-Waterloo Quantum Computing Joint Center,¹²³ and a joint research center on quantum computing established as a partnership between Chinese defense conglomerate CETC and the University of Technology Sydney.¹²⁴ There is extensive and institutionalized cooperation between researchers at Stanford University from Zhang Shoucheng's team and Tsinghua University. The Sino-British Joint Laboratory for Space Science also may work on quantum sensing.¹²⁵ Although China is clearly capable of truly indigenous innovation in these technologies, such research partnerships also can contribute to advances.

CASE STUDY: COLLABORATION IN QUANTUM MATERIALS

The pursuit of basic and applied research on quantum materials appears to be a major focus of collaborative



Zhang Shoucheng received a major award for S&T cooperation from the Chinese government, and he is pictured here with Xi Jinping and Li Keqiang in the background. (Ju Peng/Xinhua)

research between U.S. and Chinese researchers, with support through Chinese state funds and talent plans.¹²⁶ As of 2009, Zhang Shoucheng, who has received funding for his research from the U.S. National Science Foundation and Department of Energy,¹²⁷ also was selected for the Chinese government's "Thousand Talents" (千人计划) Program.¹²⁸ Pursuant to this program, he was appointed as professor at Tsinghua University's Institute for Advanced Studies and has also become a foreign academician for the Chinese Academy of Sciences.¹²⁹ In addition, Zhang has served as overseas strategic scientist on the advisory committee for Zhongguancun Science Park,¹³⁰ a state-sponsored innovation demonstration zone that also is starting to focus more heavily on military-civil fusion in next-generation technologies. In his work at Tsinghua, Zhang has collaborated closely with Tsinghua professor Xue Qiqun (薛其坤), pursuing joint research on quantum spin Hall effect and topological insulators,¹³¹ as co-director of Tsinghua's Quantum Science and Technology Research Center (量子科学与技术研究中心).¹³²

This collaboration reflects the Chinese government's focus on leveraging talent and research collaborations to advance indigenous innovation in technologies that may have impactful commercial, and perhaps future military, applications. In January 2018, Zhang Shoucheng was awarded the People's Republic of China International Science and Technology Cooperation Award.¹³³ His extensive cooperation with Chinese research institutes has been characterized as a key "bridge" contributing to China's efforts in advancing research on the quantum anomalous Hall effect and topological insulators, which could be leveraged to engender a new generation of

This collaboration reflects the Chinese government's focus on leveraging talent and research collaborations to advance indigenous innovation in technologies that may have impactful commercial, and perhaps future military, applications.

semiconductors, future techniques for energy generation, and even a promising approach to quantum computing.¹³⁴ In his remarks at the time, he particularly highlighted his commitment to the pursuit of further cooperation on overcoming the scalability limitations and challenges of error correction in quantum computing, as well as next-generation research on the use of artificial intelligence to predict new types of quantum materials.¹³⁵ Although scientific cooperation should be promoted and encouraged, there may be cases in which the potential risks or unexpected externalities also should be taken into account.¹³⁶

China's Advances in Quantum Technologies

*"Scientists are beginning to control the quantum world; this will greatly promote the development of information, energy, and materials sciences, bringing about a new industrial revolution."*¹³⁷

—Xi Jinping, General Secretary, Chinese Communist Party and President, People's Republic of China

China's advances in quantum science and technology may reflect the start of a paradigm shift in the nation's quest for indigenous innovation, building on decades of work by leading researchers. China's rapid progress in quantum technologies – and efforts to leapfrog the United States in this domain – can be evident based on such metrics as the patent applications filed in each discipline, with China leading in quantum cryptography and

second to the United States in quantum sensors, while still only ranked fifth in quantum computing as of 2015.¹³⁸ Although allegations and indications of tech transfer and intellectual property theft often have marred China's progress and reputation for scientific and technological development, these recent advances in quantum science, particularly quantum cryptography, offer compelling evidence and initial indicators of truly "made in China" innovation, though often enabled by international collaboration. In the case of China's quantum satellite, a historic milestone in the field, this element of pride was evident in its high-profile showcasing in official media. Of course, extensive and ongoing collaboration with top researchers at the University of Vienna, including Pan Jianwei's former mentor and later rival Anton Zeilinger, and from other international institutions also have contributed to this project. (Perhaps unsurprisingly, Austrian scientists' contributions are infrequently recognized or highlighted in Chinese media accounts of the project.) Increasingly, China's consistent advances in quantum technology have emerged as a flagship venture that reflects the nation's intended trajectory toward emerging as a true scientific superpower.

China's Leadership in Quantum Cryptography and Communications

Building upon robust research, China is rapidly progressing in the development and operationalization of quantum cryptography and communications. The relative maturity of these technologies is indicated by the significant, increasing number of patents and publications that Chinese universities and companies have received and released within the past several years.¹³⁹ Increasingly, national quantum networks are leveraged to secure China's most sensitive military, government, and commercial communications. These future quantum communications networks will involve both terrestrial wide-area networks over fiber and quantum satellites linked with ground stations.¹⁴⁰ At this point, the actual utility of quantum cryptography continues to be debated, but it is clear that China is heavily invested in its potential.

Recent advances in quantum science, particularly quantum cryptography, offer compelling evidence and initial indicators of truly "made in China" innovation, though often enabled by international collaboration.

CHINA'S NATIONAL QUANTUM NETWORKS

At present, China is engaged in a massive initiative to operationalize quantum communications to secure its most sensitive networks nationwide. China has completed the world's most extensive quantum communications system, which officially entered use in September 2017.¹⁴¹ The "Quantum Beijing-Shanghai Trunk" (量子京沪干线) extends 2,000 kilometers (approximately 1,240 miles) between Shanghai and Beijing, involving a total of 32 stations.¹⁴² According to Pan Jianwei, this quantum communications network will be used for the secure transmission of information in government, finance, and other sensitive domains, including national defense.¹⁴³

Within the next several years, this system is on track to be expanded nationwide, linked with multiple metropolitan-level quantum communications networks intended for use by local enterprises and governments. As early as 2009, USTC's Chinese Academy of Sciences Key Laboratory of Quantum Information (量子信息重点实验室) had established what it characterized as the world's first "quantum government network" in Wuhu, Anhui.¹⁴⁴ In 2012, for the 18th Party Congress, Pan Jianwei led a team of researchers to create networks for quantum communications to connect the venue with the delegates' hotel rooms and the leadership compound Zhongnanhai.¹⁴⁵ At the local level, metropolitan quantum communication networks also were constructed in Hefei and Jinan as early as 2012 and 2013.¹⁴⁶ By 2016, Tianjin was planning to establish a metropolitan-level quantum encryption communication network to enhance the city's level of cyber security.¹⁴⁷ In 2017, Wuhan's quantum cryptography and communications metropolitan area network was officially launched to ensure the "unconditional security" of government networks.¹⁴⁸ Also in 2017, Shandong launched the world's largest quantum communications metropolitan area network and the first commercial government special network.¹⁴⁹ Going forward, new branches of this network will include the "Wu-He Trunk" (武合干线), which will link Wuhan and Hefei,¹⁵⁰ and the "Qi-Lu Trunk" (齐鲁干线), connecting Qingdao and Jinan.¹⁵¹

Meanwhile, Chinese researchers' continued advances in QKD constitute significant steps toward the development of more secure quantum networks, which potentially could shift the balance in information security toward defense. For instance, in November 2016, a paper coauthored by Pan Jianwei described recent advances in measurement-device-independent (MDI) QKD, which overcomes potential security vulnerabilities, including through detecting attempted eavesdropping.¹⁵² The research broke records with secure transmission over 404

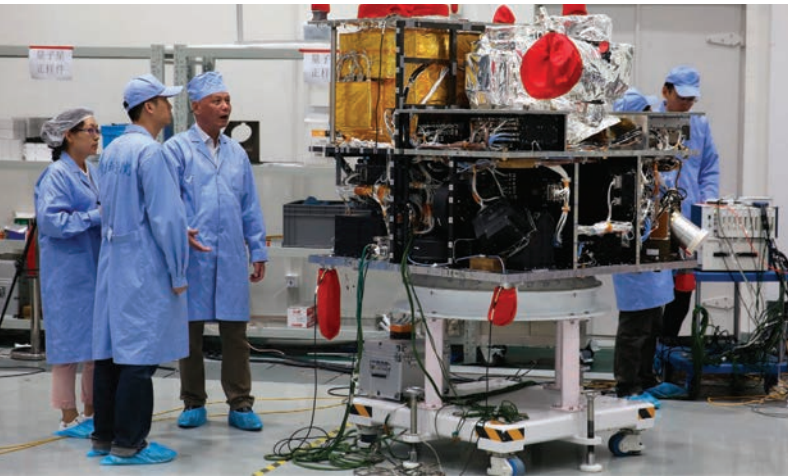
kilometers of optical fiber, concurrently demonstrating a 500-fold increase in speed, sufficient to enable encrypted voice transmission via telephone. As of November 2017, the demonstration of quantum secure direct communication, in which the message, rather than only the cryptographic key, is transmitted in quantum form, indicates that security could continue improving as well as the value proposition for quantum communications in general.¹⁵³ The Chinese defense industry appears to be working on these methods as well.¹⁵⁴

