IS CHINA IN A HIGH-TECH, LOW-PRODUCTIVITY TRAP?

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Abstract

This paper describes the paradox of China's current condition as a high-tech, low-productivity economy. It does so by identifying the means, accomplishments, and challenges associated with China's rapid innovation drive, while showing that its scientific advances have yet to yield the productivity gains that motivated its official initiatives. The push to deepen national technological capabilities gained considerable traction in the past 15 years through China's landmark "Medium- and Long-Term Program for Science and Technology Development," "Made in China 2025," and "13th Five-Year Science and Technological Innovation" plans. These policy initiatives were reinforced by unprecedented amounts of R&D spending and acquisitions of foreign technology through legal and sometimes controversial means (e.g., intellectual property misappropriation). Through these mechanisms, Chinese firms have had an uneven record in reaching the high-tech frontier. While in some areas (e.g., machine learning, 5G technology, fintech) its firms' high R&D expenditures have translated into pathbreaking technological advances, they largely lag behind in other core technologies (e.g., semiconductors/integrated circuits, airplanes, and advanced airplane turbofan engines). Chinese firms that have been successful with disruptive technologies, moreover, have had their impact felt on a global stage, as they are accounting for a progressively larger share of worldwide patent applications, scientific papers, and high-tech manufacturing. After describing these developments, this paper provides possible explanations for why total factor productivity growth has remained largely elusive despite China's rapid technological advances. Material for the paper was drawn from the academic, trade, and business literature; insight provided by leading scholars, and indicators from official sources such as China's National Bureau of Statistics (NBS), the International Monetary Fund (IMF), the Organization for Economic Co-operation and Development (OECD), the World Bank, and the World Intellectual Property Organization (WIPO).

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I. Introduction

Well into the first decade of the 21st century, China's double-digit economic growth rate was underpinned by high rates of return from factor inputs and productivity gains. However, by the turn of the century, China's reformers were already realizing that the growth strategy needed adjusting.[2] Increases to its capital stock were beginning to yield diminishing returns (gross domestic investment has been over 40 percent of GDP in the last decade),[3] while automation and a shrinking workforce were giving rise to labor shortages.[4] To reach its ambitious GDP targets, official growth policy gradually shifted to productivity as a driver of growth, which planners believed could be attained by focusing on technological catch-up and innovation. The resources that have been poured into this strategy over the past two decades have produced some noteworthy results. Patents and publications in China have soared. A number of its industries now appear to be at the technological cutting edge. However, as shall be shown, over the past decade, economic growth has been decelerating, while productivity has remained sluggish. In addition, rising trade frictions with the United States, as well as the COVID-19 epidemic, have presented new challenges to China's growth prospects.

The emphasis on indigenous technology and innovation[5] as a source of economic growth is a relatively recent phenomenon in China's modern scientific development. Soon after the communist take-over in 1949, China's government began rebuilding the country's underdeveloped and shattered economy, and there was growing recognition that technological advancement would be a key part of that development process.[6] China turned to the Soviet Union as a political and development model at the time, and it established similar research institutions to advance its technologic base.[7] While certain scientific advances were made, they largely mirrored Soviet objectives of improving agricultural productivity and developing weapons systems that had no practical links to the civilian economy.[8] The advances were also short-lived, as the destabilizing events of the Cultural Revolution thwarted much scientific progress during the 1960s and 1970s.[9] China's scientific advancement resumed by the early 1980s, following its market-oriented economic reforms. Foreign investment and technology supported industrial upgrading,

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[2] Perkins, "Reforming China's Economic System," *Journal of Economic Literature,* June 1988.

[3] IMF, *2019 Article IV Consultation Staff Report: China*, August 9, 2019.

[4] OECD, *Economic Survey: China 2019*, April, 2019. World Bank, *Innovative China: New Drivers of Growth*, 2017

[5] Innovation in this context refers to new products, methods, or ideas.

[6] Nolan and Ash, "China's Economy on the Eve of Reform," Cambridge *The China Quarterly*, December 1995; and Sachs, Fisher, Hughes, and Woo, "Structural Factors in the Economic Reforms of China, Eastern Europe, and the Former Soviet Union," *Economic Policy*, 1994.

[7] Perkins, "Reforming China's Economic System," *Journal of Economic Literature,* June 1988, 601-645; and Saich, "Reform of China's Science and Technology Organizational System," 1989, 69-88; and Wang, "The Chinese Development State During the Cold War: the Making of the 1956 Twelve-Year Science and Technology Plan," *History and Technology*, 2015.

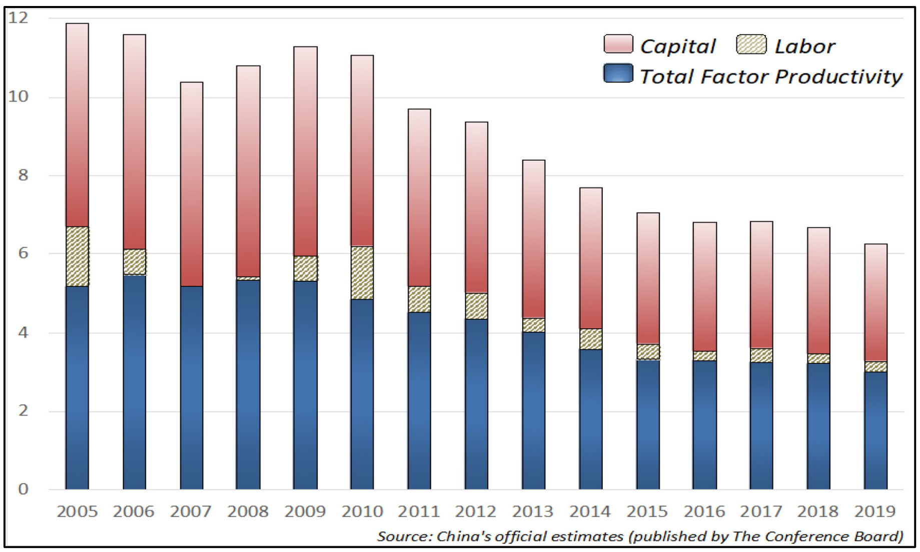
[8] Naughton, "The Socialist Era, 1949-1978: Big Push Industrialization and Policy Instability," 2007, 356; Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the People's Republic of China," August 2006.

[9] Congressional Research Service, "China's Economic Rise: History, Trends, Challenges, and Implications for the United States," July 12, 2006; *Nature*, "The Chinese Academy of Sciences at 70;" October 1, 2019; Perkins, "Reforming China's Economic System," *Journal of Economic Literature,* June 1988, 601-645; and Rawski, "Producer Industries Since 1957: Sources of Innovative Capacity," 1980.

export-led growth, and economic transformation that resulted in an average annual real GDP growth rate of 9.5 percent over the past four decades (1979–2019).[10] Appendix A of this paper provides more detail on the historic origins of China's innovation initiatives.

Before the turn of the millennium, low-cost labor and capital accounted for much of this growth, while around a quarter of it relied on total factor productivity (TFP).[11] After 2000, China arrived at the Lewis turning point, with its surplus of labor largely exhausted. This factor, a rising ICOR (incremental capital output ratio),[12] and sluggish productivity, began inhibiting China's economic growth, as shown in Figure 1.[13] In an effort to restore growth momentum, China's authorities introduced major policy initiatives and research and development (R&D) spending measures to stimulate domestic-led innovation.[14] Their intuitive assumptions that such measures should necessarily lead to productivity gains and accelerated GDP growth were not unique. As explained in Appendix B, such associations have been widely held worldwide despite the inconclusive evidence supporting them.

Figure 1. China's GDP Growth and its Factor Contributions



As shown in Figure 2, which considers countries' TFP levels relative to the United States,[15] China's productivity has remained low relative to high-tech economies such as the United States, Japan, and South Korea. It has also remained low relative to middle income countries such as Brazil and more recently India. India's case provides an important juxtaposition, and a hint that something unusual may be

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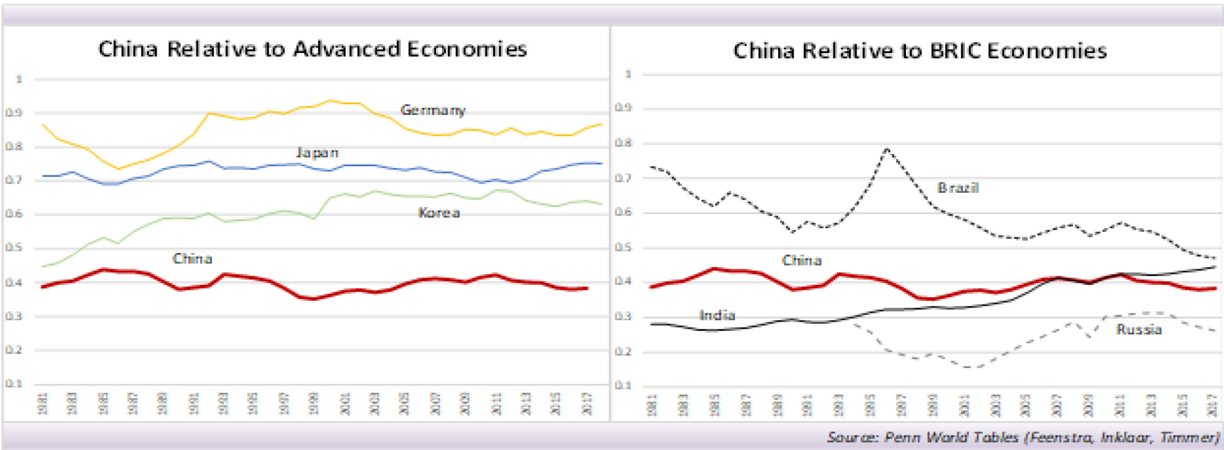
[10] Lin and Wang, "China's Integration with the World: Development as a Process of Learning and Industrial Upgrading," World Bank' *Policy Research Working Paper*, December 2008. GDP data from World Bank's 'World Development Indicators' database (accesses May 22, 2020).
[11] Wang and Yao, "Sources of China's Economic Growth, 1952-99: Incorporating Human Capital Accumulation," World Bank's *Policy Research Working Papers*, November 1999.
[12] The ICOR rose from 4.2 in 2000 to 8.3 in 2018. Orsmond, "China's Economic Choices," the Lowy Institute, Dec 17, 2019.
[13] Chen and Kang, "Credit Booms – Is China Different?" *IMF Working Paper*, 2018; *Financial Times* (Wolf), "China's Debt Threat: Time to Rein in the Lending Boom," July 25, 2018; Wei, Xie and Zhang, "From 'Made in China' to 'Innovated in China': Necessity, Prospects, and Challenges," *Journal of Economic Perspectives,* Winter 2017.
[14] Perkins, "Understanding the Slowing Growth Rate of the People's Republic of China," *Asian Development Review*, 2015; *The Wall Street Journal* (Ip), "China's State-Driven Growth Model Is Running Out of Gas," July 19, 2019 and World Bank and China's Development Research Center of the State Council, "The Productivity Challenge" (Chap 3) in *Innovative China: New Drivers of Growth*, 2017.
[15] Total factor productivity estimates can vary widely, as they are residual indicators that are determined largely by growth assumptions of GDP and its factor inputs. As such, Figures 1 and 2 use different data as they derive from different sources. Data from Figure 1 reflect official estimates published by the Conference Board which are also used by IMF, World Bank, and OECD. However, estimates by Feenstra *et al*, as well as independent estimates conducted by the Conference Board (which published their estimates in addition to official data), have assumed considerably lower growth in China's GDP and factor inputs. Despite the different values, each assessment exhibit similarly trending sluggish TFP growth and negligible contributions from labor inputs in China. See World Bank and China's Development Research Center of the State Council, *Innovative China: New Drivers of Growth*, Figure 2.1, 2019; and the Conference Board, *Productivity Brief*, 2019.

happening with respect to China's R&D spending habits. After all, R&D expenditures in China have been nearly 10 times higher than India's in recent years, yet China appears to be lagging its Indian neighbor in productivity terms in recent years.[16]

Figure 2. Total Factor Productivity (Relative to U.S. Index Level of 1)



China's modern approach to indigenizing innovation has been introduced through three landmark policies, described in detail in Part II of this analysis. The first was China's Medium- and Long-Term Program for Science and Technology Development (MLT). Initiated in 2006, this called for domestically led innovation in 402 core technologies.[17] By 2015, China's Made in China 2025 (MiC) plan placed greater emphasis on indigenizing innovation within China's manufacturing sector. Its objective was to help transform the world's largest manufacturing hub into one that was more globally competitive and markedly more dependent on home-grown technology by focusing on nine broad goals.[18] In response, Chinese firms ramped up their indigenization efforts in core technologies and attempted to increase China's domestic value-added contributions along globally integrated manufacturing supply chains.[19] Finally, China's 13th Five-Year Science and Technology Plan (an offshoot of the broader 13th Five-Year Plan) set out ambitious implementation plans aimed at transforming China into an even more innovative economy. Chief among those were plans to ensure that, by 2020, at least 60 percent of China's economic growth derived from productivity-enhancing scientific and technological advances enabled by significant increases in R&D expenditures, the doubling of patent applications, and other numerical targets.[20]

Part III of this analysis describes the vast resources China has invested in to help reach its innovation objectives. It highlights the official human capital investments China has made in the sciences, its promotion of expanded international linkages in academic and business sectors, and, of course, the unprecedented financial resources it has poured into these efforts. As a result, by 2018, China graduated about as many science and engineering undergraduate students as the United States, the EU, and Japan combined.[21] China's linkages to the scientific academic communities and advanced manufacturing

[16] National Science Board, "Research and Development: U.S. Trends and International Comparisons," chapter 4 in *Science and Engineering Indicators*, 2018.

[17] The State Council of the People's Republic of China, "The National Medium- and Long-Term Program for Science and Technology Development (2006-2020), 2006.

[18] Hammer, "'Made in China 2025' Attempts to Re-Stimulate Domestic Innovation," U.S. International Trade Commission's *Executive Briefing on Trade*, September 2017.

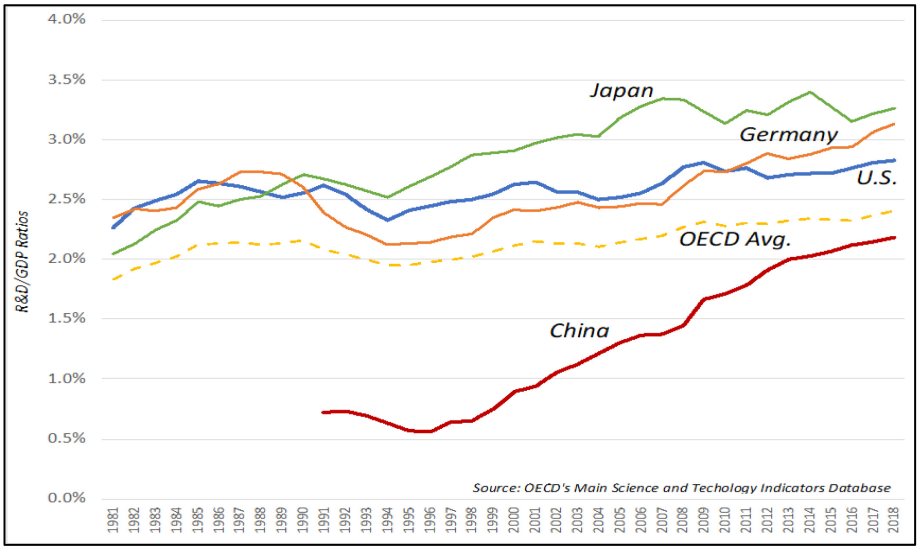
[19] China is now a key hub for a number of global value chains and leading the process of consolidation. World Bank, "Trading for Development in the Age of Global Value Chains," *World Bank Development Report, 2020.*

[20] Molnar, "Boosting Firm Dynamism and Performance in China," *OECD Economics Department Working Paper*, 2017; State Council of the People's Republic of China, "13th Five-Year Science and Technology Innovation Plan, August 8, 2016; U.S.-China Economic and Security Review Commission (Koleski), "The 13th Five-Year Plan," *Staff Research Report*, February 14, 2017.

[21] National Statistical Bureau's *China Statistical Yearbook* (2019); National Science Foundation; Europstat.

technologies has been deep and unprecedented. Perhaps most importantly, China is now the world's second-largest spender on R&D after the United States, and the ratio of R&D to GDP is converging towards the average for economies in the Organization for Economic Co-operation and Development (OECD), as shown in Figure 3.[22] Purchasing power parity adjustments for R&D spending suggests that China has already surpassed EU levels and is close to U.S. spending in this regard, even though China's expenditures still trail in per capita terms.[23] A closer examination of the sources of spending shows that much of this funding has been spent by quasi-public, quasi-private limited liability corporations (LLCs) in China. Such firms are believed to take their cues from the government while competing against private, foreign, and wholly owned state-owned enterprises within China.[24] These and other forms of enterprises in China have benefited from government support, including direct financing, financial incentives (e.g., tax), bank lending, internal financing, venture capital, fintech, and other forms of lending.

Figure 3. R&D Spending (in % of GDP)



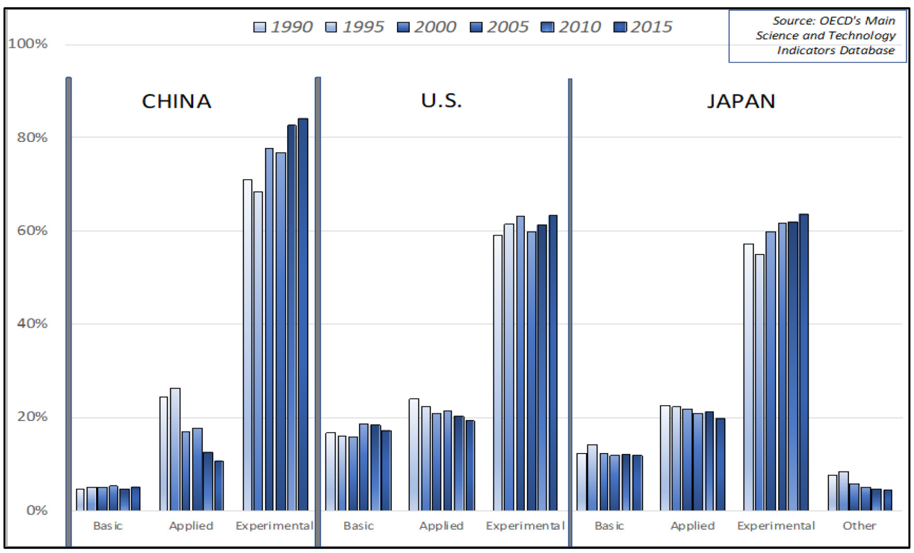
Official support of China's home-grown innovation has yielded tangible results in five primary areas, as described in Part IV of this paper. First, with regard to patents, which are an important albeit imperfect measure of innovation, China is now the largest filer worldwide.[25] While it is true that there exist broad patent quality differentials compared to other high-tech economies, higher-tech triadic and PCT[26] patents suggest that China is making substantive progress in this area. Second, with respect to high-tech manufacturing and exports, OECD data suggest that China now accounts for roughly 21 percent of the world's manufacturing of R&D-intensive products and is the world's second leading exporter of such products behind the United States.[27] Third, with respect to China's high-tech services exports, China has demonstrated dramatic gains. This has been demonstrated by its royalty and license fee data, which have historically been negligible but have surged in recent years to nearly $10 billion by 2019.[28] Fourth,

[22] OECD, 'Main Science and Technology Indicators' database (accessed May 20, 2020).
[23] OECD, 'Main Science and Technology Indicators' database (accessed May 20, 2020).
[24] Gabrielle, Enterprises, Industry, and Innovation in the People's Republic of China: Questioning Socialism from Deng to the Trade and Tech War, Springer, 2020.
[25] World Intellectual Property Organization (WIPO), 'Intellectual Property (IP) Statistics' database (accessed May 20, 2020).
[26] As described above, PCT patents, or patents that fall under the Patent Cooperation Treaty, are patents that have been filed under a unified patent filing procedure and are broadly indicative of higher-quality patents. Under an international patent law treaty, PCT patents are simultaneously applied for in 150 different countries that are party to the treaty. World Intellectual Property Organization (WIPO), "Summary of the Patent Cooperation Treaty (PCT), 1970. Triadic patent applications refer to patent applications that are simultaneously submitted to the United States' Patent and Trademark Office (USPTO), the European Patent Office (EPO), and the Japan Patent Office (JPO).
[27] OECD, 'Main Science and Technology Indicators' database (accessed May 20, 2020).
[28] IMF, 'Balance of Payments Statistics database (accessed May 20, 2020).

in the area of scientific publications, China has overtaken the United States to become the leading source of published papers.[29] Even after adjusting for the quality of publications, China has shown a "remarkable increase in the share of impactful papers."[30] Finally, in the area of human capital, China already employs some four and a half million scientists, which is a world-leading level after the United States.[31] Given its immense population, the number of scientists in China is still small relative to other countries, and demonstrates its growth potential in this area.

