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The Innovation Race: US-China Science and Technology Competition and the Quantum Revolution

Brandon Kirk Williams is a Senior Fellow at the Center for Global Security Research at Lawrence Livermore National Laboratory and a 2022–23 Wilson China Fellow

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Abstract

Technology competition is the fundamental driver of long-term US-China strategic competition. Technology racing will define the bilateral rivalry over the coming decades, and it is an innovation marathon that American policymakers must navigate to preserve the United States' security and economic competitiveness. After taking power in 2012, Xi Jinping launched a determined campaign to shift the vital center of science and technology (S&T) from the United States to China by pioneering emerging technologies such as quantum. Quantum technologies offer revolutionary potential to upend the geopolitical balance of power. Chinese champions are shifting away from deep investments in quantum communication to keep pace with American progress in quantum computing and sensing. In the next decade, quantum technologies will enter a new stage of maturity that will have the potential to disrupt economies and security. There is no certainty that the United States will retain its historic innovation leadership in quantum, nor that China will best the United States. The nation that best harmonizes its domestic innovation system will determine the course of the twenty-first century's economic and security order.

Policy Implications and Key Takeaways

- US-China strategic technology competition will be determined by the country that best optimizes its innovation system. Two innovation systems are vying for global primacy, but it remains unclear which country will capitalize on technological revolutions unfolding today and in the future. The nation that integrates the products of its S&T ecosystem and private sector will retain leadership in the decades to come.

- China aims to close the gap on the United States' public and private advances in quantum computing and sensing. The race to utilize quantum has distinct first mover advantages. Ingenuity, dedication, and luck could yield strategic surprise.

- Investing in human capital for science, technology, engineering, and math (STEM) will pay dividends for quantum and a range of other emerging technologies. US policy should address reforms for immigration and devoting resources to K-Ph.D. education that can build a heterogenous STEM talent pipeline.

- The United States possesses a well of quantum soft power that China cannot replicate. An updated National Quantum Strategy is essential for tailoring the right policy solutions for accelerating talent cultivation, public funding, research and development (R&D), and private capital.

Introduction

The United States and China are locked in an innovation race to control the technologies that will determine economic and security competitiveness in the twenty-first century. Two conflicting systems—the United States' public-private market approach and China's state-dominated economy—are searching for advantage. "Technological innovation has become the main battleground" for global leadership, Xi Jinping declared in 2021. Actions since his remarks are a testament to the centrality of technological competition between the United States and China. Although this is a contest that takes lessons from the Cold War, it is an entirely novel policy challenge. It is also occurring against the backdrop of dizzying technological revolutions that will demand agility and far-sighted resolve from policymakers.

This chapter begins historically in the Cold War and winds through the heyday of US-China science and technology (S&T) cooperation that presages the innovation race. It explains how an escalating S&T rivalry after 2012 culminated in pivotal events in 2022 and 2023 that birthed a technology competition. American policy arrived late to an innovation contest that Xi embarked upon after 2012. Washington is now announcing policies that seek to establish what National Security Advisor Jake Sullivan dubbed "a small yard and high fence," where export controls are wedded to domestic spending to boost American competitiveness. Xi's response to export controls and American industrial policy was to assert the Chinese Communist Party's (CCP) authority over S&T.

The final section addresses quantum technology competition and is written for a general audience. Quantum is equally mystifying and awe inspiring. I am not trained in quantum physics, but policy audiences require direct explanations for how the technology can shape the United States. I describe applications for quantum sensing, computing, and communications followed by an evaluation of the United States' and China's standing in public support, private sectors, and workforce. I then conclude the paper with a brief history of China's state-sponsored endeavors, primarily to control information with quantum communications. Quantum exemplifies how two divergent innovation systems are locked in a contest for supremacy. The stakes of this rivalry call for urgent policy action instead of complacency in the face of a committed adversary that seeks to commence a new era of global power by dominating innovation.

S&T Competition in the 21st Century

Xi is heeding lessons from the CCP's past to harness S&T for the state but to avoid Mao Zedong's tragedies that catalyzed an intellectual decay before Deng Xiaoping's modernization. After the Second World War, Mao welcomed the repatriation of over 1,000 professors and graduate students across scientific disciplines. Many, like Qian Xuesen, returned with a deep knowledge of advanced Western weapons. Mao's 1955 order to deliver an atomic bomb galvanized scientists in the Two Bombs and One Satellite campaign by led Qian and other scientists at the Chinese Academy of Sciences (CAS). Scientists who may have skirted the worst of the excesses of the Great Leap Forward did not escape the Cultural Revolution's ideological violence. China's S&T stagnated in the 1970s before Deng Xiaoping ushered in a new era to reform China.[1]