While such developments remain only experimental at this point, future advances in quantum communications could increase their utility for information security in a range of contexts. For the scalability of these technologies, reported progress in the development of a "quantum repeater," necessary to connect nodes in quantum networks and overcome limits on distance, reflects an important advancement of USTC's research as of November 2017.¹⁵⁵ At the same time, potential breakthroughs in the miniaturization of quantum communications also can enhance their practicality.¹⁵⁶ Significantly, there have been experimental indications of the feasibility of underwater quantum communications within a blue-green optical window in seawater of 400-500 nautical miles, in which "photons experience less loss and can therefore penetrate deeper."¹⁵⁷ Hypothetically, Chinese quantum networks also might extend underwater to include submarines, though water quality and potential interference could be a constraint in some cases.¹⁵⁸

Chinese scientists have ambitious objectives for their next five years of research in this discipline. According to the Chinese Academy of Sciences, to advance the creation of a new generation of information infrastructure, these researchers will continue the construction of a "national wide-area quantum confidential communications backbone network" (国家广域量子保密通信骨干), ensuring solid technical support for financial, government, power, telecommunications, and other private network applications.¹⁵⁹ At the same time, the researchers intend to achieve full localization of core quantum communication devices, formulate national technology standards for quantum communication, and participate in and dominate the formulation of international technical standards.¹⁶⁰

CHINA'S QUANTUM EXPERIMENTS IN SPACE

The launch of the Micius satellite in August 2016 drew global attention to China's rapid progress in quantum communications.¹⁶¹ Micius established a QKD network that transmitted information in quantum form between



The launch of the world's first quantum satellite, Micius, prominently announced China's quantum ambitions and attracted global media attention. (Cai Yang/Xinhua via ZUMA Wire)



The link between China's quantum satellite and a ground station in Tibet is pictured at night. Micius may be the first step to a future "quantum internet" that scales up secure communications within China and worldwide. (Xinhua/Jin Liwang)

Looking forward, China likely will leverage its advances with Micius to reinforce its global leadership in quantum communications.

the satellite and multiple ground stations.¹⁶² This launch was a component of Quantum Experiments at Space Scale (QUESS), a project initiated in 2011 that has involved collaboration between a team led by Pan Jianwei from the Chinese Academy of Sciences (CAS) and the Austrian Academy of Sciences. Although the Austrian and Chinese teams initially competed, this collaboration arose after the European Union was unwilling to fund a comparable project.¹⁶³ The primary mission of Micius was to engage in a series of scientific tests and experiments.¹⁶⁴ Similarly, the Tiangong-2 space station, launched in September 2016, was tasked to engage in QKD experiments.¹⁶⁵ Micius is only the first of what Chinese scientists intend to become a future constellation with multiple quantum satellites, including nano- and micro-satellites.¹⁶⁶ According to Pan's former mentor, Anton Zeilinger of the University of Vienna, who is a lead scientist in the project, this is not only an initial test of the feasibility of quantum communications via satellite but also constitutes a "a very significant step towards a future worldwide quantum internet."¹⁶⁷

The Micius satellite reflects the culmination of nearly two decades of steady progress on free space quantum teleportation, which involves the transmission of quantum states "over-the-air." As early as 2005, Pan Jianwei's team initially confirmed the feasibility of a quantum satellite in the world's first free space quantum communications experiment.¹⁶⁸ Since then, Chinese scientists have progressively increased the distance at which free space quantum communications can be operationalized, breaking several world records for distance in the process.¹⁶⁹ For instance, in 2012, Pan and his colleagues demonstrated successful quantum teleportation and entanglement across 100-kilometer free-space channels.¹⁷⁰ These experimental achievements have since extended beyond the laboratory, with the launch of this historic satellite. Sustained progress in techniques for quantum entanglement and quantum teleportation, which involves the transmission of quantum information from one location to another through entanglement, continues.

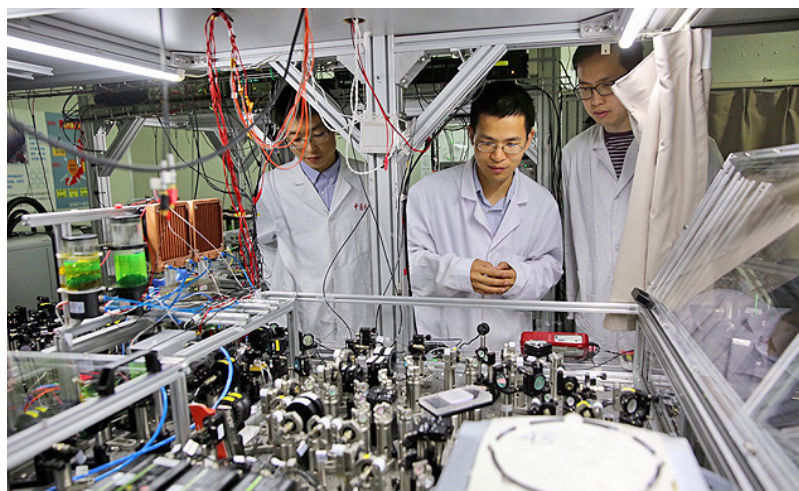
The launch of Micius has led to further advances through groundbreaking experiments. As of 2017, Chinese scientists reported successes in milestones for quantum science through a series of tests performed using this satellite through the QUESS program. As of January 2017, Chinese researchers announced their success in solving the so-called "nocturnal problem," which until then had limited the use of free-space communication to nighttime.¹⁷¹ Through Micius, Chinese scientists achieved ground-to-satellite quantum

teleportation at a distance of 1,400 kilometers.¹⁷² Micius also was used for the first realization of space-to-ground QKD, in which quantum keys were sent from Micius to ground stations at distances ranging from 645 kilometers to 1,200 kilometers, achieving a gain in efficiency an estimated 20 orders of magnitude greater than the use of optical fiber.¹⁷³ In September 2017, Micius even was used for a video call secured through QKD between the presidents of the Austrian and Chinese Academies of Sciences, the first intercontinental QKD, at a total distance of 7,600 kilometers.¹⁷⁴

Looking forward, China likely will leverage its advances with Micius to reinforce its global leadership in quantum communications. This agenda will involve not only building up quantum networks nationwide but also launching new quantum satellites that could allow expansion to Europe and ultimately worldwide. Incorporating a constellation of quantum satellites, China intends to create a quantum communications network between Asia and Europe by 2020 and a global network by 2030.¹⁷⁵ As of 2018, the Chinese Academy of Sciences Quantum Information and Quantum Technology Innovation Research Institute, with Pan Jianwei as president, established their major goals for the next five years.¹⁷⁶ In the field of quantum communications, the Institute plans to develop high-orbit quantum communication satellites, to create QKD that meets the operational requirements of sensitive sectors, and to develop and launch multiple micro- and nano-quantum satellites, forming a quantum cryptography satellite service network. Such advances would reinforce China's position as a global leader in quantum space science.