Moreover, compared to other high-technology economies, less of China's R&D spending has been geared towards the theoretical sciences—often referred to as "basic" sciences—that can prepare the ground for the invention of disruptive technologies. As can be seen in Figure 4, China's R&D spending through its various forms of enterprises and government institutions is heaviest in experimental R&D, which is on the most applied side of the innovation spectrum. That type of innovation focuses on such areas as process improvement in manufacturing and consumer-focused technological developments. This pattern is not unlike that seen in other developing countries in the catching-up phase.

Figure 4. R&D Expenditure (by type)



China's robust technological performance now appears to be moving beyond the stage where it is catching up to advanced economies. A number of Chinese firms' research and industrial products are considered to be at the frontier, in areas where technological change is most active. For example, Chinese firms are considered to be among the frontrunners in telecommunications (5G),[32] mobile devices,[33]

[29] National Science Foundation, 'Nation's Center for Science and Engineering Statistics' database (assessed May 22, 2020).
[30] Cao, Baas, Jonkers, and Wagner, "Returning Scientist and the Emergence of China's Science System," *Science and Public Policy*, April 2020.
[31] Bureau of Labor Statistics, 'Occupational Employment Statistics,' (accessed May 20, 2020); National Science Foundation, 'Nation's Center for Science and Engineering Statistics' database (assessed May 22, 2020); OECD, 'Main Science and Technology Indicators' database (accessed May 20, 2020).
[32] Huawei and ZTE are the leaders. *Forbes*, "China's Huawei 'Growing Up' To Become The World's No. 1 Smartphone Brand," May 25, 2016.; *Washington Post* (Fung), "How China's Huawei Took Lead over U.S. Companies in 5G Technology," April 10, 2019; *Yahoo Finance* and *PR Newswire*, "ZTE Helps China Telecom Deploy Industry's First Commercial Trial of 400G OTN Cluster System," March 19, 2020.
[33] Huawei and Xiaomi dominate the market for smartphones in China and are penetrating other developing economies because they offer most or more features to be found in phones by Samsung and Apple at lower prices. *Forbes*, "China's Huawei 'Growing Up' To Become The World's No. 1 Smartphone Brand," May 25, 2016; *Forbes* (Doffman), "Huawei Outguns Samsung and Apple to Target Top Spot: Blacklist, What Blacklist?" November 2, 2019; *Market Watch,* "China's Xiaomi Beats Samsung, Apple in Home Market," August 5, 2014; News18Tech, "Huawei Still on Top, Xiaomi Beats Apple in Domestic Smartphone Shipments," July 26, 2017.

commercial drones,[34] high-speed rail,[35] wind turbines,[36] supercomputers,[37] quantum computing,[38] space launch vehicles and satellites,[39] and liquid crystal displays (LCDs).[40] Chinese scientists are actively participating in the research on machine learning and neuroscience, on biogenetics, on nanotechnology—and their findings are entering the commercial domain.[41] Moreover, Chinese e-commerce firms such as Alibaba, JD.com and Pinduoduo are the technological equals of several foreign rivals, and China's social media giants such as Tencent (creator of the social messaging WeChat app) and Alibaba (which introduced the Wangxin app popular with its Taobao user base) are no less innovative. In fintech, there is an increasing use of crypto-currencies[42] and blockchain, and central bank digital currency. Chinese companies have enjoyed an edge because of first-mover advantages, a relatively large and closed market for foreign competition, the backwardness of China's preexisting retail banking infrastructure, the speed with which information and communications technology (ICT) infrastructure was developed, and the widespread adoption of mobile payments using smart phones (Alipay, WeChat pay).[43]

Despite these advances, China's effort at catching up to the production methods employed by the world's most technologically advanced countries remains incomplete. The United States, the EU, Japan, and South Korea are well ahead in a number of fields. While China is the world's largest market for automobiles, its foreign counterparts in joint-ventures, such as Volkswagen and GM, have largely retained the lead with respect to the embedded technology, product quality, production efficiency, and brand image of their produced goods.[44] This may change as the industry shifts to the production of more software-intensive and less mechanically complex new energy vehicles (NEVs), but it is by no means a given. The recent experience of Tesla suggests that Chinese firms may find that mastering NEV technology may not be much easier than mastering the technology associated with internal combustion engines, and Chinese firms haven't significantly narrowed the technology gap in either, to date. Also, China is a major supplier of active pharmaceutical ingredients and of generic medications, but indigenous innovation is on a modest scale[45] with researchers now mobilizing artificial intelligence to create new drugs.[46] Producing commercial jet aircraft is another area that is posing a challenge to Chinese manufacturers, even though they enjoy the support of foreign producers of parts and modules. And then

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[34] DJI has captured a large share of the global market and three quarters of the US market. DoneII, "Drone Manufacturer Market Share: DJI Leads the Way in the U.S.," *Drone Industry Insights* October, 2019.

[35] CRRC is the world's largest train maker. Institute Montaigne, "Europe-China Rail Competition- 'Bigger Is Better'?" February 11, 2019.

[36] Goldwind, Envision, and Guodian United Power account for a quarter of the world market. Goldwind was ranked second after Vestas in 2018. Statistica, "Global Market Share of the World's Leading Wind Turbine Manufacturers in 2018," April 28, 2020.

[37] Several Chinese groups are in the running to develop the fastest exascale computer. Feldman, "China Flashes Out Excascale Design for Tianhe-3 Supercomputer," *The Next Platform,* May 2, 2019; Institute of Electrical and Electronics Engineers (IEEE), "Will China Attain Exascale Supercomputing in 2020?" *IEEE Spectrum*, January 7, 2020;

[38] *The Washington Post (*Jean Walen), "The Quantum Revolution Is Coming, and Chinese Scientists Are at the Forefront," April 18, 2019.

[39] Center for Strategic and International Studies (CSIS), "How Is China Advancing Its Space Launch Capabilities?" (accessed May 1, 2020).

[40] BOE Technology is among the most advanced producers. *Forbes* (Will Shih), "How Did They Make My Big Screen TV? A Peek Inside China's Massive BOE Gen 10.5 Factory," May 18, 2018.

[41] Castelvecchi, "China's Quantum Satellite Clears Major Hurdle on Way to Ultra-Secure Communications," *Nature,* June 15, 2017; Deloitte, "Rising Innovation in China" *China Innovation Ecosystem Development Report 2019*," September 2019. Dong, Sinko, Wu, Wu, and Lia, "The Nanotechnology Race Between China and the USA" *Materials Today,* April 12, 2016; McKinsey Global Institute, "China and the World: Inside the Dynamics of a Changing Relationship," July 2019; Normile, "Three Chinese Teams Join Race to Build the World's Fastest Supercomputer," *Science*, October 24, 2018; Qiu, "Nanotechnology Development in China: Challenges and Opportunities," *National Science Review*, March 2016; Rhodium and Gryphon Scientific, "China's Biotechnology Development: The Role of U.S. and Other Foreign Engagement," February 14, 2019.

[42] The PBC appears to be readying a launch of a digital currency so as to partially digitize its monetary base, facilitate interbank settlements and integrate digital currency wallets into retail bank accounts. *Financial Times,* "Patents Reveal Extent of China's Digital Currency Plans," February 12, 2020.

[43] American Express (Faden), "China's Mobile Payments Phenomenon," (accessed April 20, 2020); and World Economic Forum and Statistica (Buchholz), "China Is Fast Becoming the World Leader in Mobile Payment," Payment, "May 15, 2019.

[44] Mckinsey & Company, "Winning the Race: China's Auto Market Shifts Gears," *McKinsey China Auto CEO Quarterly,* December 2019.

[45] For example, Chinese researchers have far fewer biotech patents than researchers from the United States. Rhodium Group and Gryphon Scientific, "China's Biotechnology Development: The Role of US and Other Foreign Engagement," February 14, 2019; and Atkinson, "China's Biopharmaceutical Strategy: Challenge or Complement to US Industry Competitiveness," 2019.

[46] Atkinson, "China's Biopharmaceutical Strategy: Challenge or Complement to U.S. Industrial Competitiveness," Information Technology & Innovation Foundation (ITIF) Report, August 2019; CGTN, "A 'Cambrian Explosion' in China's Innovative Drug Industry," December 26, 2019; Ni et al, "Obstacles and Opportunities in Chinese Pharmaceutical Innovation," *Globalization and Health,* March 24, 2017.

there are integrated circuits of many kinds, which China imports from overseas suppliers—foreign firms whose products are significantly more advanced than what Chinese firms have produced. While many U.S. and other countries' firms have offshored labor-intensive parts of their integrated circuit production to China,[47] they are manufacturing more utility-level products there that are designed for integration into consumer electronic devices, not cutting-edge technologies.[48]

In addition to increasing firms' R&D spending, which the government is promoting in an attempt to elevate national R&D to GDP ratio from 2.2 percent to 2.5 percent, Chinese firms have also benefitted from FDI in joint venture operations (in production units and laboratories) and licensing as a continuing source of technology transfer.[49] Its own overseas acquisitions of foreign firms (e.g., Volvo by Geely, Kuka by the Midea Group) are a means of acquiring proprietary knowledge and technical skills.[50] Chinese companies are also furthering their objectives by investing in research facilities in innovation hotspots in the United States and Europe and by supporting startups with promising ideas. Venture capital investment in the United States from Chinese sources rose to nearly $15 billion in 2018 before declining in early 2019 as trade tensions rose.[51] Harnessing the know-how of foreign researchers through the Ten Thousand Talents effort, various exchange programs, and myriad collaborative activities taps into research being done abroad.[52] The building of knowledge capital through these channels is supplemented by widespread reported IP misappropriation, forced technology transfers, and commercial espionage conducted by private and public entities, frequently using sophisticated cybertechnologies.[53]

II. Chinese Policies Promoting its Modern Innovation Initiative

From the beginning of its 1978 reforms until its accession to the World Trade Organization (WTO), much of China's development planning had focused on modernizing its industrial base. To accomplish this objective, its government provided strong financial incentives to attract FDI, encouraged multinationals to offshore their lower-value stages of production processes to China, and pursued export-oriented growth strategies that often came at the expense of domestic importation and consumption.[54] By around 2006, however, this strategy transformed into one that increasingly prioritized the development of homegrown technology. Data from China's National Bureau of Statistics suggest that this policy shift was significant, given a noticeable drop in China's imported technology expenditures to GDP ratios that started in that year.[55] It also set the stage for the ambitious "Made in China 2025" (MiC 2025) initiative and innovation objectives set out in China's latest (13th) Five-Year Plan, as described below.

China's National Medium- and Long-Term Program for Science and Technology Development (MLP) was a seminal policy document that introduced its new development focus of "indigenous

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[47] Hammer, "Why Have U.S. Firms Offshored to China?" *USITC Executive Briefing on Trade*, June 2017; and Hammer, "The Size and Composition of U.S. Manufacturing Offshoring in China," *USITC Executive Briefing on Trade*, June 2017.
[48] Verwey, "Chinese Semiconductor Industrial Policy: Prospects for Future Success," U.S. International Trade Commission's *Journal of International Commerce and Economics*, August 2019.
[49] Jiang et al, "International Joint Ventures and Internal Versus External Technology Transfer: Evidence from China," Center for Economic Policy and Research (CEPR), March 2018.
[50] *Politico* (Bennette and Neder), "How China Acquired 'The Crowned Jewels' of U.S. Technology," May 22, 2018.
[51] Hu and Jujita, "Chinese VC Money, Once Red-Hot, Is Fleeing the U.S.," *Yahoo Finance*, October 11, 2019.
[52] Cao, Baas, Wagner, and Jonkers, "Returning Scientist and the Emergence of China's Science System," *Science and Public Policy*, April 2020.
[53] Giglio, "China's Spies Are on the Offense," *The Atlantic*, August 26, 2019; National Counterintelligence and Security Center, "Foreign Economic Espionage in Cyberspace," 2018; National Defense Industrial Association, "How China Conducts Cyber Industrial Espionage," November 4, 2019; USITC, China: Effects of Intellectual Property Infringement and Indigenous Innovation Policies on the U.S. Economy," Investigation 332-517, May 2011; USTR, "Findings of the Investigation Into China's Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation Under Section 301 of the Trade Act of 1974," March 22, 2018;
[54] Atkinson, "Enough Is Enough: Confronting Chinese Innovation Mercantilism," The Information Technology & Innovation Foundations (ITIF) Report, February, 2012; Atkinson, Testimony Before the House Committee on Oversight and Government Reform (Subcommittee on Information Technology) at the Countering China: Ensuring America Remains the World Leader in Technology and Innovation Hearing, September 26, 2018; and Guo and N'Diaye, "Is China's Export-Oriented Growth Sustainable?" *IMF Working Paper*, August 1, 2009.
[55] Fu, Woo, and Hou, "Technological Innovation Policy in China: The Lessons and the Necessary Changes Ahead," *Economic Change and Restructuring*, 2016.

innovation" (*zizhu chuangxin*).[56] The MLP's stated objective was to "re-conceptualize the broader innovation policy framework," create a Leadership Small Group to guide and coordinate technology development, and make it clear that implementation would involve "key point projects and key point tasks."[57] Chief among these key points was the MLP's promotion of domestically led innovation in 402 core technologies that could sustain two-thirds of China's economic growth (presumably by steadily raising productivity), improve living standards, and compete with other advanced economies. These 402 core technologies ranged from advanced manufacturing (e.g., intelligent automobiles, integrated circuits, high-performance computers), to nanotechnology, to drug innovation and development.[58] The plan also called on China's authorities to allocate 2.5 percent of GDP to R&D, source 60 percent of its economic growth from progress in science and technology, base 70 percent of its production on homegrown technologies by 2049, and raise the share of output from strategic and emerging industries to 15 percent of GDP.[59] As such, the MLT provided centrally administered direction for China's innovation drive and helped move it into high gear.[60]

With the launch of its government's Made in China 2025 (MiC 2025) plan in 2015, the quest for innovation took on an even greater salience. This initiative built upon the founding objectives of the MPL, while modernizing its focus, broadening its scope, and attaching more defined implementation plans to effectuate its policy direction. It also represented China's first focused development plan targeting manufacturing, inspired in large part by Germany's "Industrie 4.0" initiative,[61] and is geared towards transforming the world's largest manufacturing hub into one that is markedly more innovative and globally competitive.[62] MiC 2025 has set out nine broad goals, each associated with specific implementation targets.[63] These goals include (1) improving China's manufacturing innovation; (2) integrating information technology (IT) into manufacturing; (3) bolstering China's industrial production; (4) fostering Chinese brands; (5) enforcing green technologies; (6) promoting breakthrough technologies in 10 key sectors; (7) restructuring manufacturing to accommodate technological change; (8) promoting service-oriented manufacturing; and (9) better integrating China's manufacturing with global production chains. China has also attempted to meet its objectives by sourcing the majority of robotic equipment, tools for its electric car batteries (nickel-manganese-cobalt oxide or "NMC") and other high-tech products domestically. [64] The MiC 2025 plan has ramped up the indigenization of core technologies while increasing China's forward value-added contributions along global manufacturing supply chains.[65]

China's 13th Five-Year Plan (13th FYP), which was ratified by the National People's Congress in March of 2016, set out China's principal development strategies for the 2016–20 period. The 13th FYP again underscores innovation as the cornerstone of national development strategy. Building off its experiences with the MLP and the MiC 2025, the 13th FYP has sought to use innovation as a tool to accelerate efforts to "move its manufacturing up the value-added chain, reestablish China as a global

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[56] Atkinson, "Enough Is Enough: Confronting Chinese Innovation Mercantilism," The Information Technology & Innovation Foundations (ITIF) Report, February, 2012; and Cao, Suttmeier, and Simon, "China's 15-Year Science and Technology Plan," University of Oregon's U.S..-China Relations in Science and Technology and the Challenges Ahead Research Program, December, 2006.
[57] The State Council of the People's Republic of China, "The National Medium- and Long-Term Program for Science and Technology Development (2006-2020), 2006.
[58] Cao, Suttmeier, and Simon, "China's 15-Year Science and Technology Plan," University of Oregon's U.S..-China Relations in Science and Technology and the Challenges Ahead Research Program, December, 2006.
[59] Ling and Naughton, "An Institutionalized Policy-Making Mechanism: China's Return to Techno-Industrial Policy," *Research Policy*, December 2016.
[60] Molnar, "Boosting Firm Dynamism and Performance in China," *OECD Economics Department Working Paper*, 2017.
[61] Molnar, "Boosting Firm Dynamism and Performance in China," *OECD Economics Department Working Paper*, 2017.
[62] Hammer, " 'Made in China 2025' Attempts to Re-Stimulate Domestic Innovation," U.S. International Trade Commission's *Executive Briefing on Trade,* September 2017.
[63] China's Ministry of Industry and Information Technology's, "Key Technology Roadmap," July 7, 2015; and U.S. Chamber of Commerce, "Made in China 2025: Global Ambitions Build on Local Protections," 2017.
[64] McBride and Chatzky, "Is 'Made in China 2025' a Threat to Global Trade?" Council on Foreign Relations, May 13, 2019; and the State Council of the People's Republic of China, "'Made in China 2025' Plan Issued, May 19, 2025.
[65] China is now a key hub for a number of global value chains and leading the process of consolidation. World Bank, "Trading for Development in the Age of Global Value Chains," *World Bank Development Report, 2020.*

center of innovation and technology, and ensure long-term productivity."[66] Associated with the 13th FYP have been two other initiatives with wide-ranging implications for Chinese innovation levels. The first was the *Guidelines for China's Innovation-Driven Development Model*, published in May 2016, which extends the 13th FYP objectives by setting a blueprint for China to become an "innovative nation" by 2020, an "international innovation leader" by 2030, and a major source of scientific and technological innovation by 2050.[67] By August of the same year, the State Council published its associated 13th Five-Year Science and Technology Plan, which restates three of the key innovation objectives from the 13th FYP, and seven important other ones. These targets are summarized in the table below.

In addition to the major modern innovation policy initiatives mentioned above, China's government has pursued a number of other policies and practices in support of its domestic innovation and growth objectives. These have included, but have not been limited to, the development of R&D domestic ecosystems, such as China's research incubators and some 163 national and provincial high-tech and science and technology parks, which have hosted both foreign and domestic companies. Others have included the establishment of research institutes both domestically and abroad, the creation of more extensive university-industry research linkages, the purchasing of licensed technology from abroad, and the acquisition and/or establishment of joint venture operations with foreign firms to acquire intellectual property.

Table 1. China's 13th Five-Year Science and Technology Innovation Plan Objectives

Origin	Target	2015 (Base Year)	2020
From 13th Five-Year Plan	Contribution of science and technological advances to economic growth	55.3%	60.0%
	Patents filed (per 10,000 people)	6.3	12
	R&D expenditures (% of GDP)	2.1%	2.5%
	Number of Patent Cooperation Treaty (PCT) applications (per 10,000 patent applications)	3.05	6.1
	Revenue from high-technology enterprises	22.2 trillion RMB (roughly US$3.5 trillion)	34 trillion RMB (roughly US$5.0 trillion)
	Value-added output in knowledge-intensive service industries (in % of GDP)	15.6	20
	National technical contract turnover	983.5 billion RMB (roughly US$150 billion)	2 trillion RMB (roughly US$300 billion)
	Number of R&D personnel (per 10,000 people employed per year)	48.5	60
	Population with scientific degrees (in % of total population)	6.2	10
	Global ranking for number of citations in international science and technology papers	4	2
	Global innovation ranking	18	15

Source: State Council of the People's Republic of China, *13th Five-Year Science and Technology Innovation Plan,* August 8, 2016; USCC (Koleski), *The 13th Five-Year Plan,* Staff Research Report, February 14, 2017; Molnar, *Boosting Firm Dynamism and Performance in China,* OECD Economics Department Working Paper, 2017.

[66] U.S.-China Economic and Security Review Commission (USCC, Koleski), "The 13th Five-Year Plan," *Staff Research Report*, February, 2017.
[67] State Council of the People's Republic of China, "Guideline for China's Innovation-Driven Development, May 20, 2016.

III. Fueling Innovation Through Human Capital Development, Expanded International Linkages, and Financing

The Chinese authorities have used a combination of mechanisms to realize their innovation-oriented objectives. This section describes these measures in greater detail, focusing on the major sources behind China's innovation drive: human capital development, broadened international linkages in academia and business, and, most importantly, robust R&D spending by various actors.

