Centre for International
Governance Innovation

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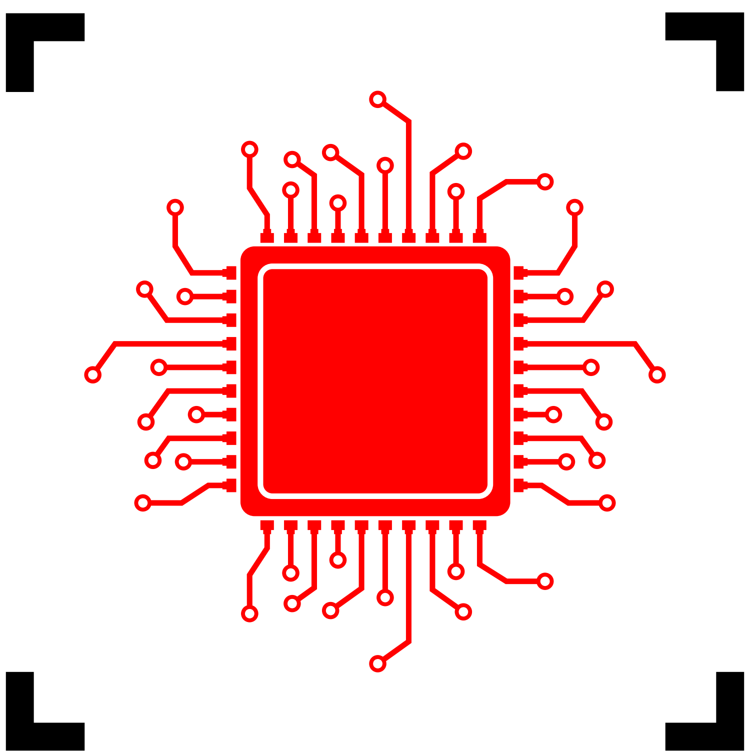
China's Techno-Industrial Development

A Case Study of the Semiconductor Industry

Alex He



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About the Author

Xingqiang (Alex) He is a CIGI research fellow. His work focuses on China and global economic governance, the Group of Twenty, domestic politics in China and their role in China's foreign economic policy making and Canada-China economic relations.

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Alex is the author of *The Dragon's Footprints: China in the Global Economic Governance System under the G20 Framework* (2016) (in both English and Chinese) and co-author of *A History of China-U.S. Relations* (2009). He has published dozens of academic papers, book chapters and newspaper and magazine articles. He has a Ph.D. in international politics from the Graduate School of CASS and previously taught at Yuxi Normal University in Yunnan Province, China. Alex is fluent in Chinese and English.

Acronyms and Abbreviations

4G	fourth-generation wireless communication network
5G	fifth-generation wireless communication network
AI	artificial intelligence
AMEC	Advanced Micro-Fabrication Equipment Inc.
BAT	Baidu, Alibaba and Tencent
CAE	Chinese Academy of Engineering
CAICT	Chinese Academy of Information and Communication Technology
CAS	Chinese Academy of Sciences
CCFEA	Central Commission on Financial and Economic Affairs
CCP	Chinese Communist Party
CDB Capital	China Development Bank Capital
CNIPA	China National Intellectual Property Administration
CNTC	China National Tobacco Corporation
CPU	central processing unit
DRAM	dynamic random-access memory
DSP	digital signal processing
EPLD	erasable programmable logic device
ESI	Essential Science Indicators
E-Town Capital	Beijing E-Town International Investment & Development Co., Ltd.
FPGAs	field-programmable gate arrays
GERD	Gross Expenditure on R&D