China's Quest for Supremacy in Quantum Computing

While Chinese advances in quantum cryptography have broken multiple world records and seemingly outpaced parallel efforts globally, Chinese efforts in quantum computing remain fairly nascent by contrast. Nonetheless, Chinese scientists are quickly starting to catch up with global progress in quantum computing, achieving notable advances.¹⁷⁷ As leading quantum scientist Guo Guangcan has emphasized, "Chinese scientists have been going all out to win the worldwide race to develop a quantum computer."¹⁷⁸ For instance, in August 2016, USTC scientists announced their successful development of a semiconductor quantum chip, which could enable quantum operations and information processing,¹⁷⁹ and also achieved a breakthrough that month in the preparation and measurement of 600 pairs of entangled quantum particles.¹⁸⁰ In October 2016, USTC researchers



Lu Chaoyang, a Chinese quantum physicist, and his students examine a prototype quantum computer. (Xinhua)

announced significant progress in quantum control that could foster future advances in quantum computing based on more precise quantum logic gates.¹⁸¹

At present, Chinese researchers are pursuing several different pathways toward future quantum computers, emerging as serious contenders in the process. These include the use of superconducting qubits, trapped ions, and topological qubits. In March 2017, a team of Chinese scientists from the University of Science and Technology of China, CAS-Alibaba Quantum Computing Laboratory, Chinese Academy of Science Institute of Physics, and Zhejiang University reported their success in entangling 10 superconducting qubits, a key step toward future quantum computing that broke Google's prior record of 9.¹⁸² As of July 2018, these Chinese scientists broke their own world record, successfully entangling 18 qubits.¹⁸³ This stable 18-qubit state is seen as a key step toward the achievement of large-scale quantum computing.¹⁸⁴

Beyond these record-breaking research advances, Chinese researchers also are progressing toward the development of quantum processors through a variety of techniques. In June 2017, Chinese scientists announced their success in achieving a new milestone in quantum computing through their construction of an initial form of quantum computer, a device known as a Boson sampling machine, capable of engaging in complex calculations.¹⁸⁵ In January 2018, a team at the USTC launched the world's first semiconductor quantum chip-based quantum computing cloud platform and a 32-bit quantum virtual machine. As of February 2018, a team of Chinese researchers jointly achieved further progress in quantum computing and quantum simulation based on a processor of ten superconducting qubits, simulating the multi-body localization effect.¹⁸⁷ In April



Leading Chinese quantum physicist Lu Chaoyang describes the applications of quantum computers during a presentation in Wuzhen. (Weng Xingyang/(Xinhua))

2018, researchers achieved experimental entanglement of 25 quantum interfaces that linked stationary qubits in quantum memory.¹⁸⁸ In May 2018, Chinese scientists from Shanghai Jiao Tong University and the USTC developed a photonic chip that can enable two-dimensional “quantum walks” of single photons in real space, which might boost analog quantum computing.¹⁸⁹

Chinese research in this discipline has started to involve a higher degree of private sector involvement and investment, motivated by the tremendous commercial potential of quantum computers. In China, the most visible and mature effort is occurring at the Chinese Academy of Sciences – Alibaba Quantum Computing Laboratory (中国科学院-阿里巴巴量子计算实验室), a collaboration between Alibaba’s cloud computing arm, Aliyun, and CAS that was initially established in 2015.¹⁹⁰ According to Pan Jianwei, who also serves as its chief scientist, the team will “undertake frontier research on systems that appear the most promising in realizing the practical applications of quantum computing.”¹⁹¹ Their pursuit of quantum computing will take advantage of “the combination of the technical advantages of Aliyun in classical calculation algorithms, structures, and cloud computing with those of CAS in quantum computing, quantum analog computing, and quantum artificial intelligence, so as to break the bottlenecks of Moore’s Law and classical computing.”¹⁹² As of March 2018, Baidu also has established an Institute of Quantum Computing,

recruiting Duan Runyao, a professor from the University of Technology Sydney, to lead their new team.¹⁹³

Looking forward, the Alibaba Quantum Computing Laboratory has articulated ambitious goals for its quantum computing efforts. Its team seeks by 2020 to achieve the coherent manipulation of 30 qubits, by 2025 to develop quantum simulation with calculation speeds to match those of today’s fastest supercomputers, and by 2030 to succeed in the “comprehensive realization of common-use quantum computing functions” through a quantum computer prototype with 50 to 100 qubits.¹⁹⁴ In November 2017, the laboratory launched a cloud-based platform for quantum computing that could start to promote the industrialization of quantum computing, in collaboration with the CAS Quantum Innovation Research Institute.¹⁹⁵ The laboratory has started to attract top talent,¹⁹⁶ including Yaoyun Shi, a world-renowned quantum computing scientist and tenured professor of the University of Michigan, who decided to join as its chief scientist in September 2017.¹⁹⁷

Since the race for quantum computing, in which U.S. teams have been leading, likely will play out over decades to come, Chinese scientists could take the lead in this marathon. As Pan Jianwei has noted, the eventual development of a quantum computer with 50 qubits could achieve “quantum supremacy,” surpassing the capabilities of classical computers, at least by certain metrics, by 2018 or 2020.¹⁹⁸ However, Pan anticipates that the creation of a “truly programmable, universal” quantum computer could require as long as between 30 and 50 years.¹⁹⁹ In addition, Pan has predicted that China will achieve leadership in quantum technologies, including computing, that is recognized internationally within ten to 20 years.²⁰⁰ According to the CAS, research objectives for the next five years involve quantum computing and simulators based on approaches that include photons, superconducting, silicon-based, nitrogen-vacancy color centers in diamonds, and super-cooled atoms, while at the same time achieving breakthroughs in topological and other systems.²⁰¹ Notably, in December 2017, the CAS established the Topological Quantum Computing Center of Innovation Excellence (拓扑量子计算卓越创新中心), which will integrate efforts across several different academic and research institutions focused on topological quantum computing, which is a more nascent but very promising pathway.²⁰² In this regard, Chinese

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researchers are focused on exploring a range of lines of effort and parallel pathways to quantum computing, which may have varying levels of maturity and probabilities of success.

QUANTUM ARTIFICIAL INTELLIGENCE

Looking forward, the potential convergence between artificial intelligence and quantum computing could constitute a particularly promising synergy, and China intends to leverage its strengths in these technologies. In February 2013, Tsinghua University's National Key Laboratory of Intelligent Technologies and Systems in partnership with the University of Technology, Sydney, a world leader in quantum computing, launched the Quantum Computing and Artificial Intelligence Joint Research Center, which is intended to pursue research on quantum software and applications of quantum computing in artificial intelligence.²⁰³ As early as 2015, Pan Jianwei reportedly achieved a breakthrough in the development of a quantum machine learning algorithm.²⁰⁴ Significantly, in January 2018, a team of researchers including Pan and Lu Chaoyang completed a proof-of-principle demonstration for an efficient quantum algorithm to extract useful information from noisy, unstructured data through use of a six-photon quantum processor.²⁰⁵ This breakthrough is characterized as providing “new insights into data analysis in the era of quantum computing.”²⁰⁶

China's New Generation Artificial Intelligence Development Plan (新一代人工智能发展规划), released in July 2017, also calls for advances in theoretical research in quantum intelligent computing.²⁰⁷ Recognizing promising convergences between AI and quantum science, the plan focuses on methods for quantum-accelerated machine learning, the establishment of models for convergence between AI and types of high-performance and even quantum computing, and the formation of high-efficiency, accurate, and autonomous quantum AI system setups.²⁰⁸ In China's quest to advance quantum computing, the use of machine learning also could support research to explore promising designs and pathways toward a future quantum computer. Once quantum computing starts to reach a point at which it is possible to operate algorithms off of quantum machines, this could accelerate the process of machine learning, for which computing capabilities remain a bottleneck

The development of quantum navigation will allow greater independence from space-based systems such as GPS or Beidou.

at present. Going forward, the trajectory of this domain remains to be seen, but China may be poised to emerge at the forefront of what has been characterized as a “quantum AI revolution.”²⁰⁹

China's Advances in Quantum Radar, Sensing, Imaging, Metrology, and Navigation

The reported advances of Chinese scientists and defense industry researchers in quantum precision measurement (精密测量), including quantum radar, sensing, imaging, and navigation, could have powerful military implications. Nor is China alone in its interest in and pursuit of these capabilities.²¹⁰ There are increasing investments worldwide in quantum radar, which may even have the potential to overcome stealth.²¹¹ The development of quantum sensing promises “spooky” sensitivity in detection, whereas quantum remote imaging and “ghost imaging” could enhance reconnaissance space-based surveillance capabilities, potentially also defeating stealth.²¹² The development of quantum navigation will allow greater independence from space-based systems such as GPS or Beidou. Going forward, China likely will prioritize capabilities with the potential to enhance intelligence, surveillance, and reconnaissance (ISR) capabilities. In particular, even if it may seem unlikely at present that these technologies will be able to overcome stealth, that potential capability may remain a priority, given the extreme U.S. advantage in stealth, the extent of U.S. reliance on stealth, and its significance in any future conflict.

It is difficult to evaluate with precision the maturity of these research and development activities. Potentially, certain claims and high-profile reporting on Chinese advances in these technologies in quasi-official media could have been intended to misdirect or exaggerate.²¹³ Since the research that has been reported and openly published likely only reflects a limited proportion of that which is occurring, it is challenging to evaluate the status of advances in this discipline. The inherent military applications of these technologies (and vagaries of Chinese propaganda) can confound outsider attempts to reach objective conclusions as to the state of Chinese progress on quantum radar and sensing. Nonetheless, the possibility that certain aspects of Chinese research in these disciplines could have advanced further than has been disclosed or expected should not be discounted. The number of research institutes pursuing quantum radar, sensing, and metrology, as well as the funding available, hint at a state-driven push to advance these technologies, with active efforts in academia and the defense industry alike.