A. Local Human Capital Development

In its pursuit of a knowledge-based economy, China wasted no time in building human capital since the 1980s. Its government has paid particular attention to the tertiary-level education system, especially as it related to science, technology, engineering, and mathematics (STEM) disciplines.[68] The enrollment rate of students in higher education and higher vocational education increased from 3 percent in 1980 to 24 percent in 2010, with the tempo accelerating after 1999 as the need for skilled workers became more urgent.[69] To raise the research capabilities and international standing of its universities, China's Ministry of Education launched a "Project 211" in 1995 that aimed to substantially raise the research standards at 112 national universities. Three years later, Project 985 (named after its May 1998 date) targeted an additional 39 schools, and provided considerable funding to build new research centers, improve facilities, and sponsor international conferences.[70] By the turn of the century, nine schools had attained elite status and received 10 percent of the research budget allocated by the central government.[71] By 2016, China was creating one additional institution of higher education every week, resulting from the realization that higher education promised substantially improved lifetime earnings.[72] In 2017, the government merged the higher education programs into the "Double First Class University Program" aimed at elevating 30 Chinese universities into the ranks of the top 100 global institutions by 2050.[73] As of 2020, according to the rankings established by the *Times Higher Education Supplement*, 7 Chinese universities were in the global top 100 list, with Tsinghua and Peking universities ranked 23rd and 24th, respectively.[74]

The "211" and "985" programs sponsored by the central government also included initiatives to substantially expand university enrollment (Figure 5).[75] As a result, the tertiary-level gross enrollment rate rose from 7.6 percent in 2000 to 50 percent in 2018.[76] By 2019, 8 million students were graduating from university and entering the job market. The number of science and engineering graduates from Chinese universities (1.7 million) in 2016 was more than double those from schools in the United States

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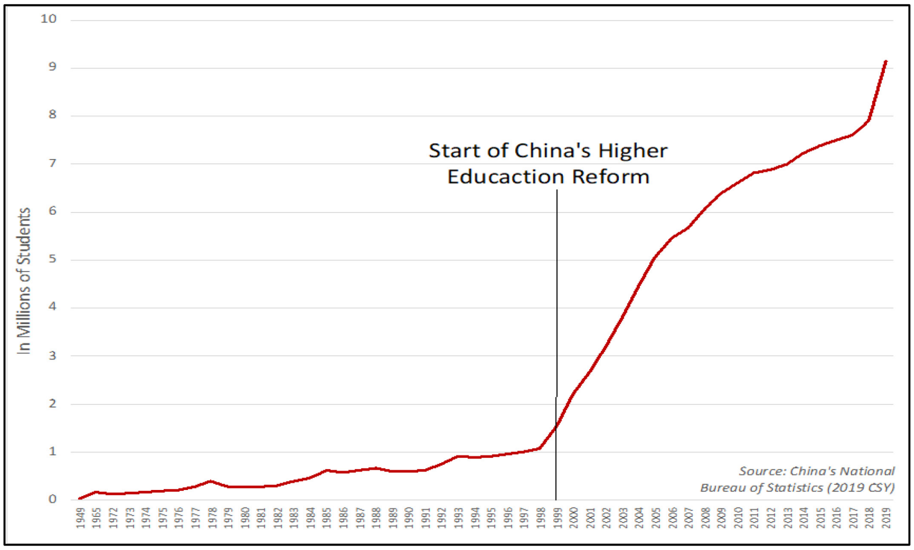
[68] STEM refers to science, technology, engineering, and mathematics. Bai et al, "Past Successes and Future Challenges in Rural China's Human Capital," *Journal of Contemporary China,* March 2019; Heckman, "China's Investment in Human Capital" NBER Working Paper 9296, October 2002; Li et al, "Human Capital in China," NBER Working Paper 15500, November 2009; Wong, "Are We Having Too Many PhDs?" China.Org, May 25, 2019; and World Bank and China's Development Research Center of the State Council, "China's Growth Through Technological Convergence and Innovation" in *China 2030: Building a Modern, Harmonious, and Creative Society*, 2014.
[69] Asian Development Bank, *Human Capital Development in the PRC and India*, 2015; Heckman and Yi, Human Capital, Economic Growth and Inequality in China, 2012; and Chi, "The Role of Human Capital in China's Development," *China Economic Review*, 2008
[70] World Educational News and Reviews, "International Rankings and Chinese Higher Education Reform," October 2006.
[71] *World University Rankings*, "Best Universities in China," (accessed June 22, 2020).
[72] Human capital may have contributed more than 38 percent of China's GDP growth between 1978 and 2009. Whalley and Zhao, "The Contribution of Human Capital to China's GDP Growth," NBER Working Paper 16592, 2010.
[73] World Educational News and Reviews, "Education in China," December, 2019.
[74] The University Rankings, "Best Universities in China 2020," September 16, 2019.
[75] Simon and Cao, "China's Future: Have Talent Will Thrive, *Issues in Science and Technology*. Fall 2009; and Stapleton, "China Now Produces Twice as Many Graduates a Year as the United States," World Economic Forum, April 13, 2017. "As a concept, talent (*rencai*) has gained increasing popularity and significance in China since the turn of the 21st century, when the leadership realized that 'empowering the nation with talent' (*rencai qiangguo*) is key to 'rejuvenating the nation with science, technology, and education' (*kejiao xingguo*), a strategy introduced in the mid-1990s" Cao *et al,* "Returning Scientists and the Emergence of China's Science System," Oxford's Science and Public Policy, 2019.
[76] World Educational News and Reviews, "Education in China," December 17, 2019.

(42,000).[77] And although more doctoral degrees in science and engineering were awarded in the United States in 2014 (40,000), China was a close second with 34,000.[78]

Figure 5. Number of Newly Enrolled University Students in China



Although the quality of China's computer science educational system has been on the rise, the United States still appears to have retained a lead in this area. Loyalka et al. (2019) find that university seniors in the United States outperform those in China, India, and Russia by roughly 0.76–0.88 standard deviations.[79]

B. Expanding International Science and Technology Linkages in Education and Business

China's efforts to implement its innovation-oriented policies have not been limited to the enrollment of more students into local universities and STEM-related disciplines. During the initiation of reforms in the late 1970s, the authorities changed their policies to allow millions of Chinese to seek education opportunities in North America, the EU, Japan, and elsewhere. The authorities also started inviting the world's academic communities to advance learning in China, and encouraging foreign-based multinational firms to heavily invest in their country. Foreign-invested enterprises were eager to conduct business in China's promising economy, as they had been clamoring to do so even before 1978. This section highlights how China's expanded international linkages in science and technology, in both academic and business circles, have helped spur technological growth and innovation.

As of 2017, 5.2 million Chinese had gone abroad to study.[80] Of this number, an estimated 3.1 million have returned, swelling the pool of skilled and technical workers. Freeman and Huang (2015) have found that returnees trained in Western and Japanese research institutions have significantly enhanced the quality of China's research capital and narrowed the country's technology gap with

[77] *Forbes*, "The Countries With the Most STEM Graduates," February 2, 2017. China had 4.7 million new graduates with degrees in STEM disciplines out of a total of 7.0 million graduates in 2016. The number of graduates rose to 7.5 million in 2018. Statistica, "Number of Graduates from Public Colleges and Universities in China Between 2008 and 2018," Accessed May 22, 2020.
[78] National Science Board, Science and Engineering Indicators database, (accessed June 2, 2020); and Veugelers, "China Is the World's New Science and Technology Powerhouse," Bruegel, August 30, 2017.
[79] Loyalka et al, "Computer Science Skills Across China, India, Russia, and the United States," Proceedings of the National Academic of Sciences of the United States of America," March 18, 2019.
[80] China's Ministry of Education, "2017 Sees Increase in Number of Chinese Students Studying Abroad and Returning After Overseas Studies," April 3, 2018.

advanced economies.[81] In the decade extending from 2006 to 2016, more than 50,000 scientists from China received their doctoral degrees in STEM fields from universities in the United States, some of whom have now made their way back to China on a full- or part-time basis.[82]

To persuade Chinese scientists to return to their country of birth after completing their foreign education, and in an effort to attract foreigners with outstanding qualifications, the government introduced a number of related initiatives.[83] The most well-known of these has been the "Ten Thousand Talents" program. Returnees and visiting foreign scholars have enriched China's talent pool and helped connect Chinese researchers with counterparts all over the world. Ganguli and Gaule have found that the scholars attracted back to China have published more in international journals and that their publications have generally had a greater impact on scientific development.[84]

Thanks to the large annual additions to the pool of researchers from domestic sources and the inflow from returnees from abroad, the numbers of R&D researchers in China climbed from 438 per million people in 1996 to 1,235 per million in 2017. While still below the numbers of R&D researchers in the United States (4,256) and Japan (5,305) per million in that year, the major gaps in pure numbers of researchers between China and other advanced industrialized countries has narrowed considerably.[85] These researchers are distributed across five institutional sectors: the Chinese Academy of Sciences (CAS), research-oriented universities, industrial enterprises (especially the larger state-owned enterprises and private firms), public research institutes reporting to government ministries, and the research ecosystem serving the military.[86]

Foreign-based multinational firms had been eager to enter China's market since the initiation of economic reforms in 1978, and the technology and modern manufacturing processes these firms have introduced to China have been an integral part of China's rapid economic development process.[87] These foreign firms ramped up their efforts to form joint ventures (JVs) with domestic Chinese counterparts beginning in the mid-1990s, pouring money into R&D initiatives that tailored their foreign technology to China's manufacturing system. Their goals were largely to gain a foothold in the Chinese market, take advantage of lower-priced Chinese research talent, and benefit from the knowledge being generated by China's burgeoning innovation system.[88] In some instances, foreign-based multinationals established research platforms in China to satisfy Chinese government requirements for technology transfer to Chinese entities. Between 2009 and 2018, moreover, FDI in joint ventures rose from $17.3 billion to $34.4 billion.[89] A fraction of this investment found its way into research laboratories, supporting a doubling in the number of such facilities between 2012 and 2017, from 1,200 to 2,400. Precisely how much of the FDI was channeled into R&D is difficult to know. Anecdotal evidence, as well as a limited amount of literature, suggests that many of these labs have had modestly scaled operations engaged in

[81] Freeman and Huang, "China's 'Great Leap Forward' in Science and Engineering," NBER Working Paper 21081, April 2015.
[82] Suttmeier, "Chinese Science Policy at a Crossroads," *Issues in Science and Technology,* Winter 2020.
[83] Cao, Baas, Wagner, Jonkers, "Returning Scientists and the Emergence of China's Science System. Science and Public Policy," April 2020; and Kennedy, "China's Rise as a Science Power," University of California Press, 2019. ; Dente, "Scientists on the Move," *Cell*, April 6, 2007.
[84] Cao, Baas, Wagner and Jonkers, "Returning Scientists and the Emergence of China's Science System," *Science and Public Policy,* 2020*; Financial Times,* "China Hushes Up Scheme to Recruit Overseas Scientists," January 9, 2019; and Ganguli and Gaule, "Will the U.S. Keep the Best and the Brightest (as Post-Docs)? Career and Location Preferences of Foreign STEM PhDs," NBER Working Paper 24838, July 2018.
[85] World Bank, World Development Indicators database (accessed June 22, 2020).
[86] Suttmeier, "How China Is Trying to Invent the Future as a Science Superpower," *Scientific American*, June 29. 2018.
[87] Chang, *Multinational Firms in China,* Oxford University Press, 2013. Investment in JVs and associated technology transfer increased growth rate by 0.43 percent per annum between 1979 and 2009. Van Reenan and Yueh, "Why Has China Grown So Fast? The Role of International Technology Transfers," London School of Economics Centre for Economic Performance Discussion Paper, 2012.
[88] Investment in JVs and associated technology transfer increased growth rate by 0.43 percent per annum between 1979 and 2009. Van Reenan and Yueh, "Why Has China Grown So Fast? The Role of International Technology Transfers," London School of Economics Centre for Economic Performance Discussion Paper, 2012; Marro, "Foreign Company R&D: In China, For China," *China Business Review*, June 1, 2015; Walsh, *Foreign High-Tech R&D in China: Risks, Rewards, and Implications for U.S.-China Relations,* Stimpson Center, 2003.
[89] China's Ministry of Commerce, "Foreign Investment," (accessed June 22, 2020).

downstream development, although a few appear to be conducting fundamental research.[90] Examples of ongoing endeavors in the automotive industry alone have included Toyota's interest in forming a JV with Chinese-based BYD to conduct applied electric vehicles research,[91] and Ford's interest in establishing a joint research lab with Changan Auto to improve the performance of both internal combustion engines and electric vehicles.[92]

Much research has been conducted to ascertain how deeply China has benefited from the legal acquisition of foreign technology and managerial learnings. Fu and Gong have shown that foreign-based multinationals have been an essential force in technological upgrading in China, particularly in high-technology sectors. [93] Chen and Qu have found that China has acquired, assimilated, and improved foreign technology in operational, tactical, and strategic learning processes. Others, including Agrewal and Khan, have examined the impact on FDI on GDP, while Grimes and Yang have delved into Chinese firms' dependence on foreign technologies along global value chains in the ICT sector.[94] Tsang has even examined the effects of domestic firms' managerial learning from foreign-invested enterprises in China.[95] While the literature is quite rich in these areas, it should be noted that the building of knowledge capital in China appears to have been supplemented by widespread reports of more nefarious practices. Such reports have included pervasive IP misappropriation of foreign patents, trademarks, copyrights, and trade secrets; forced technology transfers; and commercial espionage conducted by private and public entities, some of which appear to have gathered targeted information using sophisticated cybertechnologies.[96]

In sum, it appears as though China has benefited a great deal from its policies of opening up in both the academic and business sectors. Given China's disproportionally high integration along global supply chains and its corresponding exposure to leading manufacturing technologies, it is not unreasonable to assume that China has benefited more from these policies, at least in the business sector, than other developing countries that are not as integrated along modern manufacturing supply lines.

C. Financing

Only a small share of China's R&D outlay appears to be directly spent by the government. As shown in Figure 6, the government share has amounted to about 20 percent of overall R&D spending in recent years, and consists of R&D-related expenses for such institutions as the Ministry of Science and Technology, the National Development and Reform Commission (NDRC), the National Science Foundation of China (NSFC), the Ministry of Industry and Information Technology (MIIT), the Ministry of Economy (MOE), and the Chinese Academy of Sciences. As China's educational sector is formally considered part of China's public sector, it is likely that the government's share of R&D spending also includes spending for these institutions.

Figure 6 also shows that more than three-quarters of China's R&D spending has originated from its business sector. While at face value this appears similar in profile to the share of R&D spending seen in

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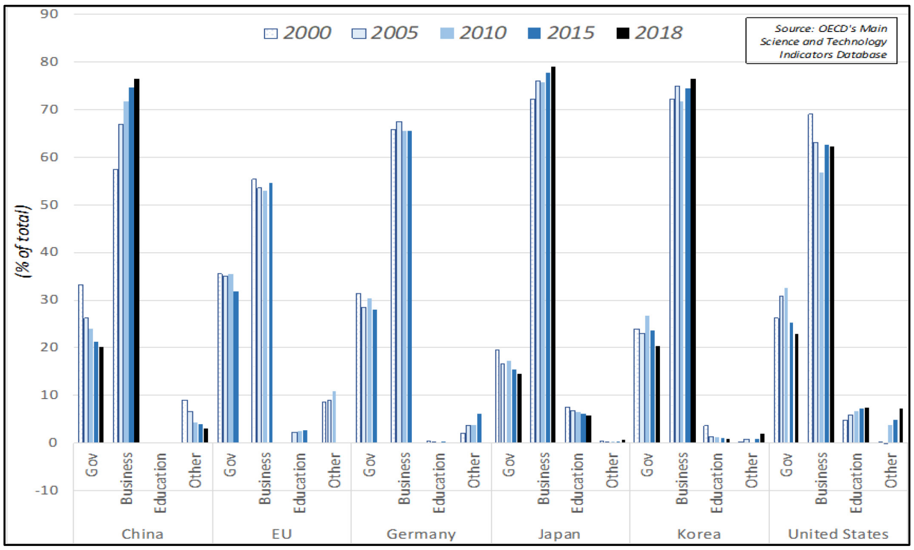
[90] Jolly, McKern and Yip, "The Next Innovation Opportunity in China: Multinational Are Shifting Their R&D Focus from Cost Saving to Knowledge-Based Research," July 27, 2015.
[91] FutureCar.com, "Toyota and BYD Establish Joint Company in China for Electric Vehicle Development," November 8, 2019.
[92] AutomoticNews.com, "Ford Opens R&D Center for Troubled Changan Joint Venture," September 30, 2019.
[93] Fu and Gong, "Indigenous and Foreign Innovation Efforts and Drivers of Technological Upgrading: Evidence from China," *World Development,* July 2011.
[94] Grimes and Yang, "From Foreign Technology Dependence Towards Greater Innovation Autonomy, China's Integration Into the ICD Global Value Chains," *Area Development and Policy*, March 2017.
[95] Agrewal and Khan, "Impact of FDI on GDP: A Comparative Study of China and India," *International Journal of Business and Management*, October 2011; and Tsang, "Managerial Learning in Foreign-Invested Enterprises in China," Management International Review, 2001 1st Quarter.
[96] Giglio, "China's Spies Are on the Offense," *The Atlantic*, August 26, 2019; National Counterintelligence and Security Center, "Foreign Economic Espionage in Cyberspace," 2018; National Defense Industrial Association, "How China Conducts Cyber Industrial Espionage," November 4, 2019; USITC, China: Effects of Intellectual Property Infringement and Indigenous Innovation Policies on the U.S. Economy," Investigation 332-517, May 2011; USTR, "Findings of the Investigation Into China's Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation Under Section 301 of the Trade Act of 1974," March 22, 2018;

the United States and other high-tech countries, it is important to remember that China's corporate sector consists of a variety of firms, including state-owned enterprises (SOEs), private firms, and combinations thereof (e.g., limited liability corporations or LLCs), not to mention foreign-invested enterprises, and that each of these forms of enterprises tends to respond to Chinese government direction in varying degrees. Even the companies that are least sensitive to government direction, and that finance their innovation through profit-seeking private sector channels, are beneficiaries of lax regulatory environments, and these companies ultimately support the government's innovation-oriented objectives.

Figure 6. Sources of R&D Financing



According to China's National Statistical Bureau, the majority of China's R&D spending is conducted by LLCs (34 percent),followed by private firms (27 percent) and foreign-invested firms (22 percent).[97] Pure SOEs generated only 2 percent of overall R&D spending in 2017.[98] Gabrielle, and separately Hubbard, explain that most of the public and private sector conglomerate LLCs consist of merged combinations of state and private sector firms, each possessing equity stakes that fall short of complete ownership from any one form of enterprise.[99] As LLC firms are partially owned by the government, and their ownership shares tend to determine the degree to which they have a say in corporate decision making, [100] it is reasonable to assume that expenditures from these most prominent sources of R&D spending would be at least partially influenced by official policy direction.

The financing of such domestic firms (e.g., LLCs, SOEs, private), as well as foreign ones, stems from a variety of sources. These include (1) direct government assistance; (2) firms' internal resources (the most prominent form of financing); (3) bank borrowing (accounting for some 20 percent of firms' financing needs);[101] and (4) other forms (e.g., corporate bond issuance, venture capital, shadow banking, fintech).

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[97] China's National Bureau of Statistics, *China Statistical Yearbook,* 2019 (citing 2017 data).
[98] China's National Bureau of Statistics, *China Statistical Yearbook,* 2019 (citing 2017 data).
[99] Gabrielle, *Enterprises, Industry and Innovation in the People's Republic of China*, Springer 2020, 105; and Hubbard, "Reconciling China's Official Statistics on State Ownership and Control," East Asian Bureau of Economic Research Working Paper Series 120, 2015, 5.
[100] Sayari Knowledge Center, "China-Understanding Chinese Corporate Structures," (accessed June 20, 2020).
[101] Ayyagari, Demirguc-Kunt, and Maksimovic, "Formal Versus Informal Finance: Evidence from China," *The Review of Financial Studies,* May 10, 2010.

i. Government Financial Assistance

Chinese central and provincial authorities have implemented their innovation-related policies in a variety of ways.[102] These have included direct funds to be used by the business sector for R&D, as well as fiscal incentives, grants, loan guarantees, vouchers, equity acquisition (especially in startups), public procurement, technology extension services, incubators, accelerators, competitive grants and prizes, science and technology parks, collaborative arrangements, and networks.[103] According to Molnar 2015, the authorities appear to be disproportionately using financial support and tax incentives relative to other innovation-promoting instruments.[104]

As of 2018, there were an estimated 1,600 government-guided investment funds in support of broader R&D efforts. Worth an estimated $584 billion, these funds came from central and local branches of government, SOES, and state-controlled financial institutions.[105] The funds' investments are typically extended to central and provincial-level SOEs and, to a lesser extent, large private firms.[106]

As of 2015, the government's financial support for R&D was mostly geared towards what it considered "strategic industries." Rail and other transportation equipment received about one-quarter of the allocation for research to promote innovation, followed by computers (17 percent) and machinery (7 percent).[107] R&D support for large private firms focused on other sectors (e.g., ICT, autos, transport). The funds were also used to support targeted private sector startups for activities ranging from environmental protection to innovation and entrepreneurship.