GPU	graphic processing unit
HTGR	high temperature gas-cooled reactor
IC	integrated circuit
ICT	information and communications technology
IDM	integrated device manufacturer
IoT	Internet of Things
IP	intellectual property
JCET	Jiansu Changjiang Electronics Tech Co.
LGSW	Leading Group on Scientific Work
M&A	mergers and acquisitions
MCUs	microcontroller units
MIIT	Ministry of Industry and Information Technology
MLP	Medium- and Long-Term Plan for Scientific and Technological Development
MOF	Ministry of Finance
MPU	microprocessor
MST	Ministry of Science and Technology
NCs	network computers
NDRC	National Development and Reform Commission
nm	nanometre
NPSTI	National Plan for Scientific and Technological Innovation
NSID	Outline of the National Strategy of Innovation-Driven Development
PPP	purchase power parity
PVD/CVD	physical and chemical vapour deposition
PWR	pressurized water reactor
R&D	research and development
S&T	science and technology
SASAC	State-owned Assets Supervision and Administration Commission
SMIC	Semiconductor Manufacturing International Corporation
SoC	system on a chip
SOEs	state-owned enterprises
TSMC	Taiwan Semiconductor Manufacturing Company
UHV	ultra-high voltage
WIPO	World Intellectual Property Organization
WTO	World Trade Organization
YMTC	Yangtze Memory Technologies Co., Ltd.

Executive Summary

Using the strategies of direct purchase and "market for technology," China has long relied on technology import for its own techno-industrial development. China attributed its low value-added exports and thin-profit-margin manufacturing at the beginning of the twenty-first century to the lack of advanced technologies and began to create national policies and plans for indigenous technological innovation and the development of advanced manufacturing. Core technologies in 13 areas and more than 20 strategic emerging industries have been specified as the priorities in China's techno-industrial development since then, and policy and financial support has been provided to promote these core technologies and related advanced manufacturing.

Although it has made noticeable progress in some areas in the past two decades, China still lags in most of the fields that its leaders and elites define as core technologies and advanced manufacturing, such as high-end chips, basic software and operating systems, and high-end precision manufacturing equipment, including machine tools, key equipment in the semiconductor industry and aircraft engines.

Problems in the state-controlled science and technology (S&T) research system and a campaign-style[1] catch-up strategy in techno-industrial development that rewards bureaucrats on short-term goals are to blame for the backwardness. The bureaucracy-standard research system has restricted China's capacity for making genuine innovations and breakthroughs in core technologies. Under the system, resources are wasted on low-level duplicate research findings instead of on fundamental research and development (R&D), researcher credibility is damaged, and academic freedom and innovation in research are stifled. Plus, as a newcomer that has been weak for years in the field of S&T, China lacks capacity for original innovation. The weak links between academic research and industry is another crucial problem in China's government-dominated research system and state-sponsored projects. In addition, a swing between the market-oriented approach for technology acquisitions and indigenous innovation for technology breakthroughs prevented consistent attention and required a huge investment in strategic industries such as semiconductors.

The ZTE event in 2018 and the Huawei ban as a result of the US-China trade and technological war cracked the facade of the recent high-tech boom in China fostered by e-commerce, online banking and mobile payment systems by internet giants such as Alibaba and Tencent. Chinese leaders and elites learned about the vulnerability of China's surging digital economy the hard way and realized that China still faced the great possibility of being "choked" in core technologies. The subsequent approach of making breakthroughs in core technologies in the semiconductor industry and other advanced manufacturing has been reinforced since then.

The decades-long development of China's semiconductor industry illustrated the problems that have long existed in China's S&T research system and national campaign-style strategies for advanced manufacturing. The semiconductor sector is different from other advanced manufacturing industries in that it is highly competitive, requires talent and capital intensity, has a high cost of trial and error, and involves fast-evolving technology. The case of China's semiconductor industry indicates that consistent, major R&D investment focused on long-term innovation, a close connection between research and the market for innovation, and vast talent and capital investment are necessary for success. The state-controlled S&T research system and correlated government-dominated campaign-style approach for quick success, however, restricted China from investing in the long-term innovation necessary for it to develop into a leading player in the global semiconductor industry.