There are indications that Chinese research on different types of quantum radar has progressed toward prototypes and field-testing of these technologies. In September 2016, a team of Chinese scientists from China Electronics Technology Group Corporation's (CETC) 14th Research Institute's Intelligent Sensing Technology Key Laboratory (智能感知技术重点实验室) reported their progress toward creating single-photon quantum radar capable of detecting targets up to 100 kilometers away with improved accuracy,²¹⁴ establishing a new record.²¹⁵ Their research was undertaken in collaboration with a team from USTC led by Pan Jianwei, CETC's 27th Research Institute, and Nanjing University.²¹⁶ The range of this quantum radar, which leveraged entanglement between photon pairs for sensing, is reportedly five times that of a laboratory prototype created in 2015 by an international team of researchers.²¹⁷ As of June 2018, CETC researchers have claimed that the next generation of their quantum radar system will be able to detect stealth bombers and "effectively monitor high-speed flying objects in the upper atmosphere and above," thus supporting the tracking of ballistic missiles.²¹⁸ Xia Linghao (夏凌昊), of CETC's 14th Research Institute, a lead scientist on this project, has said that the bulk of the theoretical work had been completed, such that it had entered the "experimental verification phase."²¹⁹ It is worth noting that this research institute and its affiliates have a fairly limited track record of available publications on these issues, which could imply that these efforts are overstated or simply could reflect the secrecy associated with their research.

In addition, there is active research under way to advance other types of quantum radar, including through leveraging photonic technologies for enhanced processing of radar. As of May 2017, the CAS Institute of Electronics (中科院电子学研究所) claimed to have successfully developed China's first prototype microwave photon radar (微波光子雷达样机), engaging in a successful "field non-cooperative imaging test," which reportedly demonstrated the rapid imaging of airborne targets.²²⁰ According to Li Wangzhe (李王哲), the researcher in charge of the project, the team succeeded

in developing the critical technologies, verifying the platform experimentally, and achieving systems integration and a series of field tests that involved the rapid imaging of random targets, demonstrating fast imaging and the capability to identify even subtler details of an aircraft.²²¹

China's advances in quantum sensing and imaging could enhance its space-based remote sensing and surveillance capabilities. Reportedly, researchers at the CAS Key Laboratory for Quantum Optics, under the leadership of prominent quantum optics physicist Han Shensheng (韩申生),²²² is building a prototype quantum "ghost imaging" device, leveraging quantum optical phenomena, for use on future Chinese satellites.²²³ Continuing from a successful experiment in 2011, their objective is to complete a prototype by 2020 and test the system in space by 2025, with large-scale applications by 2030.²²⁴ Gong Wenlin (龚文林), research director of the team, highlighted that their technology is designed to catch "invisible" targets like the U.S. B-2 stealth bombers.²²⁵ Already, a number of new devices have been developed and field-tested, and were ready for deployment on ground-based radar stations, planes, and airships.²²⁶ There is also research on high-resolution quantum remote sensing under way,²²⁷ under the leadership of prominent researcher Bi Siwen (毕思文) through the CAS Institute of Remote Sensing Applications, which reportedly has succeeded in developing a prototype.²²⁸ At the same time, China Aerospace Science and Technology Corporation 9th Academy's 13th Research Institute has been engaged in research on quantum imaging,²²⁹ while 5th Academy's 508th Research Institute established a Quantum Remote Sensing Laboratory (量子遥感实验室) in 2012 and has actively pursued research that leverages quantum optics.²³⁰

China's progress in quantum precision measurement, including new types of detection and navigation, could have particular utility for naval and maritime applications. Within the China Shipbuilding Industry Corporation (CSIC), several research institutes have specialized in quantum technologies, including the 724th in quantum detection (量子探测), and the 717th in quantum navigation.²³¹ In November 2017, CSIC and USTC also signed an agreement to establish three joint laboratories focusing on the development of quantum navigation, quantum communications, and quantum detection, which will reach receive approximately 100 million RMB (\$14.49 million) in investment.²³² Similarly, certain types of quantum detection might even spur advances in undersea warfare capabilities. The CAS has announced the success of researchers from the Shanghai Institute

China's advances in quantum sensing and imaging could enhance its space-based remote sensing and surveillance capabilities.

Such a system could have utility in the detection of U.S. submarines, thus enhancing PLA antisubmarine-warfare capabilities, if major issues such as background magnetic noise can be overcome.

of Microsystems and Information Technology in developing a superconductive magnetic anomaly detection array,²³³ which uses a range of superconducting quantum interference devices, in June 2017.²³⁴ Such a system could have utility in the detection of U.S. submarines, thus enhancing PLA antisubmarine-warfare capabilities, if major issues such as background magnetic noise can be overcome.²³⁵

The continuation of advances in quantum navigation technologies also could create new capabilities for operations in contested environments. The reported breakthroughs of the CSIC 717th Research Institute in quantum inertial navigation are seen as of great significance to improving future precision strike capabilities.²³⁶ Within the next three to five years, the CSIC seeks to achieve advances in interferometric atomic gyroscopes/atomic accelerometers, quantum gravity gradiometers, quantum time references, and atomic spin gyroscopes.²³⁷ In addition, under the China Aerospace Science and Industry Corporation, the Third Academy's 33rd Research Institute has been involved in the development of a nuclear magnetic resonance gyroscope prototype based on quantum technology that could be used in inertial navigation.²³⁸ Similarly, the Beijing Automation and Equipment Control Research Institute (北京自动化控制设备研究所) reportedly achieved a breakthrough in quantum navigation through a project that developed a magnetic resonance spin gyroscope in 2016.²³⁹ Beihang University also is recognized as a leader in quantum inertial navigation and precision measurement, and it will support the establishment of the National Defense Key Laboratory of Inertial Technologies (惯性技术"国防重点实验室) and the National Defense Key Academic and Laboratory of New-Type Inertial Instrument and Navigation System Technologies ("新型惯性仪表与导航系统技术"国防重点学科实验室).²⁴⁰ These technologies have clear applications for undersea warfare, potentially enabling greater precision in timing and navigation for Chinese submarines.

Going forward, Chinese researchers will continue to pursue a range of priorities in this discipline. For

instance, for the CAS Quantum Information and Quantum Technology Innovation Research Institute, future objectives include possessing world-leading quantum precision measurement equipment, to include research and development on quantum imaging radars and atomic gravimeters.²⁴¹ At the same time, the Institute aspires for great improvements in atomic clock accuracy and time-frequency network technologies, supporting the construction of a high precision timing system as national major S&T infrastructure.²⁴² It will be more difficult to evaluate progress in this domain due to the relative secrecy of such research and limited details released and published about scientific progress, but these lines of effort will merit continued scrutiny.

China's Pursuit of Promising Quantum Materials

Recent advances in topological insulators have promising applications in clean energy, quantum computing, and information technology. The research of Stanford professor Zhang Shoucheng (张首晟) has been particularly pioneering. By his characterization, these unique materials have the capability to act as an "electron superhighway" that could bring about a new "quantum leap for computing," such that future progress in information technology is no longer governed by Moore's Law, which is rapidly reaching its limits, but instead can enable continued growth past that quantum limit.²⁴³ There is ongoing research about the potential for topological insulators to be used in future semiconductor chips, due to their high efficiency in conducting electrons. As researcher Jian Wang from Peking University's International Center for Quantum Materials has highlighted, "Avoiding the scattering of electrons that occurs in today's computers would keep high-speed devices from experiencing chip overheating, destruction of the data stream, and a slowdown of operational speed."²⁴⁴ As the development of semiconductors remains a major priority and challenge for China, this potential next-generation semiconductor technology likely will be very appealing.

These topological insulators can act as thermoelectric materials, through which heat can be directly converted to electricity, potentially leading to a new energy revolution.²⁴⁵ Tsinghua's Quantum Science and Technology Research Center (量子科学与技术研究中心), of which Zhang Shoucheng serves as co-director, has signed a cooperation agreement with the ENN Group (新奥集团), one of China's largest private energy companies, for a project focused on thermoelectric properties of topological insulators and their applications.²⁴⁶ Zhang reportedly is acting as the chief scientist for ENN, leading

a team with members from ENN and Stanford in R&D on new-generation topological insulators for use in energy.²⁴⁷ In addition, Wuhan University's Quantum Materials Energy Conversion Collaborative Innovation Center (量子物质能量转换协同创新中心) is working on the use of quantum materials for energy generation.²⁴⁸ Although it is too soon to say whether such an "energy revolution" will actually emerge, this initial research under way may achieve further dividends in the long term.