Deng's determination to modernize China, especially in S&T, hinged on normalizing relations with the United States during Jimmy Carter's administration. Deng recognized that breaking China's S&T isolation from the United States was vital for China's recovery in the 1980s. A fact not lost on Carter or his National Security Adviser Zbigniew Brzezinski when deliberating the strategic benefits of normalization. The resulting US-China Agreement on Cooperation in Science and Technology was the first substantive accord signed by Carter and Deng on January 31, 1979. The agreement was critical for fulfilling Deng's reform oriented Four Modernizations of agriculture, defense, industry, and S&T. When the United States and Western Europe were at the dawn of the information revolution in the 1970s, China had little access to Western breakthroughs. The Four Modernizations were fundamentally driven by the necessity for China to import American technology in the 1980s. Deng nurtured the US-China S&T relationship throughout the 1980s to sustain China's recovery from Mao.[2]

Deng and his successors also committed to ambitious domestic development campaigns to overcome S&T deficits. The CCP launched several well-funded projects for scientific research in 1986 and 1997—the 863 and 973 Programs—and flagship education initiatives named Project 211 and 985 that led to the foundation of China's impressive rise in STEM education after the turn of the century. Undergraduate student numbers exploded after 1998 from 1.08 million students to 1.6 million the following year, with a growing preponderance of degrees matriculating in STEM disciplines. The

48 percent jump of new undergraduates between 1998 and 1999 ballooned further year-after-year in the 2000s according to the National Bureau of Statistics of China.[3]

Chinese S&T earned respect in many fields, such as biotech, in the 2000s for tremendous progress, but questions lingered if the headway was sustainable. A 2010 assessment of China's S&T ecosystem outlined numerous factors constraining China's optimistic plans to mature into a global S&T leader. Chinese R&D hubs failed to independently incubate the tools and talent to make significant strides. Imports constituted a critical source of R&D capital, machinery, and expertise. And although an authoritarian nation, national plans could not stem brain drain or fully capitalize on China's indigenous S&T resources. The CCP could not afford to disrupt S&T cooperation with the United States.[4]

Chinese Vice Premier Wen Jiabao in a 2008 *Science* interview captured the spirit of a high tide of US-China cooperation. Wen emphasized several pillars to sustain China's growth, principal among them creating pathways for S&T talent to flow into China. Within the same year, the CCP would also inaugurate multiple talent plans to entice Western researchers and Chinese students to return. His comments praised the decades of U.S-China S&T cooperation that attested to science's promotion of unity across borders. The Vice Premier's statements characterize a dominant perspective that collaboration, not competition, was Beijing's priority.[5]

Xi's 2012 ascension marked a rupture from the past and placed China on a course to overtake the United States in innovation unlike his predecessors. China's S&T ecosystem, in his words, would "strengthen a primary driver: innovation" that would be the basis of China's twenty-first century power. CCP leaders post-Deng certainly praised the value of S&T for China's growth and innovation capacity. None exhibited the same tenacity to employ S&T in a long-term bid to reorient the commanding heights of innovation away from the United States. For China's security, economy, and prestige, Xi envisioned a future where the world's innovation flowed outward from China. Industrial policy formulated in the 2015 strategic plan *Made in China 2025* encapsulated the muscle behind the rhetoric and his conviction that the future belonged to a China-centric Asia.[6]

Xi's determination to dominate global innovation upended claims that China could not innovate. Repeating a then-popular claim that China copied without innovating, authors in a *Harvard Business Review Article* opined that the CCP circumscribed China's innovation capacity. Xi upended this specious assertion. In 2013, he called for speedy reform of CAS and China's S&T management to elevate China's basic research to propel innovation. The CCP's 2016 Innovation-Driven Strategy bore the imprint of his resolve to move beyond rhetoric into results. The strategy inextricably merged innovation and China's development, noting that China "entered a new normal" where the old motors of development were eclipsed by emerging technologies. The strategy indicated that China lagged developed nations' S&T breakthroughs, workforce, and ecosystem to incubate innovation. "It is the nation's destiny to be innovation-driven," and China advanced with startling speed. Rankings in the World Intellectual Property Organization's annual *Global Innovation Index* charted China's dizzying ascendence from thirty-four in 2012 to the eleventh spot in 2022. The climb reflected China's human capital development, state spending on education, newfound respect for Chinese universities, in addition to leadership in emerging technologies of energy, artificial intelligence, and 5G.[7]