A few real breakthroughs in the semiconductor sector by private companies such as HiSilicon and rapid advancement in frontier technologies — artificial intelligence (AI), fifth-generation (5G) wireless communication network technology, big data, blockchain and the Internet of Things (IoT) — by private companies such as Huawei, Tencent, Alibaba and Baidu reveal the hopes for China's techno-industrial development in the years to come. The Chinese government is seeking cooperation with private companies on innovation

1 Campaign-style here refers to a way of doing things in China by concentrating money, manpower and other resources in an organized way to achieve set goals in a short period of time. It applies in particular to government-organized activities such as campaign-style law enforcement, campaign-style anti-corruption and campaign-style governance.

in these frontier technologies. China's potential to become a real technological powerhouse depends on the continuing innovation and progress of leading private companies, as well as on whether the Chinese government can continue to provide an encouraging environment for the private sector's further development in the digital economy. The recent crackdown on Jack Ma's Alibaba[2] indicated the Chinese government's deep concern over the rapid rise of private internet companies (platforms) and their potential to challenge the Chinese Communist Party's (CCP's) governance in China in many ways, as well as the delicate relations between the government and the private sector.

Chinese companies face an extremely difficult situation, with the United States essentially cutting off their access to advanced technologies. China is left with the following options: rely even more on indigenous innovation; seek possible cooperation with other advanced economies, such as the European Union, Japan and South Korea; and encourage the American business community to lobby the US government to relax restrictions for the sake of its own interest in global markets. But even then, China first needs to overcome fundamental structural problems in its S&T approach and policies.

Introduction: Foreign Technologies and China's Techno-Industrial Development

Along with the launch of the reform and opening-up policy at the end of the 1970s, China began to introduce foreign technologies for its own industrial development after the country's decades-long isolation from the world. A road map of "introduction and assimilation" has demonstrated China's reliance on imported technologies for its techno-industrial development since then.

Technology import is not something new for China's techno-industrial development. It has dominated China's development since the beginning of the twentieth century. For most of human history, China was the world's most advanced technological power. The S&T level in China slowly began to fall behind that of Western countries after the Middle Kingdom experienced a long period of scientific and technological stagnation during the late Ming dynasty (1368–1644) and the Qing dynasty (1644–1911), its final imperial dynasty.[3] The Qing dynasty began to import Western technologies to modernize its industries at the end of the nineteenth century when it was defeated by — and suffered loss and humiliation from — the industrialized Western powers, which had gradually achieved a technological edge over China after the Industrial Revolution. Technology acquisition since the end of the nineteenth century, however, failed to build China's modern industries. Import of Soviet technologies and industries helped to build China's modern industries after the founding of the People's Republic of China in 1949. Since the Sino-Soviet split starting from the late 1950s — and following domestic chaos during the 1960s and the 1970s — China experienced two decades of isolation from the rest of the world, which put its S&T and industrial development far behind that of developed economies.

The top leader Deng Xiaoping made a wise judgment and decision to introduce advanced technologies from the United States immediately after the normalization of Sino-US relations in December 1978 and the signing of the US-China Science and Technology Cooperation Agreement in January 1979. He highlighted the importance of S&T in economic development in the 1980s, saying "science and technology constitute a primary productive force" (Deng 1993, 274), displaying for the first time Chinese top leaders' understanding of the crucial role S&T played in economic growth.

In the context of China's political system and policy-making environment, top leaders' understanding of the critical role of S&T and innovation in economic growth acts as the fundamental driving force for the country's S&T advancement. Under Deng, some basic programs, such as the National High-tech Research and

2 See Elstrom and Liu (2021) for more information on the Chinese government's crackdown on Jack Ma's Alibaba.

3 The reasons for this stagnation are what the famous Needham question — why scientific and industrial revolution did not happen in China despite its earlier success — is all about.

Development Program (863 Program), were advised by four top scientists and approved in 1986.[4] The establishment of the National Natural Science Foundation, suggested by 89 academicians from CAS, was approved by Deng in the same year to fund China's S&T research nationwide.[5] The National Program for Science and Technology Development was established in 1982 and was part of the five-year plans until 2006.[6]

Deng's successor, President Jiang Zemin, continued the former's emphasis on the role of S&T in economic growth and began to put more effort toward developing high-tech technologies and industries. The National Key Basic Research Program (973 Program) was set up in 1997 to support R&D and indigenous innovation.[7] Jiang began to push forward an upgrade to China's manufacturing based on high-tech, innovation and knowledge. In sectors such as high-speed rail and telecommunication, China began to produce indigenous innovation based on imported technologies and made some notable breakthroughs (Liang and Li 2018).