The Strategic Implications of China's Quantum Leaps

*"The backbone of surprise is fusing speed with secrecy."*²⁴⁹
— Carl von Clausewitz

China's quest to pioneer rapid and disruptive advances in quantum technologies could enhance economic and military dimensions of its national power. These quantum ambitions are intertwined with the national strategic objective to become a science and technology superpower (科技强国). Rather than relying primarily on the "absorption" of foreign technologies in its pursuit of indigenous innovation, China instead intends to achieve truly disruptive, even "radical" innovation (源头创新) in strategic emerging technologies in which the United States does not yet possess, and may be unable to achieve, a clear or decisive advantage. If this second quantum revolution does prove transformative in the years and decades to come, China could emerge at its forefront. Increasingly, China is seeking to advance an "innovation-driven" strategy for its economic development and military modernization. In the near future, the commercial potential of these technologies could enhance China's economic dynamism, enabling it to seize market leadership in new industries. Despite their relative nascence, the military potential of quantum technologies is attracting the attention of PLA strategic thinkers.²⁵⁰ In particular, Xi Jinping has highlighted the

The notion or narrative that China cannot innovate, but only steals and copies, is outdated – and reflects a dangerous underestimation of growing Chinese capacity, scale of investments, and penchant for long-term planning.

A purely defensive strategy that seeks to deny Chinese firms and students' access to the U.S. innovation ecosystem is unviable and inadequate in the long term – and it would also preclude the United States from benefiting from Chinese innovation and research.

strategic imperative of military innovation, and the PLA is pursuing emerging technologies that may have the potential to disrupt the current military balance.

Increasingly, the notion or narrative that China cannot innovate, but only steals and copies, is outdated – and reflects a dangerous underestimation of growing Chinese capacity, scale of investments, and penchant for long-term planning. It is certainly true that much of China's defense innovation to date, such as in aerospace, has been enabled by and accelerated through legal, extra-legal, and illicit technology transfer.²⁵¹ Certain of China's advances in quantum science also have been accelerated through leveraging the expertise and experience of foreign researchers and leading universities. However, China's apparent success in quantum science and technology is an important bellwether for understanding the future of Chinese innovation, involving a model of state investment, international collaboration, and academic transfers of knowledge – in which Chinese students are encouraged and supported, often through state talent plans, to pursue education abroad and then return home. There likely will be continued efforts to take advantage of foreign talent and knowledge, particularly through joint laboratories and research collaborations.

In an environment in which no country has an unrivaled or preeminent advantage in emerging technologies, the dynamics of the diffusion of technologies, legal or otherwise, have shifted considerably. It is unclear whether any Chinese espionage that attempts to cut corners would actually enable future advances in this field. In any case, as the gap in innovation between China and the United States continues to narrow, traditional espionage may produce more marginal – and increasingly diminishing – returns, particularly in advanced technologies that require complex systems integration. Moreover, as China seeks to lead, rather than only catch up, in science and technology, the act of simply stealing may prove unviable and runs directly counter to the overarching objective of building up a human capital base

and research environment to sustain long-term leadership. For the United States, the challenge of defending against Chinese tech transfer is also starting to shift considerably. While the United States still possesses an advantage in quantum information science, it is no longer an undisputed leader in all disciplines and technologies that constitute this field of research. In this environment, a purely defensive strategy that seeks to deny Chinese firms and students' access to the U.S. innovation ecosystem is unviable and inadequate in the long term – and it would also preclude the United States from benefiting from Chinese innovation and research in areas where it has progressed further than the United States. As China continues to pour money into domestic capacity for innovation and support the creation of whole new markets built around these technologies, the locus of innovation may shift further away from the United States, if these trends are not met with a commensurate U.S. response in strengthening talent and its own domestic innovation capabilities.

Ultimately, the viability of China's quantum ambitions, while important, are eclipsed by the vigor in which these objectives are pursued by the Chinese government.

At the same time, certain of China's breakthroughs have resulted in excessive hype or alarm, and nuanced, balanced assessments of China's strengths and weaknesses in innovation will be critical to anticipate the implications and calibrate appropriate policy responses. For instance, it remains to be seen whether the major state-directed investments in quantum cryptography and large-scale construction of quantum communications infrastructure will deliver the desired dividends in the long term. There also may be cases in which 'technological propaganda' in official media exaggerates advances, whether to bolster Xi Jinping's narrative of China as a nation of innovation or to signal prowess to – or perhaps provoke undue concerns from – potential adversaries. Going forward, China must also confront and attempt to reconcile the apparent contradiction between the dynamism required to foster innovation and the adverse conditions, particularly increasingly authoritarian tendencies, in its regime. There are several systemic and structural factors that may act as major impediments to future innovation, from reports of aversion to risk-taking in the culture of research institutions to the impact of

guanxi and perhaps corruption or favoritism on the allocation of research funding.²⁵² Can China truly overcome these frictions to sustain innovation in quantum technologies? This report seeks to assess the reported advances carefully, but recognizes the inherent limitations in the use of open sources to this end. Ultimately, the viability of China's quantum ambitions, while important, are eclipsed by the vigor in which these objectives are pursued by the Chinese government; such efforts should be taken seriously, monitored closely, and evaluated rigorously going forward.

China's advances in quantum technologies may indicate a critical juncture in the trajectory of Chinese defense innovation and in U.S.-China techno-strategic competition. No longer content with merely being a fast follower and targeting weaknesses in U.S. ways of warfare, the PLA is seeking to emerge as a true peer competitor that might even cut ahead and surpass (弯道超车) the United States in new frontiers of military power. The United States must recognize the potential for a future in which it no longer possesses and perhaps cannot establish clear military-technological dominance relative to this great-power rival. Going forward, in a new era of Chinese military power, China intends to achieve predominance in Asia and to develop the capabilities to project power globally in defense of expanding Chinese overseas interests, with the strategic objective to emerge as a, if not *the*, world-class military by mid-century.²⁵³ In furtherance of these aims, the myriad military applications of quantum technologies could create new advantages for the PLA, perhaps even enabling an "offset" of traditional U.S. strengths. At present, quantum technologies remain at a nascent stage in their development, so it remains difficult to estimate their long-term trajectories. Nonetheless, certain PLA strategists and officers even anticipate that quantum technologies will radically transform future warfare, perhaps possessing strategic significance on par with nuclear weapons.²⁵⁴ Though seemingly unrealistic, that projection nevertheless reflects the intense interest with which PLA thinkers are already considering the military potential of quantum technology.

Going forward, quantum technologies could contribute to the disruption of today's information-centric ways of warfare, epitomized by the U.S. model of war-fighting. In particular, the advent of quantum technologies could result in new paradigms for information dominance, enhance targeting and domain awareness, and bolster economic competitiveness.

NEW PARADIGMS FOR INFORMATION

China's development of quantum cryptography and communications is occurring in the context of a broader national effort to enhance national cyber and information security. This agenda was triggered, at least in part, by the 2013 leaks by Snowden that allegedly revealed the extent of U.S. cyber espionage and signals-intelligence capabilities and China's relative vulnerability.²⁵⁵ Chinese leaders seem to hope that quantum networks can serve as a shield that ensures the "absolute security" of critical communications.²⁵⁶ That promise of perfect security likely will prove chimeric in actuality. China's massive investments in and construction of a quantum communications infrastructure could be dismissed as unlikely to achieve the desired effect. Almost inevitably, any system will have weak links in its security, and the relative complexity of quantum networks could limit their utility. Nonetheless, with China's rapid advances in quantum cryptography and communications, it does seem feasible – and perhaps not unlikely – that these technologies may turn out to have greater impact than those who dismissed their value initially had anticipated, including the enabling of communications underwater.²⁵⁷ If that is the case, then China may be well positioned to achieve an advantage in the information domain, since it is a clear leader and first-mover in the construction and employment of these networks at the national level, while also pioneering their global expansion. Moreover, this experience in research, development, and application of these technologies could ensure that China will be well-positioned to develop more advanced approaches to quantum networking in the future.

If implemented with success and at sufficient scale, the use of quantum cryptography could create new obstacles to and/or impose new costs upon collection, perhaps with the effect of functionally undermining superior U.S. cyber and signals-intelligence capabilities.