Examples of government-sponsored funds that provide capital for R&D include the central government's National IC Industry Investment Fund (the Fund). Created in 2014 by China's Ministry of Finance in partnership with some SOEs, banks, and local government, the fund invests in select semiconductor (and related) companies to help develop China's integrated circuit industry ecosystem through R&D support in chip design, production, packaging, and testing.[108] In 2015, the Fund partnered with SMIC to finance the $780 million acquisition of Jiangsu Changjiang Technology Co., the world's fourth-largest chip packaging and testing firm. A new $21 billion central government fund established in November 2019 was intended to support high-tech industry in areas such as new materials, electrical machinery, and advanced IT.[109]

ii. Bank Financing

Banks have been a central component of China's R&D and non-R&D lending mechanisms for decades. Before the start of reforms, almost all credit was funneled through a centralized and monopolistic banking

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[102] Atkinson and Foote (2019) underscore the importance of government sponsored R&D subsidies. See Atkinson and Foote, "To Understand Chinese Innovation Success, Look No Further Than Government R&D Subsidies," Information Technology and Innovation Foundation, October 23, 2019. Haley and Haley (2013) maintain that it is government subsidies, which have enabled SOEs and many subscale and inefficient producers in China to enter capital and technology intensive industries such as solar panels and out compete western producers. See Haley and Haley, "How Chinese Subsidies Change the World," April 25, 2013.
[103] Atkinson and Foote (2019) underscore the importance of government sponsored R&D subsidies. See Atkinson and Foote, "To Understand Chinese Innovation Success, Look No Further Than Government R&D Subsidies," Information Technology and Innovation Foundation, October 23, 2019; and Haley and Haley, "How Chinese Subsidies Change the World," April 25, 2013.
[104] Molnar estimates that about one half of the financing for STI is in the form of tax credits and rebates, which appear to stimulate more R&D by private firms than by SOEs. See Molnar, "Boosting Firm Dynamism and Performance in China," OECD Working Paper 1408, September, 2017.
[105] Huang, "Government-Guided Funds in China: Financing Vehicles for State Industrial Policy," Peterson Institute for International Economics, June 17, 2019.
[106] Huang, "Government-Guided Funds in China: Financing Vehicles for State Industrial Policy," Peterson Institute for International Economics, June 17, 2019.
[107] World Bank, "Promoting Innovation in China: Lessons from International Good Practice," April 2020, 7.
[108] American Chamber of Commerce in Shanghai, "China's Industrial Policy and Its Implication for Foreign Manufacturers," November 8, 2017; Crunchbase.com, "China' Integrated Circuit Industry Investment Fund," (accessed June 10, 2020), Verwey, "Chinese Semiconductor Industrial Policy: Past and Present," July 2019.
[109] Wall Street Journal, "China's New $21 Billion High-Tech Manufacturing Fund Likely to Rankle U.S., "November 20, 2019.

system controlled by the Ministry of Finance. As other sources of financing were created from the 1980s onwards, corporate borrowing from the state-owned banking system began to slowly diminish. Enterprises were progressively allowed to invest in stock and bond markets and to borrow capital from shadow institutions and online providers.[110] Today, though, despite decreasing reliance on the state banking system, that system still remains a major source of credit for SOEs and the large private firms. More than three-fourths of all deposits and commercial loans are controlled by the "Big Five" state-owned banks, which are in turn subject to the regulation and direction of China's Banking and Insurance Regulatory Commission and the People's Bank of China.[111] There are also a growing number of policy and commercial banks, including a small number of foreign banks, that are now permitted to have full or majority equity stakes since the start of 2020 and that can source financing for R&D and other corporate activities.[112]

SOEs enjoyed privileged access to bank credit at favorable rates through the 1990s, in large part because they were deemed to be less risky borrowers, had the collateral sought by lenders to underpin their loans, and were generally sensitive to government direction.[113] This access made it easier for banks to invest in R&D to promote innovation, at least relative to private firms.[114] The growth of the private sector and, in particular, of large private firms, steadily increased private firms' share of total lending until 2012. At that point, however, SOEs assumed a renewed central government prominence, and bank lending once again began favoring the state sector. As capital was finite, smaller private firms were forced to seek credit from other, higher-priced sources.[115] Between 2010 and 2016, the share of bank credit given to non-financial SOEs rose from 36 percent to 83 percent. [116]

iii. Internal Financing

As in other countries, the majority of firms—LLCs, SOEs, and private—finance a significant part of their R&D from their own revenues, with tax incentives and other policy carrots (including public procurement) providing additional inducement.[117] By contrast with firms in other upper-middle-income countries, internal financing has exceeded all other sources of financing for the majority of Chinese firms.[118] This includes financing from banks, equity and bond flotations, and others.[119] Small to medium-sized private firms in China have had to rely even more on their own resources—and, since 2010, on China's shadow banking system and on providers of venture capital.[120]

Among the corporate entities engaged in research, Huawei has been at the forefront, having raised its R&D internally by expanding its R&D budget in 2018 to $15 billion—or more than 15 percent of annual revenue.[121] It also committed to spend $20 billion on R&D in 2020, with between 20 percent and

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[110] Allen, Gu and Qian, "An Overview of China's Financial System," *Annual Review of Financial Economic*, 2017.
[111] S&P Global, "Credit Trends: Demystifying China's Domestic Debt Market," February 19, 2019.
[112] Bloomberg, "China's Finance World Opens up to Foreigners, Sort of," January 22, 2020; Elliott and Yan, "The Chinese Financial System: An Introduction and Overview," Brookings, July 2013; Hale and Long, "What Are the Sources of Financing of the Chinese Firms?" Hong Kong Institute for Monetary Research, 2010. (2010)
[113] McKinsey Global Institute, "Capturing China's $5 Trillion Productivity Opportunity," June 23, 2016. As much as one half of all bank lending was to SOEs.
[114] Lardy, "State Sector Support in China Is Accelerating," Peterson Institute for International Economics, October 28, 2019.
[115] Lardy, "State Sector Support in China Is Accelerating," Peterson Institute for International Economics, October 28, 2019; and Lin et al (2020), "State-Owned Enterprises in China: A Review of 40 Years of Research and Practice," *China Journal of Accounting Research*, March 2020.
[116] Lardy, "State Sector Support in China Is Accelerating," Peterson Institute for International Economics, October 28, 2019; and Lin et al (2020), "State-Owned Enterprises in China: A Review of 40 Years of Research and Practice," *China Journal of Accounting Research*, March 2020.
[117] Bakker, "Money for Nothing: How Firms Have Financed R&D Projects Since the Industrial Revolution," *Research Policy*, December 2013. An earlier study by Gregory and Tenev (2001) found that most private firms self-financed. Gregory and Tenev, "The Financing of Private Enterprise in China," IMF's Finance and Development, March 2001.
[118] Chen and Lei, "Financing Channels and the Performance of Chinese Small and Medium High-Tech Enterprises," *The Journal of Entrepreneurial Finance,* Spring 2009.
[119] Lardy, *Markets Over Mao: The Rise of Private Business in China,* Peterson Institute for International Economics, September 2014.
[120] As banks have remained reluctant to finance SMEs and the shadow banking sector and P2P financing channel has emerged, SMEs have sought more of their financing from this source. *Bloomberg*, "A Guide to China's $10 Trillion Shadow Banking Maze," June 7, 2018.
[121] *Bloomberg*, "No Pay, No Gain: Huawei Outspends Apple on R&D for 5G Edge," April 25, 2019; *China Daily*, "Huawei's R&D Investment in 2018 Exceeds $15 Billion," April 9, 2019; and *Reuters*, "China's Huawei To Raise Annual R&D Budget to At Least $15 Billion," July 26, 2018.

30 percent of the total allocated for basic research.[122] Worldwide, only three multinational companies spent more on research—Amazon, Google/Alphabet, and Samsung.[123] Whether private or state owned, other Chinese firms of comparable size, such as Baidu, Tencent, Legend, and ZTE, also rely on internal resources to pay for their research, although Huawei leads the field in terms of overall outlay. Supplementary financing is garnered from external sources, as shown below. Such alternative forms of financing are of greater importance for smaller firms and startups, which are unable to generate the funds exclusively from revenue flows.

iv. Other Forms of Financing (Corporate Bond Market, Venture Capital, Shadow Banking, and FinTech)

One of the central features of a mature financial market is its ability to offer a diverse set of financial instruments for firms to raise R&D and other sorts of capital. In this respect, China has made progress by developing corporate bond, venture capital, shadow banking, and fintech markets, and all of these forms of lending have ultimately helped spur China's domestic innovation.

The development of a corporate bond market in China has been primarily spearheaded by the People's Bank of China. Since 2004, it has encouraged SOEs and other large firms to tap the bond market.[124] While SOEs and private firms both have the option to raise R&D capital through this channel, central government-owned SOEs appear to be favored by the market, given investors' beliefs that they will be backed by the government. [125] On average, central government SOE bonds appear to maintain higher ratings than private sector firms and to provide lower yields than non-SOEs (reflecting lower risk premiums).[126] By 2017, China's stock of outstanding bonds amounted to $11 trillion, which was higher than South Korea ($2 trillion) but lower than Japan ($12 trillion), the EU ($20 trillion) and the United States ($41 trillion) in the same year.[127]

While Chinese SOEs have been the primary beneficiaries of R&D capital from the corporate bond market, private sector startups and new entrants with promising technologies have largely benefited from China's expanding venture capital (VC) industry. VC financing of R&D traces its roots to the 1980s in China, and has primarily focused on the provision of pre-seed, seed, and startup financing for small, high-tech firms. Its development was encouraged by the governing authorities, given their interest in boosting productivity for new entrants and providing exit channels for ill-performing startups.[128]

VC activity grew slowly in China, largely because of the absence of a functioning stock markets which facilitates the exit of venture capital and provide a legal scaffolding to support venture financing. VC lending picked up after the mid 2000s, though, following the 11th Five Year Plan's call to promote greater "independent innovation" to help China boost its productivity levels.[129] VC activity moved into

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[122] *Bloomberg*, "No Pay, No Gain: Huawei Outspends Apple on R&D for 5G Edge," April 25, 2019; *China Daily*, "Huawei's R&D Investment in 2018 Exceeds $15 Billion," April 9, 2019; and *Reuters*, "China's Huawei To Raise Annual R&D Budget to At Least $15 Billion," July 26, 2018.
[123] Bloomberg, "No Pay, No Gain: Huawei Outspends Apple on R&D for a 5G Edge," April 25, 2019
[124] Mu, "The Innovation and Development of China's Bond Market," in *Innovation for Development and the Role of the Government: A Perspective from the East Asia and Pacific Region*, World Bank, 2009.
[125] Livingston, Poon, and Zhou, "Are Chinese Credit Ratings Relevant? A Study of the Chinese Bond Market and Credit Rating Industry," *Journal of Banking and Finance*, 2018.
[126] Lin et al, "State-Owned Enterprises in China: A Review of 40 Years of Research and Practice," *China Journal of Accounting Research*, March 2020; and Livingston, Poon, and Zhou, "Are Chinese Credit Ratings Relevant? A Study of the Chinese Bond Market and Credit Rating Industry," *Journal of Banking and Finance*, 2018.
[127] Certutti and Obstfeld, "China Bond Market and Global Financial Market," IMF Working Paper (18/253), October 2018.
[128] World Bank, *Innovative China: New Drivers of Growth*. Chinese also appear to have been encouraged by the experiences of VC supported firms in the United States, which has been the source of 82 percent of the R&D spending by new public companies. In that market, patents filed by firms financed by VCs tend to be of higher quality, draw on basic research, are more frequently cited and more likely to both raise productivity and to generate net employment. See Lin, "Engineering A Venture Capital Market: The Case of China," *Columbia Journal of Asian Law*, 2017; and Strebulaev, "How Much Does Venture Capital Drive the U.S. Economy?" *Insights from Stanford Business*, October 21, 2015.
[129] Lin et al, "State-Owned Enterprises in China: A Review of 40 Years of Research and Practice," *China Journal of Accounting Research*, March 2020;

even higher gear by 2014, energized by Alibaba's IPO, which was the largest ever and demonstrated the potential opportunities for investors. In 2014, VC financing rose to $17 billion. Private funding, which now constituted the majority of VC funding, was supplemented by the State Venture Capital Investment Guidance Fund that provided an initial $6.5 billion in funding by 2015. By 2018, China's VC industry was second only to that of the United States with total investment climbing to $302 billion.[130] Interestingly, cross-Pacific research and industry networks have supplemented private sector VC domestic financing in China, attracting an additional $19 billion from U.S.-based VC into China in 2018.[131]

Shadow banking has been another form of R&D financing in China that has gained popularity in China, especially by private sector firms in search of capital following the 2009 Financial Crisis.[132] Shadow banking in China is conducted by financial intermediaries, which raise money from some of the same sources as banks – qualified wealthy private and institutional investors and the corporate sector – but are subject to less regulatory oversight. [133]

By 2018, shadow banks were responsible for intermediating $10 trillion in finances and helping to support a vast ecosystem of borrowers many of which had limited access to the formal banking sector.[134] Regulatory crackdown by the authorities in the latter part of 2018, cut the share of lending by shadow banks to 21 percent of the total. However, checks on lending by non-bank intermediaries were eased in 2019 as the economy began slowing. By the latter half of 2019, their share of total lending was back up to 39–45 percent of the total, and amounted to roughly $8.4 trillion.[135] Most of the firms borrowing from shadow banks have been smaller, privately owned companies. As investment in research by such firms tends to be limited, and the cost of borrowing from unregulated shadow banks is higher to account for risk, the contribution that shadow banks make to China's innovation drive is probably quite modest.

Financial technology, more commonly referred to as "fintech," is a term used to describe online technologies that facilitate financial services. This form of technology has been booming in China, and amounted to $41 trillion in 2018 through the use of mobile payments alone.[136] Its use by consumers and businesses is ubiquitous in China, as demonstrated by the fact that the volume of mobile payment was nearly 50 times greater in China than the United States by 2017.[137] Aside from facilitating transactions and online banking by consumers—while dispensing with the use of cash—fintech and associated peer to peer (P2P) lending has increased access to financing by small Chinese private businesses which have are typically ignored by banks.

The provision of credit options—enabled by both fintech and P2P lending—has helped fuel startup innovative activity among small private firms in China, particularly in services sector firms seeking modest amounts of capital. Noteworthy participants have included Yu'e Bao (of Ant Financial, now the largest money market fund in the world), Li Cai Tong (of Tencent) and Baifa (of Baidu). China now accounts for three-quarters of the global online lending by way of money market funds linked to payment platforms that offer ease of access and more competitive returns than the historically low deposit rates. Of

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[130] *Fortune*, "China's Tech Venture Capital Boom Is Going Cold," January 22, 2020; Huang and Tian, "China's Venture Capital Market" (in *The Handbook on China's Financial System)*, July 25, 2019; and Howell et al, "Venture Capital-Backed Innovation and Recessions," CEPR VOX Policy Portal (accessed June 22, 2020).
[131] Hsieh, "How Venture Capital in the U.S. and China Is Shifting," NASDAQ, February 28, 2020.
[132] Tsai, "The Rise of Shadow Banking In China: The Political Economy of Modern Chinese State Capitalism," Hong Kong University of Science and Technology, August 2015.
[133] Ehlers, Kong and Zhu, "Mapping Shadow Banking in China: Structure and Dynamics," Bank of International Settlements Working Paper, February 13, 2018; and Hachem, "Shadow Banking in China," *Annual Review of Financial Economics*, November 2018. Qingmin Yan and Jianhua Li (2016). *Regulating China's Shadow Banks*. Routledge.
[134] *Bloomberg*, "A Guide to China's $10 Trillion Shadow-Banking Maze," June 7, 2018.
[135] *Financial Times*, "China's Shadow Banking Industry Roars Back," September 24, 2019.
[136] Klein, "China's Digital Payment Revolution," Brookings Institutions' *Global China,* April 2020.
[137] *Financial Times, "China Mobile Payments Dwarf Those in US as Fintech Booms, Research Shows," February 13, 2017.*

the 39 (or 27) VC financed unicorns (in 2019)—fintech startups with valuations exceeding $1 billion—in the world, nine are Chinese (including one from Hong Kong) and 14 are American.[138]

In sum, direct government financial support, official incentives, as well as a more comprehensive set of financing options, have all supported SOEs, private sector firms, and hybrid forms of Chinese enterprises' innovation initiatives. To date, 80 percent of China's R&D spending comes from its business sector, and the financing channels described above have served as the primary financial tools enabling national innovation.

IV. Evidence Supporting the Success of China's Innovation Drive

There are many established indicators and studies that have helped analyze countries' scientific progress and relative levels of innovation. The Global Innovation Indicator (GII),[139] the Bloomberg Innovation Index, the Economist Intelligence Unit's Innovation Index, and studies conducted by the Information Technology and Innovation Foundation (ITIF), are all examples. They use standardized data from such places as the OECD, the World Bank, the International Monetary Fund (IMF), and the World Intellectual Property Organization (WIPO), as well as propriety information, to benchmark how far countries have evolved with respect to innovation. Despite the fact that such indices tend to use several overlapping indicators, their general conclusions, after factoring for definitional differences, are similar when it comes to China. In essence, they showcase how far and fast China has advanced technologically, and narrowed the gap between it and the world's most advanced economies. Using such data, Atkinson and Foote have suggested that a common "China cannot innovate" perception is misguided.[140]

The GII serves as a useful tool to gain a broad sense for how far China has come regarding innovation. This indicator, which is co-published by INSEAD, Columbia University, and WIPO, is arguably the most comprehensive and cited, and attempts to normalize each of its indicators to adjust for differences in output and population.[141] Through its associated sub-indices, the GII also delineates between innovation input variables that affect a country's capacity to innovate (e.g., R&D expenditures, access to financing, conducive innovation political and economic environments)[142] and country-based innovation output variables which represent tangible outcomes that have resulted because of a country's innovation initiatives (e.g., patent applications, scientific publications, production and exportation of R&D intensive goods, receipts from intellectual property, workforce concentrations of educated and employed scientists).[143]

With respect to the headline GII indicator, China has made noteworthy advances with respect to how innovative its economy has become based on the selected indicators. At the time the GII was first published in 2007 (only published by INSEAD at the time), China was ranked as the world's 29th most

[138] *The Economist,*, "Technology Startups Are Headed For a Fall," April 4, 2020; and *The Finanser*, "39 FinTech Unicorns Valued at $147.37 Billion," (accessed June 12, 2020).
[139] The Global Innovation Index and its underlying elements are standardized metrics published by Cornell University, INSEAD, and WIPO that help researchers compare various country-based attributes of innovation across time and 130 countries and time.
[140] Atkinson, Robert and Caleb Foote, "Is China Catching Up to the United States in Innovation?," Information Technology and Innovation Foundation (ITIF) Report, April 2019.
[141] Cornel University, INSEAD, and WIPO, "Adjustments to the Global Innovation Index Framework, Year-on-Year Comparability of Results, and Technical Notes" (Appendix IV), *Global Innovation Index: 2019,* December 2019; and Kennedy, Scott "China's Uneven High-Tech Drive: Implications for the United States" *China's Uneven High-Tech Drive: Implications for the United States* (chapter 1), CSIS, February 2020.
[142] The GII's innovation input variables include government education expenditures/GDP, school life expectancy rates, graduates in science and engineering; researchers/total employment ratios; R&D expenditures/GDP; amount of energy used; and others. See Cornel University, INSEAD, and WIPO, "Adjustments to the Global Innovation Index Framework, Year-on-Year Comparability of Results, and Technical Notes" (Appendix IV), *Global Innovation Index: 2019*, 2019.
[143] The GII innovation output metrics include derived variables such as patents/PPP$ GDP rates; PCT patent applications/PPP$ GDP rates; utility model patents by origin/PPP$ GDP rates; scientific & technical articles / PPP$ GDP ratios; citable publications "H" indices; intellectual property receipts/total trade, high-tech exports/total trade, and others. See Cornel University, INSEAD, and WIPO, "Adjustments to the Global Innovation Index Framework, Year-on-Year Comparability of Results, and Technical Notes" (Appendix IV), *Global Innovation Index: 2019,* December 2019.

innovative economy. In comparison, the GII's latest 2019 ranking suggests that China has recently surpassed Japan, France, and Canada to become the world's 14th most innovative country (see Table 2).[144] In fact, the latest GII indicates that China's innovation capacity now exceeds that of all other 34 upper middle-income economies and is quickly closing the gap with many high-income countries, including the United States. Whether such innovation capacity will result in improved GDP growth performance and total factor productivity is uncertain as countries with higher ratings have not clearly demonstrated such improvements in performance. In fact, China's own growth rate and productivity gains have been declining even as its GII rankings have risen.