Despite China's rise, the 14th Five Year Plan in March 2021 raised doubts about China's headway in channeling S&T for innovation-driven development. The uncertainty crystallized in a blunt appraisal. "Our capacity for innovation is insufficient for the requirements of high-quality development." The Plan extolled the urgency of fulfilling Xi's directive to establish China as a S&T powerhouse by reforming the country's innovation architecture. Key planks of this program included revamping China's S&T infrastructure to establish an innovation base that nourished state-owned enterprises while also incentivizing the private sector to bear the mantle of accelerating innovation. Incubating indigenous talent and recruiting foreign S&T expertise were singled out for a crucial role in realizing China's maturity to a world-class innovation powerhouse.[8]

Xi evoked similar concerns in his address to the 2022 20th CCP Congress. Xi touted the rise of China as an S&T power and vowed that "innovation will remain at the heart of China's modernization drive." He pledged to commit state resources to accelerating China's indigenous talent development. But, he also acknowledged setbacks. Central to them being that "there are many bottlenecks hindering high-quality development, and China's capacity for scientific and technological innovation is not yet strong enough." One of the most insightful diagnoses of China's S&T hurdles appeared in September 2022 from Zhang Yuzhuo, an energy scientist and the China Association of Science and Technology (CAST) Party Branch Secretary. Zhang candidly elucidated the factors that prevented China from pioneering S&T advances, including what he called "American containment." But he was frank that "we lack major theoretical breakthroughs and leading original achievements."[9]

Xi's ambition to overtake the United States in S&T compelled Congress and the Biden administration to act. A 2020 American Academy of Arts & Sciences publication criticized decades of post-Cold War failure to spend on innovation in a searing report titled *The Perils of Complacency*. By reducing government's primacy in funding R&D over decades—as well as lacking a vision for influencing private sector innovation—the United States ceded ground to China. The response in Joseph Biden's administration included a raft of industrial policy spending for the Inflation Reduction Act, the CHIPS and Science Act, and the Advanced Research Projects Agency for Health. The dynamics of a US-China technology race called for federal spending on R&D in the technologies that will shape the twenty-first century. Spending was married to export controls to establish, in National Security Advisor Jake Sullivan's words, "a small yard and high fence."[10]

In 2023, Xi explicitly responded to export controls and the United States' industrial policy by centralizing authority for S&T under the CCP. He chaired a February Politburo Study Session on S&T where he lauded self-sufficiency in basic research that preserves first mover advantages in the era of "big science." In early March, the National People's Congress submitted formal reforms to China's science and technology enterprise amid pressure from the United States and its allies. Xi praised the reorganization that inserts stronger party control with less authority in the Ministry of Science and Technology (MOST) and greater oversight in a newly formed Central Science and Technology Commission (CSTC). Xi insisted that China's capacity to "fully implement the strategy for invigorating China through science" demanded Party control. MOST survived but CSTC officials are entrusted with managing "the construction of the national innovation system and the reform of the S&T system." National planning duties will also fall to CSTC officials—bending China's S&T landscape to the Party's will. Xi understands the stakes of the competition, especially for quantum where he has insisted China's innovators lead the charge to best the United States.[11]

Quantum Technologies: Quantum Racing in the Era of Utility

Writing an analysis on the state of a technology risks obsolescence within a startlingly narrow window after publication. For many, jokingly, quantum use cases were always a decade or more away. Galloping advances are compressing decades-out projections for proof of concept to commercialization that are convincing skeptics. This section explains quantum applications—divided into computing, sensing, and communications—and the comparative strengths and weaknesses for China and the United States. It is then followed by a recent history and opensource analysis of China's quantum trajectory. This section does not historicize, nor is it an explainer of, quantum mechanics. As the subtitle suggests, this section adopts the premise that quantum technologies entered a new era of utility in 2023, in IBM Vice President Jay Gambetta's telling. Nevertheless, it takes a sober look at quantum to avoid the hype cycles that cloud how policy audiences should approach its revolutionary potential.[12]

General and policy audiences must understand the implications of quantum competition and how or if quantum sensing, computing, and communications will manifest in the coming decades. Although readers may be familiar with the Schrödinger's Cat thought experiment, explaining quantum states, decoherence, tunneling, or the physics of photonic, trapped ion, or superconducting qubits is a barrier to a fulsome discussion that evaluates the current state of quantum competition between the United States and China.