Could Chinese quantum networks undermine U.S. intelligence capabilities, denying collection of critical Chinese information and communications? Given the continued evolution of these technologies, and the evolving balance between offense and defense in

intelligence, that may remain an open question pending further technological advances and countermeasures, and perhaps is unanswerable for the time being. Nonetheless this is, at the very least, a question worth raising at this point, given the apparent direction of Beijing's intentions and motivations. If implemented with success and at sufficient scale, the use of quantum cryptography could create new obstacles to and/or impose new costs upon collection, perhaps with the effect of functionally undermining superior U.S. cyber and signals-intelligence capabilities. If able to better shield key military and governmental communications against adversary intelligence collection, China could achieve a key advantage in peacetime and wartime competition alike, resulting in a "going dark" phenomenon that increases competitors' uncertainty about China's plans and intentions.²⁵⁸

Looking forward, the PLA likely intends to leverage dual-use quantum networks and advances in quantum cryptography within its command, control, and communications architecture.²⁵⁹ Since the construction of a national quantum communications infrastructure is a priority in China's national strategy for military-civil fusion, those networks under construction likely will be made available for military employment, at least at the level of strategic communications for the PLA's five regional theater commands (or 'war zones,' 战区). As early as 2015, Pan Jianwei claimed in an interview, "China is completely capable of making full use of quantum communications in a local war. The direction of development in the future calls for using relay satellites to realize quantum communications and control that covers the entire army."²⁶⁰ For instance, it is significant that the Chinese military has started testing the "QNET BOX: quantum secure mobile private network equipment, which uses QKD via a local area network with a small mobile station and a handheld terminal (i.e., 'a quantum cellphone')."²⁶¹ In addition, the CSIC is planning to work on pilot experiments for QKD between Micius and different ships at sea.²⁶² As China builds up a constellation of quantum satellites, the ability to combine ground-based fiber networks with free space communications will enable the scaling of these systems to national and even global reach.

At present, assessments of the feasibility of China's quantum ambitions should account for the reality that these technologies are untested under adverse conditions, and their level of durability and survivability in a conflict scenario is unclear. Potentially, such systems could remain fairly fragile and quite vulnerable to adversary disruption. In addition, as their usage becomes

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more widespread, the incentives to develop better techniques to spoof, intercept, or otherwise interfere with such supposedly invulnerable communications will only increase. It seems to be too early to tell the extent to which it will be feasible to use quantum cryptography and communications in a contested wartime environment. Nonetheless, even if these networks prove only practical in peacetime, the potential informational and intelligence advantage that might be achieved through introducing new roadblocks to adversary intelligence collection nonetheless could increase uncertainty, perhaps even enabling strategic surprise.

Potentially, quantum communications also could have a more direct and disruptive impact if applied in the undersea domain. There have been at least experimental demonstrations that quantum communications can work underwater, and the PLA appears to plan to leverage quantum communications for its next-generation submarines.²⁶³ According to Wu Chongjian (吴崇建), a chief designer for submarines with the CSIC, the use of quantum communications could cause a “disruptive revolution in submarine technologies” that will allow China to emerge at the “world’s pinnacle” in their development.²⁶⁴ At present, submarines are limited in their capability to communicate underwater. As such, submarines only can engage in “lone wolf tactics” without coordination, which restricts their tactical usage. However, Wu argues that if this problem of underwater communications can be “fundamentally resolved” through the use of quantum communications, this will cause a revolutionary change in undersea warfare.²⁶⁵ Traditionally, the United States has had clear dominance in the undersea domain, but such advances in next-generation Chinese submarine technologies could impact that balance.

Critically, China’s nationwide transition to the use of quantum cryptography to secure communications also could have long-term dividends through creating a systemic resilience against the future capabilities of quantum computers, which may be able to defeat many common encryption standards. At that point in time,

not only will all information that is not protected by quantum-resistant encryption be vulnerable, but also all previously collected, encrypted communications could be cracked, which could reveal decades of sensitive, though historical, information and intelligence. (In this context, it is noteworthy that U.S. intelligence community guidelines requiring agencies to purge SIGINT collection after five years exempt encrypted communications.²⁶⁶) If China introduces quantum-resistant cryptography to protect its most sensitive communications sooner than other nations, then it will be less exposed at that point in time, gaining a relative informational advantage. The capacity to build this infrastructure at scale and propel a national transition to new cryptographic regimes could provide an advantage relative to other nations that might have less capacity or greater difficulties in coordinating this shift.

Indeed, since future quantum computing capabilities could undermine prevalent types of encryption, rendering computer and satellite networks vulnerable, even the distant risk of its actualization already is prompting calls for progress in options for “post-quantum cryptography.”²⁶⁷ The utilization of quantum computing for such offensive purposes, particularly to crack cryptography,²⁶⁸ is a clear and often hyped application of this immense computing power, as PLA academics affiliated with the influential Academy of Military Science have noted.²⁶⁹ For the PLA – which has characterized the United States as having a “no satellites, no fight” military and thus focuses on multiple kinetic and non-kinetic methods of targeting U.S. space systems²⁷⁰ – this capability could be seen as especially appealing and advantageous, given the potential to undermine the security of legacy communications and surveillance satellites upon which the U.S. military remains heavily dependent.²⁷¹ It remains to be seen how readily critical information systems can be updated with quantum and quantum-resistant forms of

The United States might confront the possibility that a strategic competitor such as China could develop quantum computing in secret, earlier than anticipated, and employ it against sensitive communications to outmaneuver or strategically outflank the United States.

cryptography, ranging from QKD to new techniques such as lattice-based encryption.²⁷²

Within our lifetimes, quantum computing could enable new vectors for attacks on the integrity of the battle networks upon which modern warfare is reliant. The capability to decrypt sensitive intelligence and communications, whether conveyed via fiber or satellite networks, would provide an extreme intelligence advantage, comparable to the critical advantages derived from the U.S. breaking of Japanese codes, including victory in the Battle of Midway.²⁷³ In the foreseeable future, the United States might confront the possibility that a strategic competitor such as China could develop quantum computing in secret, earlier than anticipated, and employ it against sensitive communications to outmaneuver or strategically outflank the United States. In a conflict scenario, this potential infiltration of isolated networks could feed efforts to preempt operational movements or sabotage U.S. systems, perhaps without the U.S. knowing the source of this vulnerability. So far, the majority of notable advances in quantum computing known to have occurred have been publicly announced, and there has been a high degree of openness in this field, but that could change going forward as the 'race' intensifies.

Certainly, valid concerns over the capability of quantum computing to crack encryption can be exaggerated. Although current estimates vary considerably, experts anticipate the first general-purpose quantum computer is still at least a decade away, perhaps several decades.²⁷⁴ The trajectory of future progress, however, is difficult to predict, and it is possible that a quantum computer able to run Shor's algorithm could be developed sooner than most experts now expect.²⁷⁵ At the same time, there also are reasons to question the feasibility of large-scale quantum computing given problems of de-coherence, which increase in scale as more qubits are added.²⁷⁶ There may be ample time for standard-setting bodies to develop, and for the public and private sectors to implement, new methods of post-quantum encryption. Whether they accomplish this, however, depends on whether they move with urgency and coordinate their actions across the public-private divide. As with other cyber security threats, those warning of future threats will have to persuade agencies and companies to shoulder the costs and inconveniences of adopting new, more secure protocols at scale.²⁷⁷ Increasingly, today's rapid advances in quantum computing highlight the imperative of starting the process of, at a minimum, shifting sensitive military and government networks to quantum-resistant encryption as soon as possible, which may be quite challenging when dealing with legacy

information technology architectures.

Looking forward, quantum computing could have a range of disruptive military applications given its potential to provide unprecedented computing capabilities. In the near term, types of quantum simulators or quantum annealing could enable military planners to run complex simulations or resolve highly complex problems, such as optimization. In the more distant future, quantum computing might be integrated into complex weapons systems. Although data is considered the critical strategic resource of the information age, the analytics and processing capabilities required to derive actionable insights from it could become the critical determinant of success in warfare in an age of AI. In this regard, the potential for quantum-accelerated machine learning, a priority in China's New Generation Artificial Intelligence Development Plan, could reflect a critical synergistic convergence between AI and quantum computing.²⁷⁸ The character of the information age – which has put a premium on collection, processing, and dissemination of data and intelligence – could change if once-reliable areas of collection, such as computer networks and the electromagnetic spectrum, become more contested or unavailable through technical means. As such, the immense capabilities of future quantum computers could provide a new military advantage based on the speed, precision, and timeliness of analysis and action in an environment in which information resources are limited. Are we on the verge of a new era of quantum information?

ENHANCED DETECTION AND DOMAIN AWARENESS

The distinct but interrelated disciplines of quantum radar, sensing, imaging, metrology, and navigation have direct and significant military applications that could make possible enhanced situational awareness in all domains of warfare. The "spooky" properties of quantum physics can be employed to achieve a degree of precision that goes far beyond the capabilities of classical technologies. As the future operating environment becomes ever more chaotic and complex, these new tools could provide a key edge for China as it seeks to expand its sensing and surveillance capabilities in the near seas and beyond. In particular, as the electromagnetic spectrum becomes increasingly crowded in times of peace and contested in times of war, the ability to ensure trust in sensors and operate independently of the spectrum's limitations will be critical for timing, sensing, and navigation. For instance, quantum clocks could generate greater precision in timing, critical to modern military operations, while quantum imaging and sensing could enhance future sensors.