Table 2. Global Innovation Index (GII) Rankings, 2019

	Overall Innovation Ranking	Input Innovation Ranking	Ouput Innovation Ranking
Switzerland	1	2	1
Sweden	2	4	3
United States of America	3	3	6
Netherlands	4	11	2
United Kingdom	5	6	4
Finland	6	7	7
Denmark	7	5	11
Singapore	8	1	15
Germany	9	12	9
Israel	10	17	8
Republic of Korea	11	10	13
Ireland	12	20	10
Hong Kong, China	13	8	16
China	14	26	5
Japan	15	14	17

Source: 2019 Global Innovation Index rankkings (from Cornell University, INSEAD, and WIPO)

China's relatively large and growing R&D expenditures, and investment in its scientific education system have yielded tangible results and help explain its extremely high rankings in GII innovation output metrics. As shown in Table 2, China ranked as the fifth most innovative economy in 2019 when it comes to these tangible outputs. Such high rankings, and the outputs they embody, have been attained from a combination of factors, including China's rapid growth in patent filings, high-tech production and creative goods exports, intellectual property receipts, scientific publications, and growing share of researchers in its workforce. While these factors, described below, have helped explain China's rapid technology ascension in the various global rankings, they are in no way meant to be interpreted as comprehensive.[145]

A. Patents

China's November 2001 accession to the WTO precipitated considerable reform of its patent laws that would eventually culminate into what is commonly referred to as China's "patent boom" and "great wall of patents." Specifically, as a result of the WTO negotiations, China agreed to both review and revise major components of its patent laws. By the summer of 2000, it already made considerable modifications to ensure that its patent laws were compliant with the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS).[146] These modifications included measures that prohibited the use or sale of patent infringing product (categorizing such acts as "patent infringement" regardless of whether the user

[144] INSEAD, *World Business*, Global Innovation Ranking (2007).
[145] In the area of intellectual property alone, China has also made substantive advances in its generation of high-quality industrial designs and trademarks *Global Innovation Index: 2019,* 2019, p. 20.
[146] Lin, Wood, and Jang, "Overview of Chinese Patent Law," International Congress of the Pacific Industrial Property Association, October 2004.

or seller were knowledgeable about whose intellectual property they were exchanging).[147] The reforms also provided methods for calculating infringement damages, allowed for patent-related preliminary injunctions, and ended requirements that forced Chinese applicants to file and obtain approval for patents filed abroad.[148] Hu and Jefferson also found that FDI inflows into China, as well as ownership reform that clarified the corporate-level assignment of property rights in China, have also been associated with the surge in China's patent applications in recent history.[149]

China's patent boom is exhibited in Figures 7 and 8 below. As can be seen from the WIPO data, China is now the largest filer of patents worldwide, having surpassed the United States in this regard by 2012; it filed more than 40 percent of all patents worldwide by 2017. While the speed and volume of its patent boom appear transformational on the global level, a closer inspection of China's domestic data reveals that its patent filings have been even more extensive. Specifically, under Chinese law, patent filings must be categorized as either "invention patents" (sometimes referred to as "regular patents"), "utility model patents," (largely representing modifications from existing patents) or "design patents." According to China's National Intellectual Property Administration (CNIPA) data, however, the patent filing data reported to the WIPO appear to correspond to the number of filed "invention patents" the Chinese authorities publish. According to official Chinese statistics published by CNIPA, such "invention patents" represented only about 36 percent of Chinese patent applications in 2018. While there is some double-counting among invention and utility patents in China (by Chinese law, firms have the option of filing both patent and utility patents simultaneously), utility and design patents still officially represent 48 percent and 16 percent, respectively, of all 2018 filed patents in China.[150] The existence of these "utility" and "design" patents, which do not appear to be included in WIPO statistics, suggests that the overall number of patent applications in China is likely to be even higher that what has been reported.

Figure 7. Patent Application (Number)

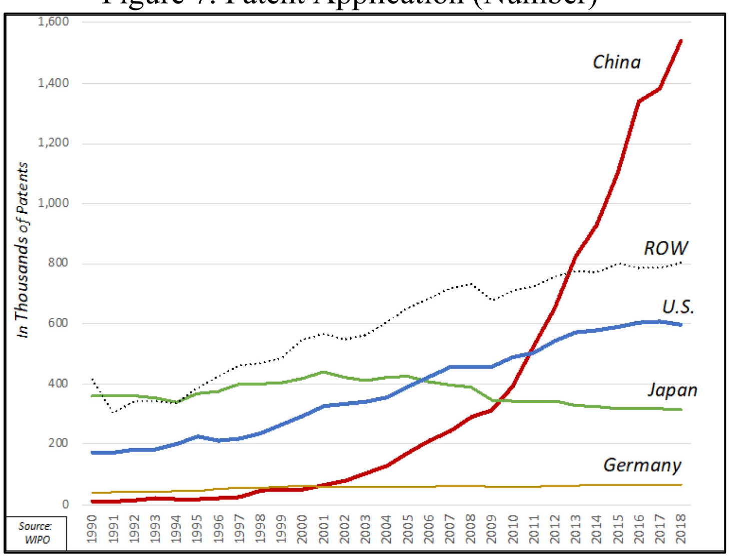
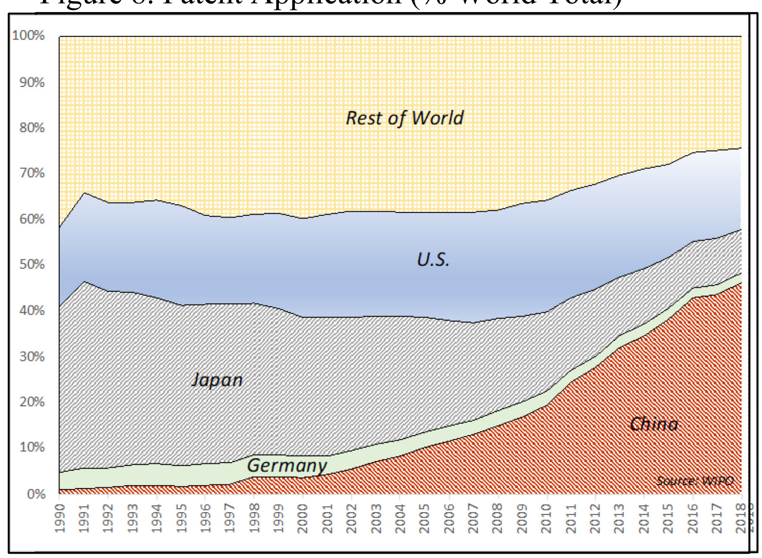


Figure 8. Patent Application (% World Total)



[147] Lin, Wood, and Jang, "Overview of Chinese Patent Law," International Congress of the Pacific Industrial Property Association, October 2004.
[148] Lin, Wood, and Jang, "Overview of Chinese Patent Law," International Congress of the Pacific Industrial Property Association, October 2004.
[149] Hu and Jefferson, "A Great Wall of Patents: What Is Behind China's Recent Patent Explosion?" *Journal of Development Economics*, Summer 2009.
[150] It is worth noting that the above referenced "utility" model definitions pertain to unique definitions employed by the Chinese authorities to their patent data. As such, there is no substantive review for such patents, as utility model applications are automatically patented upon preliminary examination. It appears as though such designated "utility model" applications are distinct from those that have been submitted to WIPO as "innovation patents" but do not represent substantially changed technology. The

Researchers examining China's patent surge over the past decade have observed that it has not, surprisingly, been accompanied by an associated strong growth in productivity.[151] Patents have been widely used as proxies for innovation[152] (and are thus included in the GII estimations), as they "not only serve as a measure of innovative output, but are indicative of the level of innovation activity itself."[153] As innovation is generally considered to be correlated with productivity, we would expect that China's patent surge would be associated with greater levels of TFP or similar measures. [154] In China's case, the data do not suggest such correlation. Hall and Jaffe provide partial explanations, suggesting that patent data are imperfect determinants of innovation.[155] Hofman, Jiwel, and Baark suggest that China's innovation system remains more focused on the volume rather than quality of innovative activity.[156] Others have found that a considerable amount of Chinese patenting has been financed (e.g., through subsidies and tax incentives) by China's government (as in other advanced countries), and it is well known that patent data are used as performance metrics in China.[157] This suggests that patent applications may reflect not so much a focus on innovative activity itself, but rather on feeding a perception of innovative activity by the authorities. To deal with such questions about whether China is a "patent paper tiger," we turn to an analysis of higher-quality patents.[158]

Data from the OECD and WIPO help us gain deeper insight into countries' relative levels of high-quality patents. More specifically, we examine the trends associated with "triadic applications" (explained below), "grant rates," and citations, to gain a better sense for how pathbreaking Chinese patents have fared relative to those submitted from other high-technology economies.

Triadic patent applications refer to patent applications that are simultaneously submitted to the United States' Patent and Trademark Office (USPTO), the European Patent Office (EPO), and the Japan Patent Office (JPO). They are broadly considered the "gold standard" for measuring the number of high-quality patents,[159] given the assumption that only the highest quality patents would be sent to the world's richest and most advanced global technology markets. Moreover, the three referenced patent offices are considered to be the most rigorous to gain approvals in (often taking 5–6 years to process patent applications) and the most expensive to file in.[160] As shown in Figure 9, China's triadic patent applications are on the rise and are rapidly approaching the levels of applications submitted by German firms. In terms of sheer numbers, they represent about a third of U.S. triadic patents submitted in the latest available year, and about a quarter of those submitted from Japan. Such measures of innovation suggest that China has made important headway in improving the quality of its patents, but the gap between it and the United States and Japan is still considerable.

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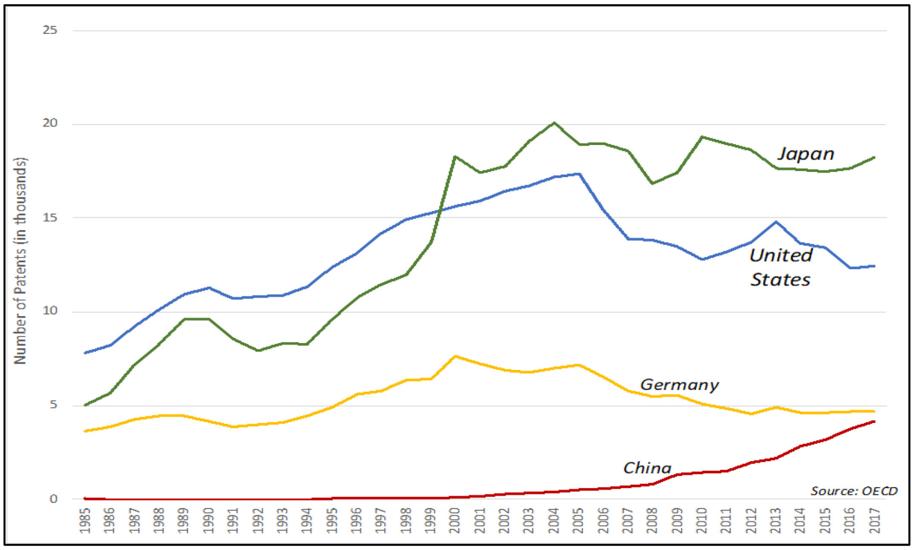
[151] See Bernard and Hammer, "The Mysterious Divergence in China's Productivity and Innovation Patterns," U.S. International Trade Commission's *Executive Briefings on Trade*, September 2019.
[152] Hall and Jaffe, "Measuring Science, technology, and Innovation: A Review," Report Prepared on Developing Science, Technology, and Innovation Indicators for the Future for the National Academy of Sciences, May 2012.
[153] Popp, "Using the Triadic Patent Family Database to Study Environmental Innovation," *OECD Working Paper*, 2005. This is the case when patenting leads to profitable commercial outcomes. The vast majority of patents die stillborn.
[154] Hall, "Using Productivity Growth as an Innovation Indicator," in *Report for the High Level Panel on Measuring Innovation*, University of Maastricht and UC Berkeley, 2011.
[155] Hall and Jaffe, "Measuring Science, technology, and Innovation: A Review," Report Prepared on Developing Science, Technology, and Innovation Indicators for the Future for the National Academy of Sciences, May 2012.
[156] Hofman, Jiwel, and Baark, "Innovation and China's Global Emergence," National University of Singapore East Asian Institute Commentary, August 2019.
[157] Hofman, Jiwel, and Baark, "Innovation and China's Global Emergence," National University of Singapore East Asian Institute Commentary, August 2019; and Huang, "Transforming China's IP System to Stimulate Innovation," paper presented at the International Conference on Innovation and China's Global Emergence, July 2019.
[158] Santacreu and Zhu, "What Does China's Rise in Patents Mean? A Look at Quality vs. Quantity," *Economic Synopses*, Federal Reserve Bank of St. Louis, 2018.
[159] Center for Strategic and International Studies (CSIS), "Are Patents Indicative of Chinese Innovation?" China Power Team, March 2020. Despite the fact that they are broadly considered the "gold standard" for high-quality patents relative to other metrics, they are still imperfect. For example, triadic patents sometimes reflect patents with high commercial potential rather than truly pathbreaking technologies.
[160] Center for Strategic and International Studies (CSIS), "Are Patents Indicative of Chinese Innovation?" China Power Team, March 2020.

Figure 9. Triadic Patent Applications



While triadic patent applications provide us a clearer picture of how rapidly China is approaching the technology frontier, the data are subject to some limitations. A review of Japan's leading triadic patent applications, in lieu of its dismal GDP growth in the past three decades, remind us that such metrics are still imperfect. Other proxies for patent quality, however, also suggest that China has made considerable progress. Specifically, grant rates, forward and backward citations, and PCT/patent family data all suggest that Chinese patent quality has been, in general, on the rise.[161] This has remained true despite the fact that a smaller share of applications are granted to filers from China, and that Chinese patents receive fewer citations than ones from advanced economies.[162] While the quality gap between Chinese patents and those from advanced economies may not yet have been bridged, Chinese firms appear to have made considerable inroads in this area, especially since the turn of the millennium.[163]

Sector-specific triadic data from WIPO providing three-year averages of patent family submissions indicates that Chinese firms have filed more patents than firms in any other country in the computer technology sector. They have also filed the second highest number of high-quality patents in the "electrical machinery, apparatus, and energy" sector, and the third-highest number of high-quality patents in the "measurement devices" sector.[164] Given these categorizations, WIPO considers the above sectors to be those in which Chinese firms have specialized over the past three years. Such observations are also supported by the fact that many Chinese companies have been the largest filers of patents worldwide and are at the forefront of their respective industries.[165] Examples of this include Huawei, ZTE, Lenovo, Shenzhen Huaxing Optoelectronic, Hongfujin Precision Industry, Sany, BYD, Tencent, SMIC, Mindray Medical, and the Alibaba Group. Between 2017 and 2019, moreover, Huawei Technologies, the world's

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[161] Patent families are similar to triadic patents in the sense that they represent patents simultaneously applied to in different patent offices worldwide. While triadic patents represent patent applications submitted exclusively to the USPTO, EPO, and JPO, patent families are not constricted to filings in those offices.

[162] The citing of Chinese patents by foreigners as an indicator of quality has been growing at an annual rate of 51 percent between 2005 and 2014. Wei, Xie and Zhang, "From 'Made in China' to 'Innovated in China': Necessity, Prospects, and Challenges," *Journal of Economic Perspectives,* Winter 2017.

[163] Boeing and Mueller, "Measuring Patent Quality Based on ISR Citations: Development of Indices and Application to Chinese Firm-Level Data," China Center for Economic Research, Working Paper No. E2018007, February 28, 2018; and Prud'homme and Zhang, "Chinese Patent Quantity and Patent Quality, and the Role of the State," February 8, 2019.

[164] WIPO, "Facts and Figures: PCT Top Tech Fields (by Country)" (accessed May 2020).

[165] WIPO, "Facts and Figures: PCT Top Tech Fields (by Country)", accessed May 2020.

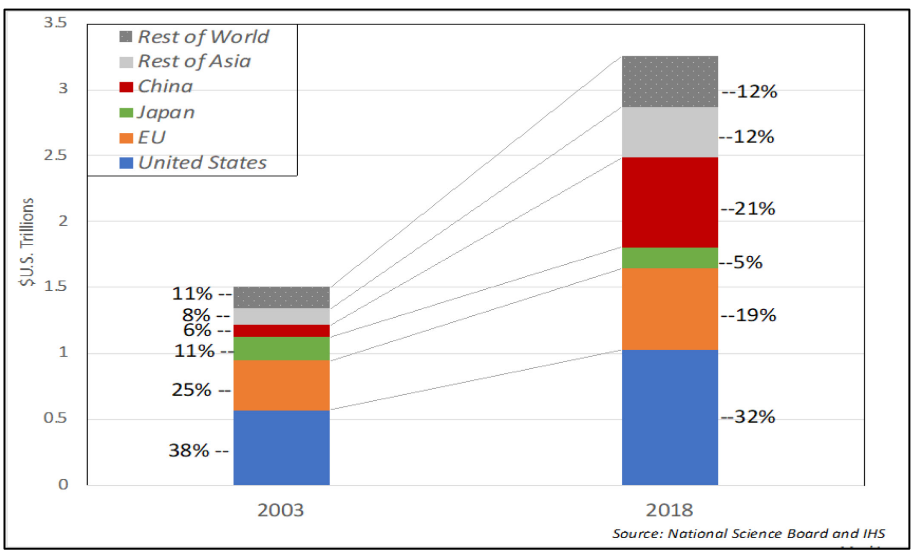
largest maker of telecommunication equipment, has remained the world's number one filer of international patent applications.[166]

B. Production and Exports of R&D Intensive Goods

China is undoubtedly the world's largest manufacturing country. According to the latest 2018 data, it produces between 28 and 35 percent of global manufacturing output, which is some 10 percentage points higher than the world's second-largest manufacturer, the United States.[167] China's ascension into this position, which has taken place over the past three decades, is due in large part to how much its economic reforms have focused on the development of its industrial base.[168]

To understand how much of China's manufacturing and exports has been high-tech in nature, we turn to an OECD definition that considers sectors that are dependent upon a relatively "high" degrees of R&D expenditures. In regard to these sectors, which include aircraft, pharmaceutical, computers, electronic, and optical industries, China has made noteworthy contributions to the global economy in both manufacturing and exportation. Figure 10 showcases the fact that China now accounts for 21 percent of the world's value added in high-tech manufacturing output.[169] While this is still considerably lower than the United States, which accounts for some 32 percent of global high-tech manufacturing, the compositional structure of such manufacturing has changed markedly over the past decade and a half. In 2003, for example, only two years after its WTO accession, China was contributing 12 percent of the world's value-added in highly R&D-intensive manufacturing output, compared to 38 percent in the United States.

Figure 10. Global Value-Added Output in R&D Intensive Industries



[166] *Reuters*, "In a First, China Knocks U.S. from Top Spot in Global Patent Race," April 7, 2020.
[167] The statistical branch of the United Nations estimates that China accounted for 28 percent of global manufacturing production , while recent reports from McKinsey suggests that this was as high as 35%. These measures were both computed on a value-added basis. See United Nations National Accounts Database (accessed May 2020 and McKinsey Global Institute, *China and the World: Inside the Dynamic Changing Relationship*, July 2019.
[168] West and Lansand, "Global Manufacturing Scorecard: How the U.S. Compares to 18 Other Nations," a Brookings Institution Report, July 10, 2018; and the United Nations Conference on Trade and Development (UNCTAD), 2015.
[169] National Science Board, *Science and Engineering Indicators Report*, 2020, Science and Engineering 2020 database, and HIS Markit.