China's quantum R&D ecosystem is vibrant, and Xi elevated quantum into the top tier of technologies for China's security and economic competitiveness in the twenty-first century. According to McKinsey, the CCP has allocated $15.3 billion for quantum that outpaces European and American government funding. That total is rounded out by a small but respectable amount of venture and private capital—however thin the boundary dividing private interests and the CCP—totaling to $255 million invested in 2022. The direction of this funding falls to various state universities and laboratories and other bureaucracies that have mostly directed resources to quantum communications. A quantum scientist and technocrat occupies a prominent position in China's state-directed efforts. Popularly referred to as the Godfather of Quantum for China, Pan Jianwei earned esteem for his role in building

China's national quantum capacity and his proximity to CCP technocrats and politicians.[13]

The United States possesses signal advantages of a dynamic private sector R&D landscape, superlative universities, a decentralized S&T infrastructure, allies and mechanisms for technology transfer, and diverse funding sources. The United States possesses quantum soft power that China cannot match. But no responsible analysis would declare the United States the inconvertible frontrunner. Ingenuity, dedication, and luck could trigger strategic surprise.

State of Public and Private Funding

Since the bipartisan 2018 National Quantum Initiative Act (NQIA), the United States government's funding has remained steady. Nearly a billion dollars was appropriated in 2022 and several billion have been spent since 2018. America's federal investments remains behind the CCP's financing and the European Union's committed funds. Not to be overlooked, the Defense Advanced Research Projects and In-Q-Tel back long-shot R&D that may prove pivotal in a quantum race by meeting national security needs and enabling consequential commercial quantum applications. Private sector champions and venture capital supplies the largest proportion of backing for quantum R&D, and commercialization guides the market rather than a government's imperatives.

Opacity reigns in China's public and private financing for quantum technologies. Official financing totals to over $15 billion, but doubts persist on the accuracy of these amounts. The CCP will remain the predominant financer for quantum development, and accordingly it steers R&D via a network of labs, professional organizations, and companies. Leading venture capital firms devoting resources to quantum, such as Shenzhen Capital, are often CCP state owned enterprises or affiliated with the state or PLA. Although the PLA's doctrine anticipates utilizing quantum technologies ranging from unhackable communications to radar to detect stealth aircraft, PLA amounts allocated for quantum R&D remain uncertain if not impossible to uncover.

State of Government and Academic Institutions

The United States government's institutional influence has remained steady thanks to the NQIA. The Departments of Energy and Defense, the National Science Foundation, the National Institute for Standards and Technology, and national laboratories influence the direction of quantum R&D. American universities across the country are global champions that attract elite talent, and university research is diffuse beyond coastal technology corridors. Public-private quantum networks in Tennessee, for instance, speak to the vitality of decentralized R&D.

China's leading universities, professional organizations, companies, and the CCP overlap on quantum R&D, often with scant distance separating each entity that orbit the sprawling National Laboratory for Quantum Science in Hefei. Distinguished academic institutions home to pioneering research are found at the Beijing Academy of Quantum Information Sciences, CAS' Institute of Physics and its Center for Excellence in Quantum Information and Quantum Physics, Tsinghua University Center for Quantum Information, University of Science and Technology of China's (USTC) Division of Quantum Physics and Information, and more centers of excellence will likely appear soon. Academics routinely publish in *Nature*, *Science*, and *Physical Review Letters* for peer review and dissemination of their research to a Western audience.

State of the Quantum Workforce

The United States lags the European Union, India, and China's talent base. McKinsey's 2023 estimate ranks America's approximately 45,000 individuals fourth compared to third place China's over 57,000 workers. Chinese education programs matriculate record numbers of STEM graduates, but both the United States and China are vastly outpaced by the European Union and India. Neither the United States nor China can meet the needs of domestic quantum industries with a heterogenous STEM talent pool. The United States, on the other hand, has the outsized benefit of attracting foreign talent if immigration policies are smartly reformed.

State of the Private Sector

Several American companies occupy industry leader positions in the race to dominate quantum computing. IBM, Google, Microsoft, Amazon, and Intel top the list of United States-based companies. IonQ, Quantinuum, Atom, PsiQuantum, and nearly 350 startups exist in a thriving ecology. IBM is peerless in its investments in R&D, quantum cloud access, international partnerships, talent development, public outreach, and sales of quantum computers. No other corporation publishes a detailed roadmap that charts a plan for routine scaling of quantum software and hardware. IBM may be best positioned to build and commercialize a functioning quantum computer with an integrated hardware and software stack. Industry stakeholders are also connected via the Quantum Economic Development Consortium (QED-C). QED-C is joined by other associations such as the Chicago Quantum Exchange to network between industry, academia, government, and national labs.