However, indigenous innovation was rare and the mainstream policy in China's techno-industrial development still relied heavily on the "introduction and assimilation" model during Jiang's era. Significant changes gradually happened in China's S&T development after its entry into the World Trade Organization (WTO) in 2001. While seeking legitimate, rules-based methods of technology acquisition, such as outbound mergers and acquisitions (M&A), patent portfolio purchases and competition law enforcement for technology progress instead of "forced technology transfers" (Malkin 2020), the Chinese government encouraged more indigenous innovation for its techno-industrial development.

This paper reviews the strategies and plans, policy-making institutions, process and existing problems in China's techno-industrial development since it entered the WTO, with a focus on the recent decade under President Xi Jinping. Based on the review, the paper assesses the status quo of China's techno-industrial development, indicates why China has lagged in core technologies and advanced manufacturing, and identifies the problems that exist in China's S&T research system, which are largely responsible for the technological backwardness.

China, since 2015, has turned to developing its digital economy and has put more attention on emerging technologies such as AI, 5G and big data to seek breakthroughs in core technologies and advanced manufacturing. The paper argues that state-sponsored technological innovation and breakthroughs have been crippled by the existing problems in China's S&T research system, despite the country's giant private internet companies that are making technological breakthroughs and innovation in the digital economy. The paper examines China's semiconductor industry in recent decades as a case study to demonstrate both the problems and progress in China's techno-industrial development and the implications for China's prospects of evolving into a technological powerhouse.

A Trade-Inspired Strategic Plan for Pursuing Core Technologies

Beyond the thrill of rapid export expansion after joining the WTO in 2001, China began to feel the pain of its low-value-added exports at the beginning of the twenty-first century. The popular saying of "exporting 800 million shirts to buy one Boeing plane"[8] shocked and reminded Chinese people, although in an exaggerated way, of the reality in China's manufacturing sector: cheap labour, a low-end position in the global value chain and very thin profit margins. The thin profit margins facing China's manufacturers in mobile phones, computers, automobiles, electronic devices, computer numerical control machine tools and so on, lie in the high patent fees paid to foreign companies. The patent fees account for a significant

4 For an introduction of the 863 Program, see the website of the Chinese Academy of Sciences (CAS): www.cas.cn/ky/kyxm/863xm/.

5 For an introduction of the National Natural Science Foundation, see the website of CAS: www.cas.cn/ky/kyxm/zrkxjj/.

6 For an introduction of the program, see the website of Consulate-General of China in Chicago at: www.chinaconsulatechicago.org/chn/ywzn/kj/t39930.htm. The name of the program was changed to the National Key Technology R&D Program in 2006.

7 For an introduction of the 973 Program, see the website of CAS: www.cas.cn/ky/kyxm/973xm/.

8 This is a popular saying lamenting China's low-value exports since the early 2000s. It could originate from Bo Xilai, then China's minister of commerce, who said in Paris in 2005 that "China needs to sell 800 million shirts to import one Airbus A380 plane" to try to ease worries on China's rapid increased export of textile products to the EU countries (*Private Economy News* 2005). The saying spread quickly and evolved later into "800 million shirts for a Boeing plane" instead of the original mention of an Airbus 380 plane, as importing Boeing planes sounds more symbolic in China's foreign trade.

percentage of the selling price and erode the profit margin in China's manufacturing industry.[9]

Technological backwardness in core technologies is to blame for the disadvantaged situation and thus the need to import foreign technology and the associated patent fees. In the eyes of insightful people in the S&T circle, failure to own core technologies would keep China's manufacturing at the low-medium end of the global value chain and paying high costs to foreign companies for the use of their intellectual property (IP) rights. Chinese elites and leaders began to seek ways to change the technological backwardness. President Jiang made clear the importance of indigenous innovation in high-technology development at the National Technological Innovation Conference in August 1999. He said that China must rely on itself for strategic and fundamental technologies, achieving capacity in indigenous innovation and acquiring independent IP rights. Otherwise, China's national security could be in danger (Jiang 1999).