China's rapid growth in manufacturing was conducted, in large measure, with the assistance of foreign firms and along global supply chains. Such measures have not only helped China integrate into the global economy and production methods, but have supported the remarkable growth in its share of high-tech manufactured exports. With respect to its globally integrated manufacturing capabilities, the McKinsey Global Institute has estimated that more than 90 percent of the technologies used in China's manufacturing sector (across 81 technologies and 11 sectors) "follow global standards."[170] Other researchers have found that China's high-tech manufacturing, and exports for that matter, have been dependent on FDI and incorporated high-tech components.[171]

China's high-tech exports have exhibited similar trends. In highlighting the highly R&D-intensive sectors just discussed, Figure 11 shows that China's export performance for these high-tech goods is converging with EU value levels. Koopman, Powers, Wang, and Wei, and others who have provided insight into ways to measure these flows on a value-added basis, have cautioned that such analyses tend to overemphasize the importance of exports, since many countries, including China, import a high degree of intermediate goods.[172]

Although we do not apply value-added calculations to the highly R&D-intensive sectors of the economy selected by the OECD, as that lies outside the scope of this paper, a review of the trade balance data does provide some insight into the role that highly R&D-intensive imports have played. Figure 12 shows that China's net exports of these goods has been considerably more modest, but notably higher than other advanced economies. Researchers at the McKinsey Global Institute have explained that China still imports considerable amounts of high-tech reduction gears, power electronics, and other intermediary equipment (e.g., semiconductors).[173] Moreover, while China's trade balance in these high R&D intensive products suggests that its global contributions are modest, it is still generally a net exporter for such products, unlike many of the other high-tech economies. More research along these lines would help delineate more clearly how China's performance in relative terms in specific highly R&D-intensive sectors.

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[170] McKinsey Global Institute, *China and the World: Inside the Dynamic Changing Relationship*, July 2019.
[171] Moran, "Foreign Manufacturing Multinationals and the Transformation of the Chinese Economy: Faustian Bargain to Trade Technology for Access?" Testimony before the U.S. Economic and Security Commission, March 30, 2011.
[172] Koopman, Powers, Wang, and Wei, "Give Credit Where Credit Is Due: Tracing Value Added in Global Production Chains," *NBER Working Paper*, December 2011.
[173] McKinsey Global Institute, *China and the World: Inside the Dynamic Changing Relationship*, July 2019.

Figure 11. Goods Exports From R&D Intensive Industries

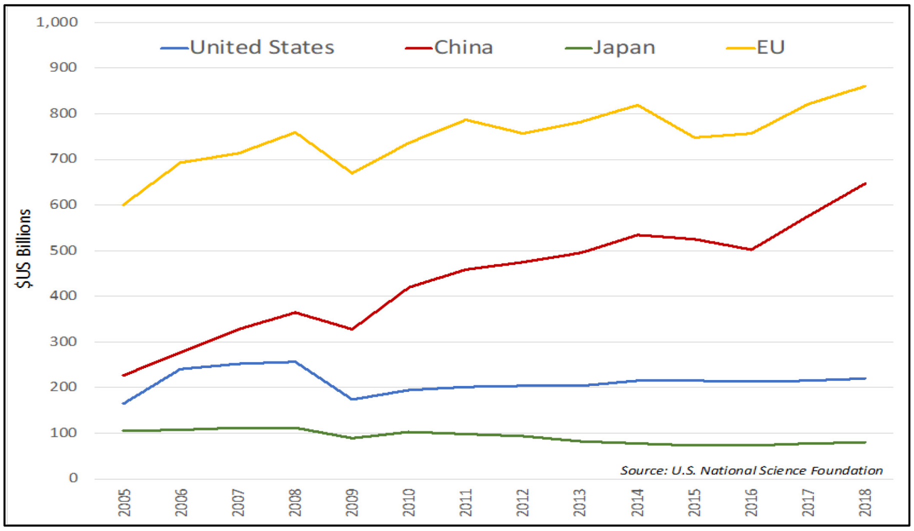
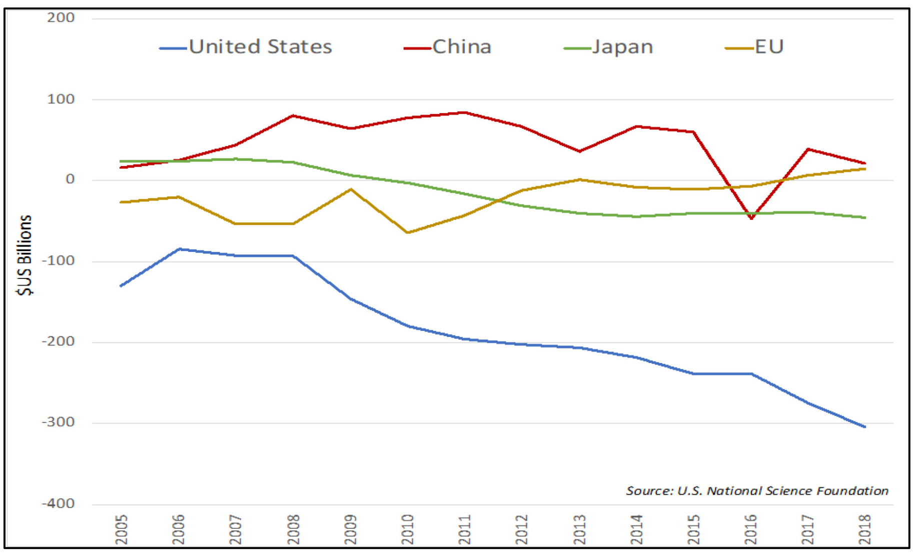


Figure 12. Goods Trade Balance in R&D Intensive Industries



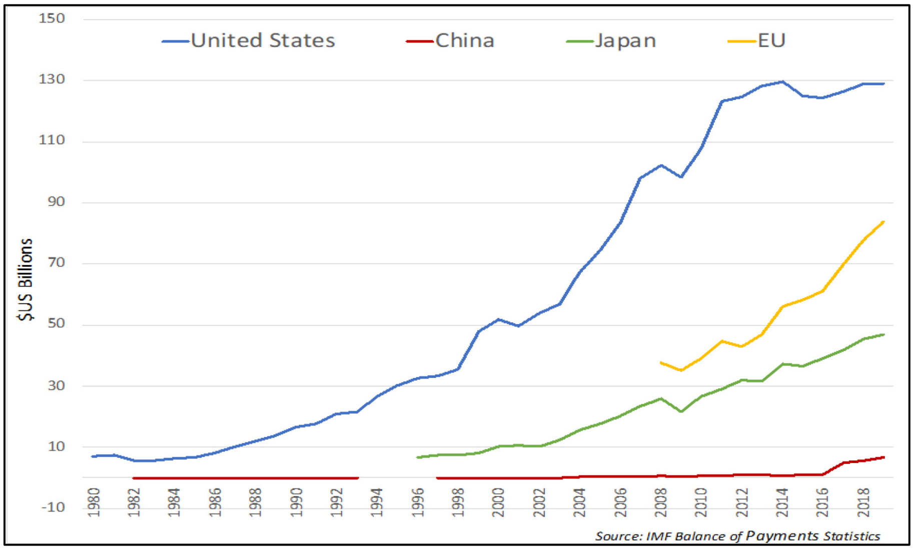
C. Exportation of IP Intensive Services

While the amount of information available for countries' highly R&D-intensive services exports is not comparable to its goods statistics, one can gain a sense of conditions by reviewing countries' royalty and licenses receipts, as shown in Figure 13. These are forms of intellectual property whose authority (in the form of license fees) can be granted by the owner to another party for the purposes of making, reproducing, using, buying, or selling a product.[174] For example, if a U.S. based company sells software to a Chinese firm, the compensation to the U.S. firm for the intellectual property embedded in its software export (which is typically patented, copyrighted, and/or trademarked) is typically represented by

[174] OECD, *Glossary of Industrial Organization Economics and Competitive Law* (accessed May, 2020).

a fixed licensing payment and/or royalty rate.[175] China's exports of such services have grown steadily since 2016.

Figure 13. Receipts from Intellectual Property



D. Scientific Publications and Research Institutions

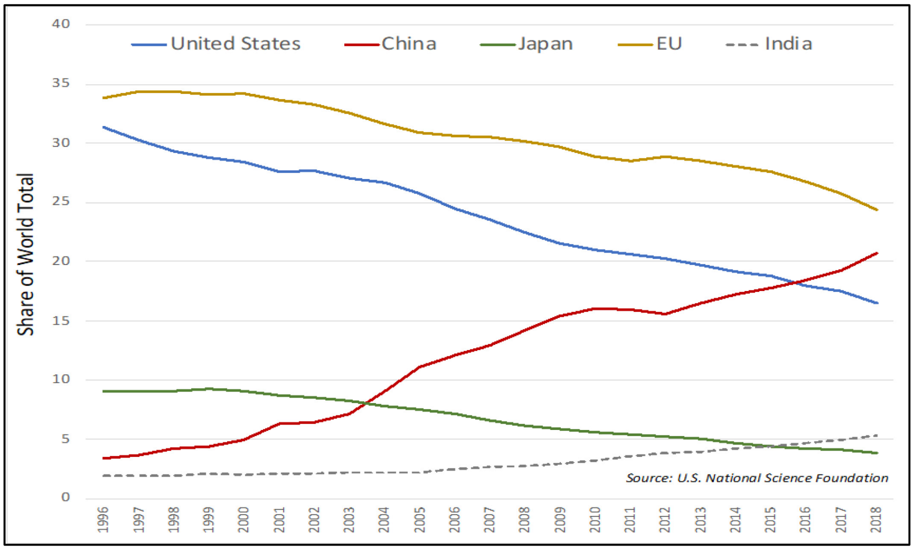
Another way of capturing aspects of a country's scientific advancement is through an analysis of its contributions to the scientific literature.[176] In this regard, analyzing China's total number of scientific publications, commonly used estimates of their quality, and the institutional sources behind the underlying research, has yielded insight into how far China's relative scientific contributions have come. According to the latest data from the NSF, China has overtaken the United States as the global leader in the number of published scientific and engineering publications (Figure 14). By 2018, approximately 21 percent of all scientific and engineering publications originated from China, compared to roughly 17 percent from the United States. Moreover, Xie and Freeman (2019) have explained that the above data appear to underrepresent the extent to which Chinese researchers have contributed to the science and engineering literature, given location and language limitations of traditional literature searches. They argue that when taking into account articles authored by Chinese researchers at non-Chinese addresses; articles in the Scopus database,[177] which originate from authors' with addresses in China; and articles in Chinese language journals not in the Scopus database, Chinese contributions account some 36 percent of global scientific publications.[178] This is approximately twice the standard address-based measure of papers in international scientific journals and a comparable share of global scientific citations.

As with the case in patent applications, comparing the sheer number of scientific and engineering publications and citations is not always the most precise way of conducting such country-based comparative analyses. It would be better to weigh these factors in accordance with population and/or GDP levels, and filter the number of publications to account for minimal levels of quality. In this regard, Xie

[175] OECD, *Glossary of Industrial Organization Economics and Competitive Law* (accessed May, 2020).
[176] United Nations Educational, Scientific, and Cultural Organization, "Research Evaluation Metrics," 2015.
[177] Scopus is a widely-used abstract and citation database from Elsevier publisher. It covers 36,377 titles from 11,678 publishers, and over 34,000 of its considered journals are peer reviewed. Scopus also publishes 4 indices which benchmark the quality of the considered publications: the *h-Index*, CiteScore, SJR (SCImago Journal Rank) and SNIP (Source Normalized Impact per Paper). The frequently cited h-index is also a metric used by the GII output innovation sub-index.
[178] Xie and Freeman, "Bigger Than You Thought: China's Contribution to Scientific Publications and Its Impact on the Global Economy," *China and the World Economy,* November 2019.

and Freeman have found that the proportion of articles and citations from China is already more than twice the country's share of global population or GDP, and China has thus "achieved a comparative advantage in knowledge-based activities."[179]

Figure 14. Science & Engineering Publications



Analyzing the quantity of published papers by country is of course fraught with problems, as publication in lower-quality journals, as defined by citation measurements, is unlikely to be representative of pathbreaking innovation. Moreover, ethical issues have surfaced regarding the manner in which some scientific papers from China have been published.[180] Chinese "paper brokers," or agents who are paid to secure a publication for a researcher, have been accused of using fraudulent sources and distorting the review processes. To deal with these issues, Chinese authorities have started investigating these claims. Between 2012 and 2017, the authorities retracted more scientific publications from their domestic sources than in all other countries put together for similar problems.[181] In their investigation, they also found a "thriving online black market" selling positive peer reviews, full research articles, and related services.[182] Also, in 2017, China's Ministry of Science and Technology launched a survey to examine the extent of its domestic peer review fraud after a well-known international scientific publisher, Springer, retracted over 100 papers for such fraudulent activity in its *Tumor Biology*.[183] The Ministry subsequently took aggressive measures to curb such activity, stating that it has "seriously harmed the international reputation of [the] country's scientific research and the dignity of Chinese scientists at large."[184] There is also some disagreement about how pervasive this problem is. While many contend that it is widespread, others have suggested that it is not, adding that when it is, it is typically confined to lower-level domestic research institutions.[185]

Notwithstanding such issues, citation indices have been helpful in filtering scientific and engineering publications for quality. While this has historically been more of a challenge for Chinese

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[179] Xie and Freeman, "Bigger Than You Thought: China's Contribution to Scientific Publications and Its Impact on the Global Economy," *China and the World Economy,* November 2019.
[180] Enago Academy, "China Overtakes U.S. With the Highest Number of Scientific Publications," Last updated June 13, 2018.
[181] *New York Times* (Qin), "Fraud Scandals Sap China's Dream of Becoming a Science Superpower," October 13, 2017.
[182] *New York Times* (Qin), "Fraud Scandals Sap China's Dream of Becoming a Science Superpower," October 13, 2017.
[183] *Financial Times* (Yang and Zhang), "China Launches Crackdown on Academic Fraud," June 18, 2017.
[184] *Financial Times* (Yang and Zhang), "China Launches Crackdown on Academic Fraud," June 18, 2017.
[185] *The Guardian* (Ball), "China's Great Leap Forward in Science," February 18, 2018.

researchers, this is now showing signs of improvement.[186] For example, in 2005, only 5 percent of China's scientific publications were among the top 10 percent of papers that were commonly cited. By 2017, this figure had risen to 9 percent of the top 10 percent of most cited papers. According to Cao et al., while China is still somewhat below the world average of 10 percent of high-impact publications, it has shown "a remarkable increase in the share of impactful papers while expanding its total publication output exponentially."[187] The field-weighted citation impact (FWCI) index, published by Elsevier's SciVal/Scopus database, provides deeper insight into how the quality of China's scientific contributions have changed over time. It measures the number of citations received per paper relative to the average number of citations received by papers in the same field and year of publication.[188] The indicator shows that scientific papers from China are still below world citation averages, but are rapidly catching up.

It is worth mentioning that researchers in China are given financial and other incentives to publish in scientific journals.[189] Premiums have been as high as $43,783, paid by Chinese universities between 2008 and 2016 for publication in top journals such as *Nature* or *Science*.[190] The highest known prize was $165,000, or 20 times the average university professor's salary in a given year.[191]

Educational institutions are the locations from which most of the researchers are making their scientific contributions. To understand how impactful such institutions have been on research output, and to avoid double-counting, we review their fractional counts (FCs). Such measures provide insight into how many unique contributions each researcher has made every year, and such research-based values can be aggregated by institution for comparative purposes.[192] In so doing, we see that three Chinese educational institutions were ranked in the world's top 10 most prolific producers of research in top scientific journals in 2019. [193] Most notably, the Chinese Academy of Sciences was ranked as the world's most prolific producer of research in top scientific journals, earning an FC score that was nearly twice that of the world's second-largest contributors to those journals, Harvard University.[194] In that year, China's University of Science and Technology and its Peking University ranked 8th and 10th according to that metric.[195] After adjusting for a disproportional amount of scientific publications in astronomy and astrophysics, a weighted version of the FC, appropriately named the WFC, finds that 16 Chinese institutions were among the top 100 institutions worldwide, compared with 44 from the United States.[196] Such analyses have also found that China is a leading source of worldwide innovation in artificial

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[186] "Five percent (4 percent fractional) of China's publications were among the top 10 percent most highly-cited papers (field normalized) [in 2005]; but in 2017, that statistic rose to 9 per cent (8 per cent fractional: that is fractionalized and field normalized). China is still somewhat below the world average of 10 per cent in terms of high-impact publications as a share of its total output, but it has shown a remarkable increase in the share of impactful papers while expanding its total publication output exponentially." Cao, Baas, Jonkers, and Wagner, "Returning Scientist and the Emergence of China's Science System," *Science and Public Policy*, April 2020.

[187] Cao, Baas, Wagner, and Jonkers, "Returning Scientist and the Emergence of China's Science System," Science and Public Policy, April 2020.

[188] By design, a score of 1.00 represents the world average, while values above and below it represent citation impact above and below world averages. See Elsevier (SCOPUS), "What Is Field-Weighted Citation Impact (FWCI)?" April 2020.

[189] arXiv Team, "The Truth about China's Cash-for-Publication Policy," *MIT Technology Review*, July 12, 2017; and Quan, Chen, and Shu, "Publish or Impoverish: An Investigation of the Monetary Reward System of Science in China (1999-2016)," Cornell University's *Aslib Journal of Information Management*, September 2017.

[190] arXiv Team, "The Truth about China's Cash-for-Publication Policy," *MIT Technology Review*, July 12, 2017; and Quan, Chen, and Shu, "Publish or Impoverish: An Investigation of the Monetary Reward System of Science in China (1999-2016)," Cornell University's *Aslib Journal of Information Management*, September 2017.

[191] *The Guardian* (Ball), "China's Great Leap Forward in Science," February 18, 2018.

[192] All authors of publications receive a maximum score of 1, and attain that score if they are the sole authors. For multiple authors, the score of 1 is equally divided by the number of authors under the presumption that each author equally contributes to each article.

[193] Nature Index, which aggregated fractional counts by educational institutions. Crew and Jia, "Leading Research Institutions 2020," *Nature*, April 29, 2020.

[194] Nature Index, which aggregated fractional counts by educational institutions. Crew and Jia, "Leading Research Institutions 2020," *Nature*, April 29, 2020.

[195] Nature Index, which aggregated fractional counts by educational institutions. Crew and Jia, "Leading Research Institutions 2020," *Nature*, April 29, 2020.

[196] *Nature,* Nature Index Database (accessed May 24, 2020).

intelligence, and that Chinese Academy of Sciences was the highest-ranked contributor in the world in both the physical and environmental sciences.[197]

E. R&D Staffing

Much of the R&D spending made by China's authorities has been directed towards expanding the country's pool of domestic and international scientists. Their goal, according to Mu Ming Poo of the Institute of Neuroscience of the Chinese Academy of Sciences in Shanghai, is to develop a homegrown, innovative research environment.[198] Official efforts to improve China's educational system, especially as it relates to graduating significantly higher numbers of students in the STEM disciplines, were described in part III of this paper. Here, we consider the outcome indicators of that imitative, which are the number of scientists and other researchers in China's modern workforce.[199]

Figure 15. R&D Personnel (FTEs)

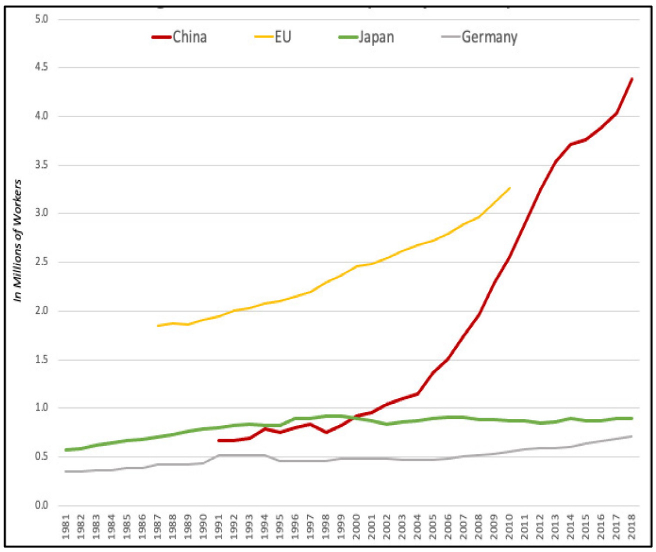
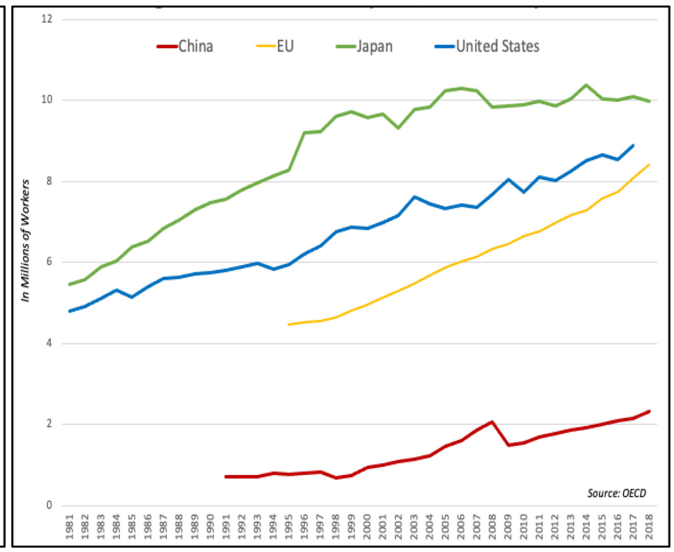


Figure 16. R&D Personnel (per 1,000 workers)



As shown in Figure 15, the number of R&D personnel in China, measured as full-time equivalents of scientific-oriented jobs, reached near four and a half million in 2018. With the exception of the United States, this surpassed all other high-technology countries by 2010. While the OECD does not publish comparable statistics for the United States, estimates from the U.S. National Science Board (NSB) suggest that the number of science and engineering jobs (e.g., software developers, computer systems analysts, chemists, mathematicians, economist, psychologists, and engineers) amounted to roughly 7.0 million workers in 2017.[200] Institutions such as the U.S. Congressional Research Service (CRS) have focused their attention on a narrower component of scientists in the United States, which reflect those scientists that are most closely associated with the policy debate on the scientific base of the country, including computer occupations, mathematical occupations, engineers, and physical scientists. Using CRS's narrower definition and applying it to employment data published by the U.S. Bureau of Labor Statistics, we find that U.S. employment of scientists amounted to roughly 6.9 million and 5.7 million in 2016 and 2019, respectively.[201] While not perfectly comparable to the definitions employed by

197 *Nature*, "Leaders in High-Quality Natural-Sciences Research By Subject," August 12, 2019.
198 *The Guardian* (Ball), "China's Great Leap Forward in Science," February 18, 2018.
199 *South China Morning Post*, "The Rise of China's Millionaire Research Scientists," April 27, 2016.
200 National Science Board, *Science and Engineering Report*, 2020.
201 The size of the S&E workforce varies substantially depending on which occupations are included in the definition. The National Science Board stated, "In 2013, estimates of the size of the S&E workforce ranged from approximately 6 million to more than 21 million depending on

the OECD, the above range of estimates from the National Science Board and CRS point to three things: the United States' scientific workforce appears larger than that of China's; the U.S. scientific workforce appears to be shrinking in absolute terms; and the gap between the absolute number of Chinese and American scientists appears to be narrowing.