Alibaba, Baidu, TenCent, Origin, and QuantumCTek have the largest quantum market share in China. Many Chinese private entities and startups welcome the commercial opportunities from quantum computing and cloud services, such as from Alibaba's Quantum Laboratory that was jointly created by Alibaba and CAS. One question that arises is the autonomy of Chinese companies and their proximity to government labs and funding. Analysis from a 2023 Center for Strategic and International Studies' Big Data China report outlines how the CCP exerts control over the management and daily operation of businesses. As mentioned above, the overlap between public and private quantum interests is extensive.

Numerous established technology firms invest in quantum globally, and startups are populating developed nations. Although this chapter concentrates on American and Chinese competition, an abundance of international companies sit at the cutting edge of quantum innovation. Global companies may deliver quantum sensors to market before China or the United States. Preparing for this likelihood requires that policy audiences understand the applications of quantum technologies and stakes of leadership in this field.

A Basic Quantum Introduction for Policy Audiences

Quantum technologies use theories and discoveries from quantum mechanics for a range of use cases. Contemporary lasers, electron microscopes, atomic clocks, and magnetic resonance imaging (MRI) machines operate on principles of quantum physics. The difference between today's tools and future quantum sensing or computing can be distilled to acute improvements in precision and speed. Quantum is best divided into sensing, computing, and communications. These three fields possess the latent potential for transforming a range of applications that will reshape security, economics, and everyday life. Preeminence in quantum carries distinct first mover advantages for a diverse set of industries and nation-states. Quantum computers will not replace a modern desktop or laptop computer, nor will civilians possess portable quantum sensors in the near term. Quantum technologies will enable faster processing and utility for AI, cloud computing, communication networks, biomedical research and design, and myriad other fields.

The fundamental data unit for quantum technologies is the quantum bit, known as a qubit. There are many types of qubits, and each qubit possesses unique properties for diverse applications. Currently, the best funded quantum experiments use superconducting, trapped ion, neutral atom, or photonic qubits. No one qubit will dominate computing, sensing, or communications based on today's technology readiness levels. Accordingly, R&D for quantum applications will remain heterogenous and necessitate diverse supply chains, laboratory components and materials, and expertise. The heterogeneity warrants steady experimentation, investment, and patience with routine monitoring for operational potential. Ensuring a robust quantum R&D ecology in the United States will prevent a latent technology from altering the balance of power via strategic surprise.

If such potential exists, why haven't quantum technologies transitioned from laboratories to prototypes or real-world use? The current state of technology readiness level varies by qubit and application, but quantum technologies are brittle. Experiments with superconducting qubits require optimal temperatures in a cryogenic chamber known as a dilution refrigerator that hovers around -460 degrees Fahrenheit, near absolute zero and colder than outer space. For photonic qubits, lasers measure changes at the atomic level without dilution refrigerators. Several obstacles ranging from heat, improper materials, or interreference at the atomic level can cause qubit experiments to easily fail. Scott Aaronson, among others, urges caution in inflating the practicality of quantum devices owed to the steep costs of time, capital, and talent for operation and experimentation. News in 2022 and 2023, nevertheless, inspires confidence that quantum technologies are embarking on a new era of utility for sensing, computing, and communications.[14]

Sensing

Quantum sensing acutely measures changes to electrical and magnetic fields at the atomic level. The acute sensitivity from quantum sensing improves on today's sensors such as radar or sonar by detecting shifts in atoms. This mode of measurement enables leaps in precision to identify minute variances. Different qubits have innate strengths for sensing, including but not limited to: trapped ion measures time, cycles, and disturbances in electrical fields; photonic assesses temperature; superconducting detects change in magnetic and electrical fields.

Quantum sensing has the highest potential for products that will reach commercial sales in the next five years. The disruptive effect of today's prototypes will be limited initially due to constraining factors such as size, reliability, and resilience. Rising availability of quantum sensors will nourish an economy of scale where established industry manufacturers and startups will miniaturize and harden sensors for use. Prohibitive cost barriers will most likely decline over time. Industry and government clients stand to benefit from accuracy for medical diagnostic devices, underground and deep-sea resource detection, design and manufacturing for efficient chemical processes, global positioning systems, and a host of use cases relying on hyper-precise, rapid measurement.

For national security, quantum sensing will offer numerous defense solutions for position, navigation, and timing in denied environments with high levels of friction. Unmanned aerial and underwater vehicles could operate with newfound autonomy. Threat detection and monitoring of military assets—ranging from antisubmarine warfare to radar—also stands to benefit. Ensuring rugged and secure utility, however, will demand a high tolerance for trial and error in addition to leveraging federal funding to shape the quantum sensor market. Interoperability with allied military systems will pose unique challenges, and the United States' technology sharing alliances such as the Quad and AUKUS are routes for boosting integration of quantum sensing into allied militaries. Preserving the United States' national security may also require a tailored export control regime that is proactively enforced in advance of quantum sensors reaching commercial sales.