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If operationalized, quantum radar could have the potential to overcome superior U.S. stealth capabilities through its extreme sensitivity, perhaps enabling the PLA to undermine this critical pillar of U.S. military power. PLA media has highlighted quantum radar as the “nemesis” of today’s stealth fighter planes that will have “remarkable potential” on the future battlefield,²⁷⁹ while the development of “ghost imaging” satellites has been characterized as potentially capable of seeing through stealth to overcome the ‘fog’ of the battlefield.²⁸⁰ In addition, certain descriptions of quantum radar even suggest that it would be able to defeat radar jamming techniques such as digital radio frequency memory jammers, which spoof a radar’s broadcasted signal to conceal an aircraft’s true location.²⁸¹ At present, it remains difficult to evaluate the timeframe within which quantum sensing and imaging will become a reality beyond the laboratory in a military context (or whether that would be publicly disclosed), including the challenges of miniaturization.²⁸² Certainly, China’s claims to have developed prototypes for quantum radar and quantum remote sensing should be met with some skepticism. Nevertheless, beyond the hype and enthusiasm, there appears to be broad consensus in the research community that these capabilities could become feasible eventually.²⁸³

Nonetheless, even the distant possibility of China developing sensing and imaging technologies capable of overcoming stealth merits consideration as a major disruption to the current military balance. Chinese strategists recognize that developing and deploying these systems early could enable China to achieve an initiative on future battlefields.²⁸⁴ In any conflict with China, the use of stealth would be a strategic imperative for the United States, critical to aircraft penetrating Chinese airspace to hold Chinese operational assets at risk. Therefore, quantum radar and imaging could be massive disruptive force – an “offset technology” – within the PLA’s suite of so-called anti-access/area denial or “counter-intervention” capabilities. If operationalized successfully, these new types of sensing could not only

undermine the U.S. advantage in stealth but also increase the likely costs of war, forcing the United States to accept higher levels of operational risk – and perhaps, at worst, someday nullifying billions of dollars spent on stealth for platforms operating in the Indo-Pacific. Given this risk, the United States should closely monitor Chinese developments in these technologies and should recognize that stealth might not be an assured advantage in a future conflict scenario.²⁸⁵

At the same time, quantum navigation and positioning, already relatively mature as technologies, could provide a new and valuable option for navigation. This “new generation of inertial navigation” will enable high-precision navigation without GPS, including for the guidance of precision weapon systems.²⁸⁶ This so-called “quantum compass” would be particularly useful for submarines and other maritime platforms, allowing them to determine their position with high levels of accuracy, without reliance upon satellites that might be taken out in a conflict scenario.²⁸⁷ The PLA intends to ensure that next-generation submarines will be equipped with quantum navigation, giving them independence from space-based positioning systems, which can be easily jammed.²⁸⁸ Indeed, Fan Guoping (范国平) of the China Shipbuilding Industry Corporation has highlighted:

A missile can be positioned with the help of satellite navigation; what if it is subject to interference? A nuclear submarine is hidden under water, but after a period of time it needs to ascend into a calibration position; what do [we] do about it being detected? Quantum navigation technology primarily solves these problems. Depending upon its own inertial navigation; without requiring satellite navigation, it can achieve long-term navigation time, high-precision, fully-autonomous navigation, and concealed operation for strategic nuclear submarines’ missions, for continuous execution of missions extending for hundreds of days, significantly increasing the concealed combat capabilities of these strategic submarines.²⁸⁹

For the United States, quantum navigation also might represent an option to overcome the risk that GPS might be unreliable or even entirely degraded in a future conflict scenario.

ECONOMIC COMPETITIVENESS

Beyond their utility in defense, quantum technologies will have a range of commercial applications that could create and transform markets. Given its emergence as a leader in quantum communications – and increasingly a serious contender in quantum computing – China could be in a prime position to be competitive in these emerging technologies. Increasingly, world-leading Chinese tech companies like Baidu and Alibaba seek to be at the forefront of this growing competition, and there are a number of enterprises, such as Quantum CTEK (科大国盾量子), which originated in research from the University of Science and Technology of China, that specialize in quantum communications.²⁹⁰ In October 2016, the first China Quantum Information Technology Industry Development Forum was convened in Beijing, which also marked the establishment of Quantum Information Branch of the China Information Association (中国信息协会量子信息分会), a new industry association.²⁹¹ Within Jinan's "Quantum Valley," a growing number of companies are involved in a nascent quantum industry.²⁹² For instance, Quantum CTEK has launched the QSS-ME, an open platform product supporting the development of mobile application products and also a new "quantum mobile phone," in partnership with ZTE.²⁹³ Meanwhile, Alibaba's cloud computing team Aliyun also has launched a cloud-based quantum cryptography platform for enterprises.²⁹⁴

Looking forward, Chinese leaders recognize that current U.S. dominance in information technologies may not confer any substantial advantages in pursuit of quantum science and technologies, resulting in a more level playing field. In the near term, some of the leading research and commercial applications of quantum computing will include in complex biology and chemistry, as well as machine learning.²⁹⁵ In addition to their military applications, quantum sensing and metrology also could be used in everything from medicine to oil and gas exploration. Concurrently, if the use of quantum materials, namely topological insulators, could lead to new and powerful semiconductors, then China's persistent struggles to gain ground in this industry could prove successful through a more radical disruption of the existing market. Meanwhile, its active initial exploration of the thermoelectric properties of these quantum materials also places

China in a favorable position to lead in what has been characterized as a potential new energy revolution.

If successful in its development of these technologies, China would benefit from a first-to-market advantage that, when coupled with its human capital and manufacturing foundation, could allow it to achieve and sustain global leadership in quantum technologies that could catalyze the next industrial revolution. Looking forward, as China pursues an innovation-driven strategy for both military and economic developments, its potential leadership in quantum technologies could thus create a range of new commercial opportunities across a wide variety of industries.

Conclusions and Recommendations

"Any sufficiently advanced technology is indistinguishable from magic."

— Arthur C. Clarke

China's high-level prioritization of quantum science reflects the recognition that this future technological revolution could enhance its military and economic competitiveness. In its quest to emerge as a scientific superpower on par with the United States, China is embarking on a major national endeavor to advance innovation in quantum technologies. As strategic competition intensifies, China is seeking to leapfrog the United States to seize the "commanding heights" in those emerging technologies critical to future power, including biotechnology, artificial intelligence, and quantum technologies. These megaprojects are undertaken in the tradition of Chinese techno-nationalism, with an approach linked to and modeled after China's "Two Bombs, One Satellite" (两弹一星) megaproject, which is celebrated for enabling China to catch up rapidly in scientific and defense capabilities despite its technical limitations at that time.²⁹⁶ Despite its traditional technological predominance, the United States does not possess – and may be unable to achieve – a clear or uncontested advantage in these new domains. If successful, China could thus offset current U.S. advantages by emerging as a pioneer in technologies that transform and reshape the dynamics of national economic competitiveness and military competition.

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For the first time in recent history, the United States is facing real dangers of technological surprises.

For the first time in recent history, the United States is facing real dangers of technological surprises.²⁹⁷ Of course, it is likely that U.S. efforts in quantum science extend well beyond those known and documented in the open source, and the United States also has opportunities to achieve its own “quantum surprise” through continued advances in and employment of these disruptive technologies. Nonetheless, at a time when China is redoubling its commitment to invest in and support basic research, there are real reasons for concern about the future of U.S. innovation given persistent declines in funding for basic research. Several U.S. government reports have documented shortcomings in the U.S. quantum innovation ecosystem, including the lack of high and consistent amounts of funding to sustain long-term research and development, institutional stovepipes that have prevented collaboration across disciplinary boundaries, and a lack of an adequate talent pipeline to attract and retain top scientists in this field.²⁹⁸ It is true that many U.S. teams and enterprises are actively investing in and pursuing quantum computing, among other quantum technologies. However, their priorities, incentives, and time horizons will not necessarily be in close alignment with those of the U.S. government and military.²⁹⁹ Whereas commercial advances in China might be more readily transferred for military employment pursuant to a national strategy of military-civil fusion, the historical closeness between industry, academia, and the military that fostered successful U.S. defense innovation in the past has since started to erode.

In response, the United States should consider redoubling existing initiatives that might advance U.S. leadership and innovation. Building upon ongoing and existing initiatives, U.S. policymakers should pursue the following measures to preserve American leadership in quantum technology and innovation.