China's trends, when considering scientists' relative share of domestic employment, also suggest that China's workforce is employing greater concentrations of scientists, as is shown in Figure 16. Further, the large gap between it and the other countries shown reveals, perhaps, its growth potential in this area. It should be noted that OECD data reveal that the number of scientist employed in various official branches of China's government is considerably greater than in the other countries shown.

Finally, China's National Bureau of Statistics reveals important characteristics about researchers in China. Between 2013 and 2018, for example, over 81 percent of all R&D full-time equivalent (FTE) personnel were concentrated in "experimental development" research.[202] This type of research can be described as that that uses "the knowledge from basic and applied researches or from practical experience to develop new products, materials and equipment, to establish new production process, systems and services, or to make substantial improvement on the existing products, process or services."[203] In other words, this is the most applied form of research, and these definitions are broadly consistent with U.S. and other international standards (it is part of the OECD's "Frascati Manual").[204] Over the same period, approximately 12 and 7 percent of China's scientific workforce concentrate in "applied" and "basic" research, respectively, where "applied" represents research that builds upon core findings from "basic research," and "basic research" refers to the pathbreaking, empirical or theoretical, research that aims to provide new knowledge on fundamental principles.[205] The finding that China employs such a disproportionate number of scientists in the "experimental development" research is supported by the fact that an outsize amount of spending in China (which has surpassed U.S. levels in this category) has targeted this type of research.[206]

V. Where China's Technological Achievements Lag Its Aspirations

A number of observers have noted that China is close to achieving technological parity with advanced countries in a number of areas including telecommunications, AI, storage batteries, commercial drones, Fintech, and several manufacturing industries.[207] But the score is inevitably less than perfect. Measured by the outputs described above, China has made impressive strides in less than four decades while allocating a smaller percentage of GDP to R&D than South Korea, Japan, Germany, and the United

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the definition used," further noting that "when defined by occupation, the S&E workforce totals between 6.2 million and 6.3 million people according to the most recent estimates" National Science Board, *Science and Engineering Indicators Report*, 2016.

[202] China's National Bureau of Statistics, *China Statistical Yearbooks, 2019*, 2019, Table 20-1 (accessed May 22, 2020).

[203] China's National Bureau of Statistics, *China Statistical Yearbooks, 2019*, 2019, (accessed May 22, 2020).

[204] National Science Foundation, "The United States Invests More in Applied and Basic Research Than Any Other Country, But Invests Less in Experimental Development Than China," December 3, 2019; *Nature*, "A Great Lead Forward, But China Needs More Scientists,," March 21, 2017; and OECD, "Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development," *The Measurement of Scientific, Technological and Innovation Activities Report*, 2015.

[205] According to China's National Statistical Bureau, "basic research" refers to empirical or theoretical research aiming at obtaining new knowledge on the fundamental principles regarding phenomena or observable facts to reveal the intrinsic nature and underlying laws and to acquire new discoveries or new theories. Basic research takes no specific or designated application as the aim of the research. Results of basic research are mainly released or disseminated in the form of scientific papers or monographs. This indicator reflects the innovation capacity for original knowledge. Similarly, "applied research" refers to creative research aiming at obtaining new knowledge on a specific objective or target. Purpose of the applied research is to identify the possible uses of results from basic research, or to explore new (fundamental) methods or new approaches. Results of applied research are expressed in the form of scientific papers, monographs, fundamental models or invention patents. This indicator reflects the exploration of ways to apply the results of basic research. China National Bureau of Statistics, *China Statistical Yearbook: 2019*, 2019 (accessed May 22, 2020).

[206] National Science Foundation, "The United States Invests More in Applied and Basic Research Than Any Other Country, But Invests Less in Experimental Development Than China," December 3, 2019.

[207] Fanin, *Tech Titans of China: How China's Tech Sector is Challenging The World By Innovating Faster, Working Harder, And Going Global*, 2019; and Lee, AI Superpowers: *China, Silicon Valley, and the New World Order*, 2018.

States. Its spending is still below the OECD average. There remain a few industries whose technologies have been beyond the reach of China's scientists and engineers since the 1990s. Among the technologically complex products that China has had difficulty mastering are semiconductors/integrated circuits, high performance turbofans, and commercial airliners.

The dependence on foreign suppliers for its expanding semiconductor needs is particularly limiting for the Chinese government because the developing of a world-class semiconductor industry is central to the "Made in China 2025" Plan.[208] As of 2019, 95 percent of the high-end chips used in computer processors were imported, as were 70 percent of the ones used for both smart devices and the majority of memory chips.[209] China spent more on importing semiconductors than it did on petroleum, and the United States is one of the principal suppliers of those essential computer components.[210]Although Chinese firms' science and chip design capabilities have caught up with the front-runners, China's largest semiconductor manufacturer, SMIC, is still two generations behind that of leading-edge companies for entire chips.[211] This has materialized despite the fact that Chinese firms acquired AMD's x86 processor technology by way of a joint venture between AMD and a state-backed firm, Sugon Information Industry.[212] Chinese firms are manufacturing an advanced server chip using ARM technology made available through a joint venture between Qualcomm and Huaxintong Semiconductor Technology,[213]and Suzhou Powercore is producing a CPU based on IBM's Power architecture.[214] State majority-owned Tsinghua Unigroup is building a $4.3 billion factory to produce 7 nanometer (7nm) chips by 2022. However, by then competitors will have moved on to the still smaller 5nm chips and to more complex architectures.[215]

Some have ascribed China's failure to catch up—in spite of substantial funding dating back to projects 908/909 in the 1990s—to its lack of defined goals and clear implementation strategies, its bureaucratic redundancies, and its reliance on SOEs that are poorly managed, have low innovative capacity, and are unable to attain the needed levels of production efficiency.[216] Others note that with every succeeding generation of chips, semiconductor technology has become more demanding and difficult. The leading firms invest billions in research and ever-increasing billions in semiconductor fabrication plants, with the latest now costing close to $10 billion apiece. Even for the likes of Intel and TSMC, each technological leap is a struggle. And although the tools such as EUV (extreme ultraviolet) lithographic machines can be acquired from ASML, it is the non-lithography work and the tacit knowledge ensuring consistent chip quality that determines whether a firm can stay in the race.[217]

Designing and manufacturing advanced turbofans has proven to be equally challenging. Although China was able to reverse-engineer Russian fighter aircraft and produce homegrown variants such as the J-7, J-8, J-11, J-15, J-16 (derived from the MiG-21), and Sukhoi 27/33 aircraft,[218] it was forced to source

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[208] *National Interest* (Levesque), "Here's How China Is Achieving Global Semiconductor Dominance," June 25, 2018.)
[209] *Financial Times (*Yang, Liu, and Wang), "China Pushes Self-Made Chips in Response to U.S. Threats," May 29, 2019.
[210] As tensions with the United states have mounted, the desire among many firms to indigenize technology has mounted. For example, memory chip maker Fujian Jinhua Integrated Circuit was depending on Micron and others for technology. As a result of the bans on technology transfer, it is now forced back on its own resources. *WSJ* (Yap and Kubota), "U.S. Bank Threatens Beijing's Ambitions as a Tech Power," October 30, 2018.
[211] SMIC is manufacturing chips using 14nm technology, whereas the leading producers TSMC and Intel have moved 7nm circuitry.
[212] *The Wall Street Journal* (O'Keeffe and Spegele), "How a Big U.S. Chip Maker Gave China the 'Keys to the Kingdom'," January 27, 2019.
[213] *PC World* (Agam Shah), "New 'Made in China' Chip on the Way as Country Boosts Indigenous Innovation," January 30, 2017.
[214] *PC World* (Agam Shah), "New 'Made in China' Chip on the Way as Country Boosts Indigenous Innovation," January 30, 2017
[215] *Financial Times (*Yang, Liu, and Wang), "China Pushes Self-Made Chips in Response to U.S. Threats," May 29, 2019; *PC World* (Agam Shah), "New 'Made in China' Chip on the Way as Country Boosts Indigenous Innovation," January 30, 2017; *The Wall Street Journal* (White), "China's Ability to Make Computer Chips Still 'Years Behind; Industry Leaders," January 21, 2018.
[216] Verwey, "Chinese Semiconductor Industrial Policy: Prospects for Future Success," U.S. International Trade Commission's *Journal of International Commerce and Economics*, August 2019.
[217] Some like GlobalFoundries and United Microelectronics have found that it is too costly to stay in the running. *The Wall Street Journal* (White), "China's Ability to Make Computer Chips Still 'Years Behind; Industry Leaders," January 21, 2018.
[218] *Popular Mechanics* (Hollings), "Counterfeit Air Power: Meet China's Copycat Air Force," September 19, 2018. Hallion, and Saunders eds. *The Chinese Air Force*. National Defense University Press 2012.

engines from Russia because domestically produced ones could not match performance and reliability.[219] In more recent years, as China has begun fielding fourth- and fifth-generation aircraft and begun designing a twin-aisle commercial airliner, pushing engine technology to the frontier has become more of a priority, especially with the formation of the Aircraft Engine Corporation conglomerate in 2016.[220] Replacing the Russian AL31 and AL41 engines with nearly equivalent Chinese turbofans has proven a struggle, with the Chinese WS10 falling short—although it may now finally have overcome its prolonged teething problems.[221] With the advent of the WS15 and other engines now being showcased, China may be narrowing the gap, aided by acquisition of German companies.[222] However, with Western technologies continuing to evolve, catching up could be a slow process, as China is still a generation and more behind the frontrunners.

Until the turn of the century, China's aircraft industry mainly served the military. This changed with a 2002 decision to produce a regional jet. This plane, the ARJ21, demonstrated the complexity of commercial aircraft manufacturing,[223] even though the design of the aircraft drew extensively on the McDonnell MD 80/90 aircraft, which were assembled in China during the 1990s. The ARJ21 cabin cross section, nosecone, and tail were identical to the McDonnell aircraft. COMAC was assisted by a slew of Western companies, which supplied the engines (GE), the landing gear (Liebheer), the flight controls (Parker), the avionics (Rockwell Collins), and wing design (Antonov Design Bureau of Ukraine).[224] In spite of this head start, the first flight was delayed by two years, and certification took another five years. Soon after the plane entered service in 2015, problems began coming to light that affected performance. Fixing these and integrating the avionics took years, and only 23 ARJ21-700s were delivered as of end 2019.[225] In 2008, China launched its bid for the single-aisle airliner market. Development of the C919 prototype commenced in 2010 and after a lengthy delay, the plane made its maiden 19-minute flight in May 2017. But as with the ARJ21, COMAC is rediscovering that manufacturing a complex machine that can stand up to rigorous testing is a difficult undertaking even with the involvement of experienced suppliers.[226]

Two and a half years into the testing process, with only a fifth of the 4,200 hours of flight testing completed, the plane is now five years behind schedule, and further delays are likely because of a mathematical error and COVID related supply chain complications. "COMAC engineers miscalculated the forces that would be placed on the plane's twin engines in flight—known in the industry as loads—and sent inaccurate data to the engine manufacturer, CFM International. As a result, the engine and its housing may both have to be reinforced."[227] By the time the plane enters service, it will technologically lag offerings from Boeing and Airbus. While it might be adequate as a shuttle for the Chinese market,

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[219] Farley and Lovell, "China's Airforce Is Being Held Back by Its Terrible Jet Engines," *National Interest*, April 3, 2020; Strategy Page. China Finally Masters Jet Engines. 2020.. Not Top Gun Yet.
[220] Shenyang Aeroengine and Xian Aeroengine are other manufacturers.
[221] *Asia Times* (Makichuk), "Throttle Up: China Closes the Jet Engine Gap," December 23, 2019; *DefenseWorld.net,* "China Replaces Russian Engine in J-10C Jet with Locally-Made WS-10 Taihang," March 4, 2020; *The National Interest* (Farley), "China's Air Force is Being Helpd Back by Its Terrible Engines," April 3, 2020; *Strategy Page*, "Procurement: China Finally Masters Jet Engines," January 28, 2020.
[222] *The National Interest* (Farley), "China's Air Force Is Being Held Back by Its Terrible Engines," April 3, 2020; It is believed that China has build approximately 50 J-20s by the end of 2019, but complications with their jet engines delayed production. Delayed production has also affected production of high-thrust turbofan WS-15 engines for the J-20. *South China Morning Post* (Zhen), "China Is Behind on Production of Its Most Advanced Fighter Jet," January 21, 2020.
[223] Crane and Berkowitz, "The Effectiveness of China's Industrial Policies in Commercial Aviation Manufacturing," *Rand Corporation Report*, 2014.
[224] Avgeekery.com, "Is China's ARJ21 Just a MD-80 Copy or Is It the Beginning of China's Rise in Commercial Aviation?" (accessed May 22, 2020.
[225] *The Points Guy*, "China's COMAC Receives 105 Orders for ARJ21 Regional Jet," (accessed May 22, 2020).
[226] ZDNet (Cimpanu and Day), "Building China's COMAC C919 Airplane Involved a Lot of Hacking, Report Says," October 14, 2019.
[227] *Reuters* (Qiu and Hepher), "China's Bid to Challenge Boeing and Airbus Falters," January 9, 2020.

overseas sales may be sparse, even with financing from Chinese entities and inducements offered by the government.[228]

The design and manufacturing of complex high-tech equipment is a demanding enterprise, which involves managing a vast supply chain, integrating numerous parts and modules, and meeting exacting standards of precision and quality. To arrive and remain at the technology frontier, firms must steadily accumulate knowledge—some of it tacit—by developing one generation of technology after the other. The few companies capable of producing commercial aircraft, aero engines, automobiles, and semiconductors testifies to the difficulty a new entrant faces. China may yet match Intel, TSMC, and Samsung in the production of the most advanced chips; the C929 might equal the twin-aisle aircraft marketed by Boeing and Airbus; Chinese turbofans might one day compete on equal terms with those from GE and R&R; and a few years from now, Chinese firms might produce EVs that have the features responsible for Tesla's success. But it is clear from the above that catching up can be time consuming, and that throwing resources at a project does not necessarily quicken the pace of knowledge acquisition.

VI. Conclusion

This paper has described China's noteworthy scientific advancements and the policies and practices that have helped its firms attain parity with global leaders in several important high-tech industries. Despite its slow start, and the scientific stagnation that broadly characterized the 1960s and 1970s, the introduction of foreign technology through FDI in the 1980s and 1990s helped catapult China's scientific advancement to globally competitive levels. It wasn't until around 2006, however, that China's policies prioritized top-down, indigenous innovation. Through massive spending in R&D, which is now the second highest in the world and rapidly converging on U.S. levels, China has accomplished what no other developing country has. It is now the global leader in patent applications and close to the global leaders in the number of high-quality patent submissions. It is also the world's second-largest manufacturer and exporter of R&D-intensive goods, and its exports of high-tech services, as measured by its royalty and license fee receipts, are on the rise. China's pool of researchers is expanding rapidly, while the number of scientific papers emanating from China is now second to none.

It is useful to analyze China's scientific advances within the context of its original ambitions. On the one hand, its firms have fielded major advances in areas such as image recognition using machine learning, digital payment technologies and mobile financing, 5G telecommunications, and quantum communications. On the other hand, despite official goals and unprecedented amounts of R&D spending, China has yet to realize what its government assumed to be concomitant productivity gains which would buttress growth performance over the medium term and beyond. China's GDP growth is on a downward trajectory, from a high of 10.6 percent in 2010 to 6.2 percent in 2019, and remains increasingly dependent upon capital inputs.[229] Its recent rate of investment at 44 percent of GDP is far above the OECD average. Factor productivity in manufacturing, which was 16 percent of the U.S. level in 2000, had only risen by 5 percentage points by 2014.[230] Total factor productivity, a critical measure of the economic value of innovation and the one that Chinese planners have relied on to meet growth targets, has been trending downward and is in the 1 percent range or less.[231] The level of China's TFP has been unchanged since 1981 at about 40 percent of the U.S. level.[232] The experience of countries such as Japan, Germany, and

[228] Entry of the GE/SAFRAN Leap-1C engines could be delayed even longer. *Flight Global* (Chua), "U.S. Mulls Halting Leap Engine Sales to C919 Programme: Reports," February 16, 2020; and *Simple Flying* (Cummins), "Is China's COMAC C919 Serious Competition for the 737 Max?" March 24, 2020.
[229] OECD, *Economic Survey: China 2019*, April, 2019.
[230] OECD, *Economic Survey: China 2019*, April, 2019.
[231] World Bank, *Innovative China: New Drivers of Growth*, 2017 and The Conference Board, "The Conference Board Productivity Brief 2019," 2019. According to the Conference Board, China's annual average TFP growth between 2010 and 2017 was -0.4 and -0.6 percent, respectively.
[232] Feenstra, Inklaar, and Timmer, "The Next Generation of the Penn World Table" *American Economic Review*, 2015 and accompanying "World Penn Tables" (accessed May 22, 2020).

the United States, each of which is high on the scale of innovativeness and each of which produces vast numbers of scientific publications and patents, shows that such indicators of innovativeness have done little to enhance productivity or growth.[233]

Several plausible factors could help explain the disconnect between China's dramatic scientific advancements and its sluggish productivity levels. First, given the substantial investments being poured into experimental R&D, which focuses on the most applied forms of research such as process improvements and consumer-based innovation, it is quite plausible that such advances do not represent innovation that is pathbreaking enough to materially impact productivity at a national level. Relatedly, it is also possible that the sensitivity to government direction has oriented research by LLCs and other prominent domestic Chinese firms towards incremental, instead of pathbreaking, technologies. Third, it is also possible that the lending mechanisms made available in China to domestic firms induce them to pursue safer investments with guaranteed returns, as opposed to the "high risk, high reward" strategies embodied in VC firms in the United States and other advanced economies. Other, more optimistic theories include the possibility that productivity measurements aren't accurately measured, and that it is only a matter of time before China's high R&D investments translate into higher productivity gains at the national level. Chinese authorities appear to have been clinging on the latter explanations, given their strong and sustained investments in these areas.

A further slowdown of TFP could be in the cards for China, as has been experienced by highly innovative economies, and could suspend questions over the efficacy of China's science and technology drive. With geopolitical tensions mounting, the likelihood of some technological decoupling, and a possible downturn in FDI, the returns from investment in R&D could be lower still, even if China continues churning out patents and scientific publications and enlarging its scientific workforce. Following the COVID shock, the authorities might well temper their growth ambitions and settle for lower TFP and GDP growth rates as China transitions to a more inward-looking, services-driven economy. If that were the case, pumping extensive resources into innovation-promoting measures with low returns may become less of a priority.