Computing

A quantum computer is a computer that uses principles from quantum physics and calculates data or information in qubits. A quantum computer differs from a classical computer—such as today's laptops and desktop computers—that uses binary 1s or 0s and functions via silicon chips and transistors. Many quantum computers require optimal conditions to operate, and thus struggle with interference commonly referred to as noise that generates error-ridden results lacking steady replication. The current state of quantum computing is commonly referred to as the era of noisy intermediate-scale quantum. The promise of quantum computing is that it will overcome errors to process calculations faster than a classical computer could accomplish in thousands of years. Crossing that threshold is known as quantum supremacy. The nation or company that achieves stable error correction and scaling up qubits will achieve first mover advantages over peers.

A number of global companies are building quantum computers, and most use diverse tools, methods, and qubits. Differing qubits may be advantageous for various applications, and it is too soon to claim that one qubit type is guaranteed to operate without error. In fact, error correction remains one of the most tenacious difficulties for quantum computers' ability to surpass classical computers. Thus far a handful of companies have claimed to attain the milestone of quantum supremacy. Quantum computers may have considerable potential for biotechnology, energy, chemical production, and finance.

Trends from patent data reveal an appetite for Chinese and global companies to vie for market control in quantum computing. This push will likely persist in a climate of heightened technology competition. Patents for quantum computing tell a story of North American dominance. American firms and Canadian company D-Wave notch eight out of the top ten spots for most quantum computing patents. IBM's total of 1,323 patents are followed by

Google's 762. Origin places sixth on the list with 234 and Baidu at eighth with 186. Other Chinese companies such as Tencent climbed from two patents in 2020 to ninety-three by 2022—evidence of several Chinese entities such as SpinQ surging into quantum computing patents. European companies, although behind the United States and China, are joining in the rising tenor of controlling intellectual property for quantum computing. Patents represent an imperfect snapshot of the quantum ecosystem, but they document Chinese companies' climb that shows no signs of abating.[15]

Communications

Quantum communication uses qubits to protect and transmit data. Quantum communication via quantum networks can encode qubits for only two parties to decode the data, known as quantum key distribution (QKD). One approach entails data sent via particles of light known as photons, and this enables space-based quantum communications that joint Chinese-Austrian researchers demonstrated in 2016 via the Micius satellite. Quantum key distribution degrades over distances, and it requires a trusted network supporting its fidelity across terrestrial or space domains.

No other nation funds more R&D for communications than China. Origin Quantum, founded by Guoping Guo and teams at CAS and USTC, possesses singular global market control for quantum communication hardware and software. Chinese telecommunications companies are pouring capital into R&D for a next generation quantum communication stack that will optimize 5G and 6G. Debate exists on the utility and security of quantum communications. The United States' National Security Agency disputes the reliability of QKD and instead promotes post-quantum cryptographic algorithms for secure communications. No evidence exists that Chinese investment in communications will dwindle, and it remains a preoccupation of China's quantum community as it has for a decade.[16]

From 863 to a Quantum Moonshot: Quantum in China

China's first published acknowledgement of a quantum research agenda appeared in the 1986 863 Program before assuming a prime spot in 2015 in Xi's agenda to lead the world in emerging technologies. China's quantum ecosystem sprouted in the early 2000s before adopting a new logic to achieve strategic advantage over the United States. Established private companies such as Alibaba and Baidu are joined by Origin and QuantumCTek alongside a host of startups like TuringQ. State energies emerge from Hefei where Pan Jianwei and scientists supporting USTC toil to realize a quantum moonshot.

Although Chinese quantum physics programs predated Xi's rise, Pan's 2013 briefing for Xi on quantum's security implications commenced a national campaign for quantum primacy. Pan earned a Ph.D. at the University of Vienna in 1999 under the direction of Nobel Laureate Anton Zeilinger. Pan returned to China where he was elected to the CAS in 2011 as the youngest member to date and was full-time faculty in quantum physics and information at USTC.