1. Enhance U.S. national competitiveness in quantum science and technology

The United States should work toward a national strategy that ensures that basic and applied research in quantum information science receives adequate funding, while working to attract and retain top talent. Such an effort should build on existing programs advanced through

DARPA, IARPA, NIST, the Department of Energy, and the National Science Foundation, as well as national and military research laboratories. The United States should look to deepen and expand upon partnerships with academia and the private sector, while ensuring that there are sustainable levels of funding for basic and applied research that can be continued even in the face of budgetary uncertainties across the timeframes required for these technologies to come to fruition. To inform the development of national priorities and strategy, the Office of Science and Technology Policy might consider creating a Quantum Innovation Advisory Committee, composed of leading academics and researchers, which would provide independent assessments of the value and relevance of different disciplines of quantum science and technology.

It is important to create a center for gravity for U.S. quantum science in order to attract leading researchers, provide the specialized facilities and equipment necessary for high-end research, and encourage interdisciplinary collaboration. For that reason, the U.S. government should consider creating and funding a national laboratory for quantum science and technology that recruits top researchers, promotes partnerships among defense, academic, and commercial enterprises, leverages synergies among different disciplines of quantum science, and receives high levels of funding and freedom for long-term projects. The DoD also might consider establishing a “Quantum Center of Excellence” that coordinates among and/or consolidates existing military research initiatives.

Today, several new initiatives under consideration in Congress reflect critical progress but do not yet provide a fully integrated strategic approach. It is encouraging that Senator Kamala Harris (D-CA) recently introduced a bill in the Senate that would create a “Defense Quantum Information Consortium,” composed of defense, academic, and commercial researchers, which would focus on supporting and aligning quantum communication and quantum computing research between these sectors across the United States.³⁰⁰ Such a consortium should include a focus on quantum sensing, imaging, and metrology, given their potential military and commercial applications. This model, which bridges the divide between research efforts across sectors, can start to answer critical institutional and cultural limitations in promoting a unified, coordinated direction for U.S. quantum information science research. The House Science Committee also has introduced a bill to create a ten-year National Quantum Initiative to bolster R&D and pursue deeper public-private partnership.³⁰¹

Current efforts under consideration, however, have not yet fully addressed the talent gap in emerging technologies. The United States must recognize that top talent is the most important strategic resource and should seek to attract and retain leading researchers. To start, ensuring consistent and basic levels of funding will do much to retain talented researchers and incentivize others to stay in their fields, but it is inadequate in building a skilled pipeline of human capital able to meet the demands of industry and academia. The United States should consider establishing a scholarship program under the National Science Foundation, either parallel to or in conjunction with government-wide research initiatives mentioned above, perhaps modeled after the “cyber corps,” to encourage students to pursue careers in emerging technologies such as quantum science. Such a program would require a service commitment from students, which could be filled by work in government, military, academic, or research institutions participating in government-led quantum initiatives.

2. Evaluate the risks of quantum computing to critical infrastructure and calculate the costs of mitigation

While continuing to explore the variety of options for post-quantum encryption that NIST is pursuing, the U.S. government also must start to evaluate costs and timeframes associated with a military, government, and even private sector transition from today's encryption to a new regime resistant to quantum computing. The U.S. government should direct the DoD and Department of Homeland Security to jointly prepare a study assessing the length of time, cost, and technical challenges associated with transitioning government networks to quantum-resistant cryptographic standards. The study should assess ongoing modernization efforts of military and federal networks to identify the earliest date where network infrastructure, systems, and devices would be able to accommodate the technical challenge posed by adopting quantum-resistant cryptographic standards. These time lines should be evaluated against potential “Q-Day,” the theoretical date in which a quantum computer able to crack most modern cryptographic standards is developed. Though estimates of this Q-Day vary considerably, the study should assess whether the required transition time exceeds the most optimistic estimates for “years to Q-Day” (or “Y2Q”) and evaluate the likely costs associated with closing this gap.

3. Evaluate the impact of and prepare indicators and bellwethers for “quantum surprise”

Although the potential dates for ‘Q-Day’ are hard to predict, there is a distinct possibility that a nation-state could conceal its development of a quantum computer able to break modern encryption, perhaps achieving “quantum surprise.” Thus, that actor would be able to crack and decrypt susceptible adversary communications and years of collected intelligence, all the while without betraying the capability to do so. The arrival of such a quantum surprise would be difficult to assess and judge, and could confound U.S. intelligence assessments.

The U.S. government should develop a set of metrics and observable externalities, either real or artificial, that would act as bellwethers in detecting adversarial achievement of quantum surprise despite likely attempts to conceal it. Additionally, the Office of the Director of National Intelligence should assess the potential impact of “wait and see” intelligence, the counterintelligence risks associated with years of collected communications being unmasked by a future quantum computer.

4. Engage in more thorough study and evaluation of the military applications of quantum technologies

Given the complexities and uncertainties of these issues, the DoD should create a “Quantum Futures Working Group” to track and evaluate trends in U.S. and global advances in these technologies, drawing upon scientists and defense experts from across and outside of government to conduct a full net assessment of the state of the “quantum balance.” In the process, it is important to take into account that the possibility that the supposedly revolutionary implications of quantum technologies can be overhyped and exaggerated in some cases, such that realistic expectations and a nuanced understanding of the challenges and shortcomings of these technologies will also be important. In the short term, the DoD also should undertake further analysis of the utility of available forms of quantum cryptography and communications to secure military command and information systems, taking into account recent advances in this discipline. As research and development in quantum sensing and metrology, including quantum timing and navigation, become more mature, the DoD also should consider initial experimental employment of these technologies where appropriate.

5. Task the National Counterintelligence Executive with a broad review of counterintelligence risks to U.S. quantum research programs and commercial endeavors

Although openness and collaborations in research are vital to the dynamism of scientific advances, the sensitivity of these technologies may increase given their strategic importance. While China's advances in quantum technologies do not appear to have relied on the same pattern of tech transfer and industrial espionage that has been characteristic of its defense innovation in other domains, the risks are worth evaluating. Given China's high-level prioritization of quantum technologies, there are reasons for concern that there may be more outright attempts at tech transfer through licit and illicit means going forward, meriting a review of risks of tech transfer or intelligence activities.

Although the active research collaborations that are currently ongoing are often of mutual benefit to U.S. and Chinese institutions – and such engagements should be sustained as much as possible with appropriate precautions and safeguards – there may be circumstances under which such activities start to raise questions and provoke concerns.³⁰² At the very least, certain academic and commercial partnerships should be fully transparent regarding any potential conflicts of interest, the sources of funding, the objectives of the research under way, and the ultimate ownership of intellectual property generated through its activities.³⁰³

In this regard, recent directions in Chinese policies raise concern about whether there will be a free flow of data and knowledge that allows reciprocal benefits to emerge from scientific cooperation. As of April 2018, the State Council released new policies stipulating that any scientific data generated within China must receive government approval prior to being published or otherwise transferred outside of China.³⁰⁴ In an open, globalized world, international collaborations among scientists can be critical in advancing the frontiers of the field, and the United States has been one of the greatest beneficiaries of this ecosystem. At the same time, it is concerning that Chinese policies and state-directed initiatives can start to introduce distortions into those dynamics, such as through heavily subsidizing research or aggressively targeting scientists for recruitment via state-driven talent plans.

6. Restore science and technology capacity and expertise to U.S. Congress

At a time when U.S. technological advantage continues to diminish, the stakes never have been higher in ensuring the U.S. technological ecosystem maintains the dynamism required to sustain innovation into the future. This places a premium on prescient and informed lawmaking, which can anticipate changes and shape U.S. leadership in emerging technology. For this reason, Congress should restore funding to the Office of Technology Assessment (OTA). Between 1972 and 1995, OTA assisted Congress through providing in-depth assessments of emerging technologies and relevant, comprehensive legislative and policy options for lawmakers. Since OTA was de-funded, current congressional support agencies like the Government Accountability Office (GAO) and the Congressional Research Service have not been able to fully fill the void in technical expertise left by OTA, typically producing reports with less frequency and at higher cost than those produced by OTA. The academic and private sectors, through think-tanks, universities, and national academies, have been able to compensate this lack of expertise to some extent, but are not capable of providing the same level of peer-reviewed assessment with the comprehensiveness, timeliness, and depth that OTA once provided. While Congress has reduced its access to such expertise, other nations, including China, have promoted the role and influence of S&T advisory mechanisms. For China, this approach has paid considerable dividends in apportioning state funds toward R&D efforts in support of long-term economic and military objectives. The revival of OTA could contribute to ensuring that Congress has full capacity for critical S&T expertise going forward.

Concluding Reflections

The advent of the second quantum revolution introduces a new age of uncertainty. The United States must be prepared for a future in which its traditional technological predominance faces new, perhaps unprecedented challenges. Going forward, the United States must rise to this challenge of techno-strategic competition with China through enhancing the dynamism of its own innovation ecosystem to advance technologies that could be integral to future national competitiveness. Despite their spookiness, and even seemingly magical properties, the impact of quantum technologies will be very real.

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