[233] Productivity growth in the United States fell from an average annual rate of 2.57 percent during 1995-2004 to 1.02 percent during 2004-2016 and dropped to 1 percent since. Over the same periods, Germany's productivity went from 1.69 percent to 0.95 percent, and that of Japan declined from 2.03 percent to 0.79 percent Both countries have seen their productivity erode further during 2017-2019. Federal Reserve Bank of San Francisco, Total Factor Productivity database (accessed at various dates). Baily, Bosworth, and Doshi, "Productivity Comparisons: Lessons from Japan, the United States, and Germany," Brookings, January 22, 2020.

Appendix A

The Development of China's Scientific Base Since the 1950s

By the 1950s, China's new regime was consolidating its governing position and attempting to restore its shattered industrial system. At the time, there was a keen awareness by Premier Zhou Enlai and others in its leadership (including Marshals Chen Yi and Nie Rongzhen who were educated in France) that building China's technological capacity would be a necessary component of its broader development process.[234] As such, research institutes were established by ministries and major state enterprises. They broadly followed in the footsteps of the Soviet Union, which served as its solitary model at the time.[235] China's early advances in innovation in that decade were focused on developing weapon systems and extracting higher agricultural yields, largely based on Soviet technology.[236]

Starting in 1953, China began implementing its country's First "Five-Year Plan," which placed special emphasis on developing heavy industry.[237] Although most loans from the Soviet Union were geared towards purchases of Soviet weapons,[238] other loans financed the acquisition of equipment for power plants and industries that produced machinery and construction materials.[239] Soviet loans financed purchases of equipment for manufacturing and mining activities.[240]

Soviet specialists also helped devise the First Five-Year Plan of China's Academy of Sciences (CAS), which is considered to be the country's preeminent research institution since its founding in 1949.[241] Tens of thousands of Soviet advisers were sent to China in an effort to help adapt growing imports of Soviet capital equipment to local conditions.[242] They assisted China in formulating its "Twelve-Year Plan for Science and Technology Development" introduced in 1956, which many consider the time when China's science and technology drive began gaining traction.[243] "The 1956 Chinese 12-year science and technology plan reflected both the urgency of national security needs and the developmental aspiration that unified a fractious Chinese party-state leadership that had been divided over the pace and direction of China's modernization drive. [Moreover], it mobilized Chinese scientists who had often fallen under political suspicion."[244] To advance learning, more than 20,000 Chinese also went to

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[234] Wang, "The Chinese Development State During the Cold War: the Making of the 1956 Twelve-Year Science and Technology Plan," *History and Technology*, 2015.
[235] Perkins, "Reforming China's Economic System," *Journal of Economic Literature,* June 1988, 601-645; and Saich, "Reform of China's Science and Technology Organizational System," 1989, 69-88.
[236] Naughton, "The Socialist Era, 1949-1978: Big Push Industrialization and Policy Instability," 2007, 356; Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the People's Republic of China," August 2006.
[237] Nolan and Ash, "China's Economy on the Eve of Reform," Cambridge University's *The China Quarterly*, December 1995, 980-998;
[238] Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the People's Republic of China," August 2006.
[239] Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.
[240] Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the PRC," *Comparative Technology Transfer and Society,* 2006.
[241] While China's Academy of Sciences was formerly established in November 1949 (one month after the founding of the PRC), its origins date back even further to the research institution it grew out of (the Academia Sinica). China's "Academia Sinica" (Latin for "Chinese Academy") was established in 1928 by the governing Republican leadership at the time. After 1949, many of its researchers moved it to Taiwan, but the one remaining in the mainland was subsequently called the Chinese Academy of Sciences. For years these two institutions were referred to as "the two academies." Soviet specialists helped devise the first five-year program in China's Academy of Sciences. See Juan, "Academia Sinica of the Republic of China," *Asian Studies*, March 1964; Wu, "China: How Science Made a Superpower," *Nature*, October 1, 2019; Yan, "The Construction of the Chinese Academic System: Its History and Present Challenges," *Frontiers of Education in China*, 2009.
[242] Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.
[243] Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the PRC," *Comparative Technology Transfer and Society,* 2006; Zhang, Zhang, and Yao, "Technology Transfer from the Soviet Union to the People's Republic of China," August 2006. Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.
[244] Wang, "The Chinese Development State During the Cold War: The Making of the 1956 Twelve Year Science and Technology Plan,"*History and Technology*, 2016.

the Soviet Union for training.[245] These included China's new computer scientists, most of whom were trained in Russia during the 1950s.

In addition to research aimed at building weaponry, Chinese efforts in the 1950s and early 1960s sought to improve agricultural productivity, advance public health training, and bring infectious diseases under control by enlarging the pharmacopeia. With respect to agricultural science at the time, CAS researchers found more advanced ways of controlling pests using insect predators, developing higher yielding crops, and cultivating disease-resistant agricultural crops.[246] These advances in agricultural research materialized despite the famine that crippled the economy during 1959–61.[247] In the mid 1960s, Mao launched a major research effort (Project 523) to find a cure for malaria.[248] This resulted in the identification of artemisia annual (sweet wormwood) by Tu Youyou and the extraction of the active compound with the help of ether at low temperatures. She became the first Chinese national to be awarded a Nobel Prize in physiology/medicine in 2015.[249]

The inauguration of China's Strategic Weapons Program also began in 1956. As mentioned, Soviet assistance in developing a stronger scientific base in China was focused in part on the development of weapons systems.[250] The partnership enabled China to later develop nuclear weaponry as a part of the "Two Bombs and One Satellite" program, in exchange for uranium ore that China provided its Soviet counterparts.[251] China's first fission device was tested in October 1964, and a hydrogen bomb (fission-fusion) device was exploded in June 1967.[252] Missiles to deliver the warheads were developed by the Chinese themselves with some initial help from the Soviets.[253] One of the major challenges Chinese scientists and engineers faced was in devising the electronic components, precision instruments, and metering devices once Soviet assistance was withdrawn by 1960 following mounting bilateral geopolitical tensions. As a result, China depended on a modest homegrown research program to fuel such advances in the 1970s.[254]

The achievements in nuclear technology were not paralleled by technological advance elsewhere in the industrial sector. Manufacturing remained reliant on imported Soviet technology of the 1950s. This technological backwardness was reflected, in part, by China's exports that through the early 1980s were comprised mainly of resource-based products. Following the breakup with the USSR, China's auto industry struggled to achieve self-sufficiency. Although the number of factories increased from 417 in 1964 to 1,950 in 1976, most shunned foreign technologies and produced in small lots with a focus on trucks. Less than 2,500 cars were produced annually through the mid-1970s based on indigenous or

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[245] Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.

[246] Pu Zhelong, an entomologist at the Chinese academy of Sciences, was largely credited for scientific advances in of controlling pests using insect predators. Later, in the in the 1970s, Yuan Longping developed a hybrid rice variety suited for China's agroecology.

[247] China's great famine at the time mostly resulted from government-driven efforts to divert agricultural labor and material resources to the production of (backyard) iron and steel, 1959 floods, and the 1960–61 droughts that diminished grain supplies to highly populated urban centers. At the time, Mao's instructions to farmers to "close plant' seeds of different species, to "deep plough", not to use fertilizer, and to practice fallowing of land – all contributed to the shortfall in output. Alpha History, "The Great Chinese Famine," (accessed May 24, 2020); Smil, "China's Great Famine," U.S. National Institute of Health (NIH), National Library of Medicine, December 18, 1999; Yushi, "Lessons From China's Great Famine," *CATO Journal*, Fall 2014.

[248] *U.S. News and World Report*, "The Secret Project that Conquered Malaria," October 6, 2015.

[249] Su and Miller, "The Discovery of Artemisinin and Nobel Prize in Physiology or Medicine," U.S. National Institute of Health (NIH), National Library of Medicine, July 29, 2016.

[250] Shen and Xia, "Between Aid and Restriction: The Soviet Union's Changing Policies on China's Nuclear Weapons Program," *Asian Perspective*, 36, 2012. Although the USSR began assisting China in developing nuclear energy capabilities starting in 1954, it withdrew its support following the Taiwan Straits Crisis in 1958 and never delivered a "teaching model A bomb." Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.

[251] Bernstein and Li (Editors), *China Learns From the Soviet Union (1949-Present)*, 2010.

[252] Atomic Heritage Foundation, "Chinese Nuclear Program," July 19, 2018; Lewis and Xue, *China Builds the Bomb.* Stanford University Press, 1991; Weintz, "China's Nuclear Weapons: Everything You Always Wanted to Know," *The National Interest*, May 25, 2018

[253] These were referred to as the "*liangdan yixing*" ("two bombs, one satellite") programs. Springut, Schlaikjer, and Chen, "China's Program for Science and Technology Modernization," U.S.-China Economic and Security Review Commission Report, January, 2011.

[254] *New York Times*, "China's Atomic Weapon Story Told," May 5, 1985.

Soviet designs.[255] Despite Chinese engineers' efforts to reverse-engineer the Boeing 707-320C in the 1970s, the Y-10 aircraft, which made its first flight in 1980, proved unviable and quickly became technologically obsolescent. The three prototypes ended up in an airplane boneyard.

A hiatus caused by the Cultural Revolution in the 1960s and 1970s, which brought many of China's leading scientists to work on farms and participate in reeducation camps, was followed by a 'reform and opening' of the economy in the 1980s under Deng Xiaoping.[256] Since then, China used a variety of channels to acquire technologies from abroad and invested in its R&D infrastructure so as to facilitate the assimilation of technology and develop research capabilities.[257] State-led research infrastructure building began in the 1980s[258] with increased funding for CAS and the creation of the CAS Science Foundation/National Natural Science Foundation in 1981–86. Starting in the 1980s, China was also quick to take full advantage of the globalizing trend, by acquiring technology in exchange for market access. This was initially conducted via trade activities, but was subsequently done through FDI and licensing arrangements. Chinese firms also benefited from technical assistance provided by foreign governments, international finance institutions, and private entities who often conducted overseas training.[259]

Technology embodied in imported capital equipment, FDI in manufacturing (from the foreign components of joint venture enterprises), and infrastructure development helped transfer technology in the early stages of China's economic reform era. As China gradually became the hub of global manufacturing, and its firms became increasingly linked along vertical global production chains (first as final assemblers, later as a mix of final assemblers and upmarket suppliers), the 1990s witnessed a marked change in global production patterns, and China was its manufacturing epicenter. Scientific and technical training of Chinese workers in foreign invested enterprises operating in China, also played an important role in raising technical capacity levels at that time. By the end of the 1990s, thanks to the scale of the investment in hardware and technical expertise as well as the acquisition of technology from abroad, China's manufacturing sector was extending its reach into mid and high-tech assembly and processing activities with electronic and telecommunication equipment enlarging their share of total exports.[260]

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[255] By the mid 1970s, trucks imported from Japan began to supplement domestic production. E. Harwitt, *China's Automobile Industry*, M.E. Sharpe. 1995.

[256] During this time, many universities were closed, many scientists were deployed to work in other areas, and many scientific books were destroyed. See Part II for more information. *Nature*, "The Chinese Academy of Sciences at 70," October 1, 2019.

[257] Fuller, "Technology Transfer in China," Oxford Bibliographies in Chinese Studies, April 2018; and Jiang et al, "Joint Ventures and Technology Transfer: New Evidence From China," April 15, 2018.

[258] The Key Technologies Research and Development Program was initiated in 1982; the National Hi-Tech Research and Development Program (863) in 1986; the Spark Program in 1986; and the Torch Program in 1988. Ministry of Commerce of the People's Republic of China, "National Programs for Science and Technology," May 22, 2012.

[259] Jacobson and Oksenberg, *China's Participation in the IMF, the World Bank, and the GATT: Towards a Global Economic* Order, 1990; and Bottelier, "China and the World Bank: How a Partnership Was Build," *Stanford University Center for International Development Working Paper Series*, April, 2006.

[260] Brent, "How China Rode the Foreign Technology Wave," *The American Interest, October 22, 2019.*; Breznitz and Murphee, *Run of the Red Queen,* Yale University Press, 2011; Nahm and Steinfeld, "Scale-Up Nation: China's Specialization in Innovative Manufacturing*," World Development,* February 2014.

Appendix B

Does R&D Spending Growth Lead to Higher Productivity?

There is a famous and frequently repeated observation by Robert Solow that "you can see robots everywhere except in the productivity statistics."[261] That remark dates back to the late 1980s, yet it reverberates through the productivity statistics for high and upper middle-income countries to this day. Since the 1980s, digital and other technologies have diffused widely and have transformed production processes in most manufacturing industries as well as services such as retail, logistics, finance, wholesale, telecom, and multimedia.[262] Automation has displaced workers and facilitated workflow. The quality and capability of many products has improved, new devices have enormously facilitated communication, a steady flow of innovations has improved healthcare and others are making available a host of new materials superior to the ones currently in use. AVs could become ubiquitous presence a decade from now and huge strides in machine learning are on the near horizon.

There was and, in some quarters, remains a widespread expectation that the new technologies and the numerous innovation that they sparked and continue to introduce would lead to a surge in productivity, which in turn would be translated into higher GDP growth rates. This is not what has transpired thus far. As computerization, ICT and automation were assimilated by industry in the United States, total factor productivity (TFP) did increase from an average rate of 0.68 percent per annum between 1985 and 1995 to 1.52 percent between 1996 and 2004.[263] Thereafter, it dropped back to a 0.55 percent per annum during 2004–16 and fell below 0.5 percent between 2017 and 2019. The TFP growth of European countries has benefited even less from technological advances. According to the estimates made using the EU-KLEMS database, TFP was increasing annually at a 0.65 percent rate between 1985 and 1995; it declined fractionally to 0.43 percent between 1995 and 2007; and slid further to a 0.23 percent annual rate from 2007 to 2015.[264]

As Crafts and Mills (2017)[265] note, over a 50-year period starting in 1967, TFP in the United States has trended downward. European countries are on the same trajectory starting at a lower rate but with productivity gains largely erased in the decade following the financial crisis and the Great Recession that followed in its wake. From this experience it would appear that the resources human and material ploughed into research and innovation over the past four decades have yielded meager results—at least in terms of aggregate growth rates.

Several reasons have been advanced to explain these anomalous outcomes. One is that computerization and the proliferation of digital technologies gave rise to exaggerated expectations with regard to their likely implications for GDP growth. Some commentators such as Robert Gordon and Tyler Cowen[266] are of the view that the low-hanging technologies have already been exploited, that promising ideas are becoming much harder to find[267] and that digital offering do not compare with such General Purpose Technologies (GPTs) as electricity and the internal combustion engine. A second view espoused

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[261] Solow, "Manufacturing Matters," New York Review of Books, July 12, 1987.
[262] A sectoral decomposition of productivity growth in the U.S since 1947 has been constructed. See Jorgenson, Ho, and Samuels, "Education, Participation and the Revival of U.S. Economic Growth," Conference on Research in Income and Wealth, May 16, 2016.
[263] Shackleton, "Total Factor Productivity Growth in Historical Perspective," Congressional Budget Office Working Paper Series, March 2013; and Bosworth and Doshi, "Productivity Comparisons: Learning from Japan, the United States and Germany," Brookings, January 22, 2020.
[264] Computations by the OECD yield slightly higher numbers with TFP increasing by 0.06 percent per annum between 2007 and 2015. See Fernald and Inklaar, "Does Disappointing European Productivity Growth Reflect a Slowing Trend?" Federal Reserve Bank Working Paper Series, May 2020.
[265] Crafts and Mills, "Economic Models vs. Techno-Optimism, VOX/CEPR Policy Portal, July 17, 2017 .
[266] Cowen, *The Great Stagnation: How America Ate All the Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel* Better, Dutton, 2010; and Gordon, "Book Review: *The Great Stagnation: How America Ate All the Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel*, January 25, 2011.
[267] Bloom et al, "Are Ideas Getting Harder to Find?" *American Economic Review* 2020, 110(4): 1104–1144, January, 2020.

by techno-optimists is that the effective utilization of new technologies can take decades, since digitization and automation is proceeding slowly[268] and since it requires complementary organizational, infrastructural, and institutional changes plus the retraining of the workforce. They believe that in a decade or two, the downturn in total factor productivity will be reversed. [269]

The possibility that the productivity gains from the new wave of technologies is not being accurately measured is a third reason put forward to explain the shortfall. Although the claim has been rigorously examined and found wanting, it lingers in the minds of some as a possibility.[270] A fourth reason could be that the benefits being derived from new technologies are being masked by inefficiencies that have come in their wake.[271] In other words, technological change has been of a zero-sum sort.[272] Lastly, there is the view that a reallocation of resources from manufacturing to services and from more to less productive services—a shift that has not been paralleled by the emergence of sectors benefiting from accelerating productivity or capital deepening—may be responsible for the slowdown. A decline in the share of manufacturing in GDP has been ongoing in the United States since the mid-1990s (and to a lesser extent also in Germany and Japan), but this may not account for a weakening of growth performance.[273] Productivity growth in manufacturing has slowed in all three countries since about 2004 (Baily, Bosworth and Doshi 2020). Additional corroboration is provided by the research of Acemoglu et al. (2014).[274] They find little evidence of faster productivity growth after the late 1990s in industries that are intensive users or producers of IT. In those instances where labor productivity in IT-intensive industries has risen, it is because the decline in labor utilization has been faster than the fall in output. "If IT is indeed increasing productivity and reducing costs, at the very least it should also increase output in IT-intensive industries. This does not appear to be the case."[275]

For these reasons, and in the face of the evidence that has accumulated, countries such as China that are banking on productivity gains derived from technological advances face a conundrum. Should they side with the optimists, continue investing heavily in ST&I in the hope that productivity will revive and serve as the principal driver of growth? Or should their expectations be substantially tempered by the experience of advanced countries, which have seen productivity growth plunge to one-tenth the level of what it was 40 years ago? [276]

As of now, Chinese planners are siding with the optimists and are placing their bets on productivity growth, fueled by a massive effort to close technology gaps and to perfect an innovation system which will be equal to that of the most advanced countries. Their expectation is that in due course, innovation will displace capital as the primary source of China's longer-term growth.[277] The trends since 2006 present a different story. The growth in TFP has been declining ever since. According to the most optimistic official estimates TFP growth is down from over 5 percent per annum in 2006 to a little over 3 percent per annum in 2019. Estimates by the IMF show TFP down from over 6 percent to about 2 percent over the same period. The calculations by the World Bank and the DRC showed TFP sinking from a 1

[268] Krishnan et al, "Is the Solow Paradox Back?" *McKinsey Quarterly, June 4, 2018.*
[269] Brynjolfsson et al, "Artificial Intelligence and the Modern Productivity Paradox," NBER Working Paper 24001, November 2017; and Saniee et al, "Will Productivity Growth Return in the New Digital Era?" *[Nokia] Bell Labs Technical Journal*, June 16, 2017.
[270] Byrne et al, "Does the U.S. Have a Productivity Slowdown or a Mismeasurement Problem?" Federal Reserve Bank of San Francisco Working Paper Series, April 2016; and Syverson, "Challenges to Mismeasurement of the U.S. Productivity Slowdown," *NBER Working Paper* 21974, February 2016.
[271] Nixon, "Is the Economy Suffering from a Crisis of Attention?" November 24, 2017; and Vitak, "Personal Internet Use at Work: Understanding Cyberslacking, *Computers in Human Behavior*, 27(5): 1751-1759, September 2011.
[272] Turner, "Capitalism in the Age of Robots," Institute for New Economic Thinking Working Paper Series, May 2018.
[273] Manyika et al, "The Productivity Puzzle: A Closer Look at the U.S.," McKinsey Global Institute *Discussion Paper*, March 2017.
[274] Acemoglu et al, "Return of the Solow Paradox?" *American Economic Review: Paper & Proceedings*, 104(5): 394-399, 2014.
[275] Acemoglu et al, "Return of the Solow Paradox?" *American Economic Review: Paper & Proceedings*, 104(5): 394-399, 2014.
[276] McKibben and Triggs, "The Future Will be Shaped by What Global Productivity Does Next," Brookings, March 2, 2020.
[277] Jones, "The Facts of Economic Growth," Stanford University's Hoover Institution, April 6, 2015; and OECD-NBER, *Productivity and Growth in the Long-Run*, Proceedings from Joint Conference, September 56-56, 2014.

percent per annum average rate during 1997-2008 to an under 1 percent rate during 2008-2017.[278] The Conference Board's alternative estimate shows TFP growth falling from 2.8 percent in 2006 to a negative rate from 2102 onwards ranging from 0.5 percent to 1.5 percent.[279] By all accounts, TFP is on a downward slope the reverse of what one would expect from China's R&D output and innovation rankings.

[278] World Bank, *Innovative China: New Drivers of Growth*. Figure 2.1, 2019.
[279] Conference Board, *Productivity Brief*, 2019.

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