Research conducted by Strider Labs charted an initiative led by Pan at USTC to send aspiring Chinese quantum physicists to earn Ph.D.s in Europe to export European expertise to China. In his own words, Pan bluntly stated "'we've taken all the good technology from labs around the world, absorbed it and brought it back.'" He leveraged his personal ties to Heidelberg University and throughout Europe to erect a quantum beachhead where aspiring Chinese scientists were directed to study. Cosponsored programs connected cutting edge S&T institutes in Europe to Chinese labs. European experts were also enticed by talent programs, like the Thousand Talents Plan. Strider's researchers concluded that this strategy achieved its goals in a startlingly fast period. China's capacity to test and deploy dual use quantum technologies blossomed within a few years with low investment. Europe's quantum community unwittingly enabled China to make its own quantum strides to potentially outpace Europe and the United States. Pan's connection to Zeilinger and European physicists was elemental to China's growth.[17]

In 2013 Pan proposed a visionary space based QKD experiment with Zeilinger at the Austrian Academy of Sciences. The fruits of their collaboration in the world's first quantum satellite, Micius, was a landmark achievement that boosted Pan's reputation and respect for China's S&T prowess. Xi's backing resulted in a vast influx of funding for the Quantum Experiments at Space Scale (QUESS) project that launched Micius and catapulted China's quantum communication program. Micius weighed in at 600 kilograms and was launched at the Jiuquan Satellite Launch Center on August 16, 2016. Pan and a team of researchers experimented with transmitting data via photons within China between the Nanshan Telescope in Xinjiang and Xinglong Observatory in Yanshan. The QUESS team confronted the obstacles that photon signals decay across distances, thus degrading QKD's reliability. QUESS's team sustained photon signals between Xinjiang and Yanshan and other ground stations before initiating the next step of the collaboration with Zeilinger's team. The next and more significant stage tested a secure seventy-five-minute video conference from QUESS to the Austrian Academy of Sciences in 2017 via Micius. QKD secured the Beijing-Vienna call by transmitting secure keys to decrypt in real time.[18]

Scientific, reputational, and political accolades followed Micius's success. Micius proved the possibility of encrypted quantum communications for a backbone of a space-based quantum internet. It also earned notoriety as the first quantum experiment that captured the imagination and attention of today's global media, technologists, and rivals. Pan was named to *Time* magazine's Top 100 People—where Zeilinger praised his former student for advancing a quantum internet—and he won a raft of prestigious international scientific awards.[19]

Did Micius test and prove QKD as a viable path for secure quantum communications? Not at first. QUESS programed Micius with the keys to transmit and assumed the satellite was a trusted entity for the experiment, and not the subject of eavesdropping. Results from the 2017 test lacked error detection and correction. QUESS also relied on optimal conditions, timing, and alignment for Micius to operate. The QUESS teams, nevertheless, demonstrated in 2020 that satellite-based quantum communications could prove secure. Researchers transmitted keys between Delingha and Nanshan, separated by nearly 700 miles, and resolved the trusted satellite program by tasking the satellite with sending and not relaying the keys.[20]

Chinese investments in mixed-public private enterprises for quantum computing steamed ahead alongside the enduring R&D for quantum communications. Xi urged China's S&T community in 2020 to adopt a newfound sense of urgency in attaining growth in all aspects of quantum. In 2020 Pan's team published breakthrough findings in a *Science* article, "Quantum Computational Advantage Using Photons," achieving quantum supremacy with a photonic quantum computer named *Jiuzhang*. Similarly, a joint CAS-QuantumCTek quantum chip named *Zuchongzhi*-2 boosted its total qubits from sixty-six to 176 in 2023, with a new online platform that is open to researchers globally. Advances in quantum computing will enable cloud computing, like Alibaba's eleven qubit cloud, and the steady evolution of China's aim to control and secure information via quantum communications.[21]

Pan and other scientists in China maintain an active research agenda into 2023 for boosting QKD's fidelity, and they continue to achieve breakthroughs. Dual papers published in *Physical Review Letters* by teams led by Pan and a Chief Scientist at the Beijing Academy of Quantum Information Sciences Zhiliang Yuan tested and substantiated QKD's transmission over 600 miles via optical fibers without intermediary tools to repeat the signals. The separate tests gained efficiencies across distances and reliability of data transmission. Pan, Yuan, and others' published research is a testament to China's near monopoly of quantum communications peer reviewed publications and R&D for commercialization.[22]

The PLA aspires to operationalize quantum communications for strategic and tactical use. A 2011 MOST press release shared that the PLA deployed its first quantum-encrypted communication tool. In 2014, an article in a PLA publication *China National Defense News* proclaimed quantum encryption's potential to ensure secure PLA communications for joint operations.[23] Several years later in 2018, a PLA post on WeChat publicized the military's use of a device with dimensions akin to an iPhone that functioned as a quantum encrypted terminal. The 2018 post touted that the terminal was integrated with Micius for space-terrestrial quantum communication. Although the PLA exhibited a sample terminal at the 2018 Ninth Military-Civilian Dual Use Technology Expo, the network had yet to graduate from testing to utility. PLA investment in quantum branched out from communications into sensing and training a generation of experts. In July 2022, the National University of Defense Technology opened a quantum research institute with focus areas in quantum simulation, navigation, materials and equipment, and sensing.[24]

After the 2015 military reforms, it appears that PLA leadership embraced the futurist promise of quantum communications despite reasonable doubts on reliability. It is a beguilingly attractive option for joint operations that hinge upon uncompromised communications. But the technical limitations of quantum communications—ranging from photon fidelity to potential eavesdropping on user endpoints—raises questions. PLA Commanders and CCP elites would place considerable faith in the communication infrastructure supporting quantum encryption, presuming its durability under wartime stress or adversary deployment to compromise China's space and terrestrial information architecture.

The Quantum Information Association of China's 2022 *Quantum Security White Paper* reports that a quantum computer will soon break today's standard encryption schemes that will thus endanger the security of China's information architecture. The report writers insist that a US-China "qubit war" is unfolding for quantum advantage. Urgency is paramount to protect vulnerable systems, the report concludes, because the time for safeguarding networks and data is shrinking. The White Paper emphasizes that the stakes for preserving information security will prove essential in a post-quantum world where crippling an adversary's networks are "'silver bullets'" for combatting rivals.[25]

Although the theme of quantum security predominates the document, the White Paper also clarifies the necessity of China sustaining quantum leadership for economic and technological competitiveness. Capitalizing on quantum's commercial applications for "biomedicine, materials science, chemistry, code breaking, weather forecasting, aerodynamic calculations, weapons development, artificial intelligence, energy," and data science will preserve China's strategic edge. The report also praises the efforts of USTC, Tsinghua University, Alibaba, Tencent, Baidu, and Huawei for investments that elevated China to race with the United States and its industry leaders. The report also notes that a revolution in quantum computing will overcome the restraints of Moore's Law for semiconductor processing power—an argument even more salient after the release of the United States' export controls.[26]

Conclusion and Policy Recommendations

Winning the twenty-first century innovation race will not be distilled down to the system that delivers the most cutting-edge semiconductor. The country that best channels its people's ingenuity and productivity with new technologies will set the world's economic and security agenda in the decades to come. Urgent policies are necessary to preserve the United States' short- and long-term innovation competitiveness for S&T as a whole and quantum technologies:

- Invest in People Immediately—America's immigration system for highly skilled individuals requires immediate overhaul and the United States suffers from the lack of a bold nation-wide push for STEM K-Ph.D. education. The United States' historic innovation excellence was partially owed to its ability to attract the best and brightest. Highly skilled immigrants must navigate a byzantine immigration process. Legislation to remedy this is key to recruit and retain the world's best and brightest—including Chinese nationals—for competing in quantum by developing a heterogenous STEM talent pipeline. Fixing immigration must be paired with enduring investments in America's STEM education to prepare US citizens for the technology revolutions ahead.

- Forge A New Innovation Consensus—The old balance of Washington taking a back seat as Silicon Valley set the nation's innovation trajectory is broken. Government once again must reassert its primacy in shaping innovation for national security. The Trump administration's Operation Warp Speed and the Biden administration's industrial policy and export controls point to the right direction of this rebalancing by leveraging federal spending to both shape incentives and cooperate with the private sector. The next few years are critical for cementing a new innovation consensus that benefits from historical lessons while also paving the way for an S&T ecosystem that delivers tangible gains for national security.

- Make Enduring S&T Investments—Government is the only national institution that can ensure guaranteed funding for frontier, risky S&T that is a critical enabler for the United States' competitiveness. For instance, preeminence in quantum technologies, as with other critical emerging technologies, can only thrive with sustained federal funding. The Departments of Energy and Defense will play a key role in nurturing S&T fields that the private sector cannot fund. Lower technology readiness levels fall outside industry's risk profile, and government must fill the gap to maintain the path for the private sector to deliver products to market.

- Update the National Quantum Strategy—Since the first and only National Strategic Overview for Quantum in 2018, the field has grown by leaps and bounds, US-China competition is amplifying, and, most importantly, technology readiness level timelines are compressing. The intersection of science and geopolitics requires that White House convene experts from industry, academia, and government to publish a new guide for national planning. The report can appraise progress of the National Quantum Initiative, identify shortcomings, and propose new national goals for funding, talent, and R&D. Principal among the recommendations should be categorizing skills that will establish a quantum ready workforce where benefits will accrue for the nation at large and not quantum industry leaders.

The opinions are those of the author and do not necessarily represent the opinions of LLNL, LLNS, DOE, NNSA, the US government, Carnegie Corporation of New York, or the Wilson Center.

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