Jiang suggested the idea of making a long-term outline for S&T development in China at the 16th National Congress of the CCP in 2002. The report Jiang Zemin gave at the congress prioritized the strategy to implement a new type of industrialization based on high and new technologies and related manufacturing industries, and "acquire key technology and independent intellectual property rights in key areas and a number of domains in frontier science and technology" (Jiang 2002) stands out as the guiding principle for China's techno-industrial policy in the following decades. After the 16th CCP National Congress, the newly established government under President Hu Jintao and Premier Wen Jiabao began to study and make an outline for China's medium- and long-term S&T development.

What, then, are these "key areas and domains in frontier science and technology," or the "strategic and fundamental technologies"? The top leaders did not identify them in their speeches. Under China's policy-making system, the responsibility to specify these core technologies falls on the shoulders of the officials and experts in the S&T field. A premier-led leading group consisting of 24 ministerial-level officials and 18 prestigious scientists was formed in March 2003 to lead the work for drafting the outline. More than 3,000 experts from across China in all kinds of S&T fields were called for the job. It took more than three years for them to eventually finish it (Chen 2019). The outline of the 2006–2020 Medium- and Long-Term Plan for Scientific and Technological Development (MLP) was finally released by the State Council on February 9, 2006.

Among 260 major programs discussed in 20 groups for 20 special subjects that cover all the S&T fields, including R&D, development of the manufacturing sector, energy, agriculture, urban development and reform of the S&T system, 16 major special projects were selected as the "key areas and domains in frontier science and technology" (ibid.). Thirteen major special projects were finally announced in the MLP. They were called the National S&T Major Programs, which represent the top priorities and the key areas in China's long-term S&T development. The projects covered semiconductors, information technology, telecommunication, advanced manufacturing, energy and biology, areas that China's officials and experts think are key to China's economic growth and national security in the coming decades (see Table 1 in the appendix for the list of the 13 major projects).

The MLP was the beginning of China's genuine efforts for self-sufficiency for high technology. It was also regarded as the beginning of China's tech decoupling with the world.[10] It has been carried out and followed up by relevant ministries and state-affiliated institutions since then under the coordination of the Ministry of Science and Technology (MST) and two other powerful government departments: the National Development and Reform Commission (NDRC) and the Ministry of Finance (MOF). A specialized agency under the MST was created to specifically manage the 13 major projects on a daily basis.[11] By 2017, the agency had co-organized eight news conferences with each of the relevant ministries and institutions to announce the achievements accomplished, involving the major projects of core electronic devices, high-end general-purpose chips

9 A typical example was the patent fees Chinese DVD player manufacturers paid to foreign patent holders, which accounted for 50–60 percent of the selling price for each DVD player during the period of 2000–2006. Patent fees for each DVD player that sold for $32 were between $16 and $19, and Chinese manufacturers' profit for each DVD player was just $1. See Bou (2007).

10 The US-China tech decoupling only occurred during the Trump administration. In retrospect, some would say China's self-sufficiency measures in the MLP seem like a way to begin self-imposed tech decoupling.

11 See the website of the agency under the MST: www.most.gov.cn/zdzxb/zdzxbjtzz/.

and basic software, next-generation broadband mobile wireless communication, the invention and production of major new drugs, and pressurized water reactor (PWR) and high-temperature gas-cooled reactor (HTGR) nuclear power stations (State Council Information Office 2017).

Techno-Industrial Policy under President Xi: Institutions, Progress and Problems

After the MLP was released, and in particular since Xi Jinping came to power in 2012, more major follow-up policies and initiatives were introduced to promote innovation in China and cultivate emerging industries based on technological innovation. However, the problems in China's S&T research system and techno-industrial field remained in the way of its rise as a real technological power. Before introducing these major policies and initiatives and addressing these problems, this section will employ an institutional framework to examine the driving forces behind China's techno-industrial policy making, to provide an understanding of how these major policies and initiatives were made and why these problems remained.

Policy-Making Institutions and Process

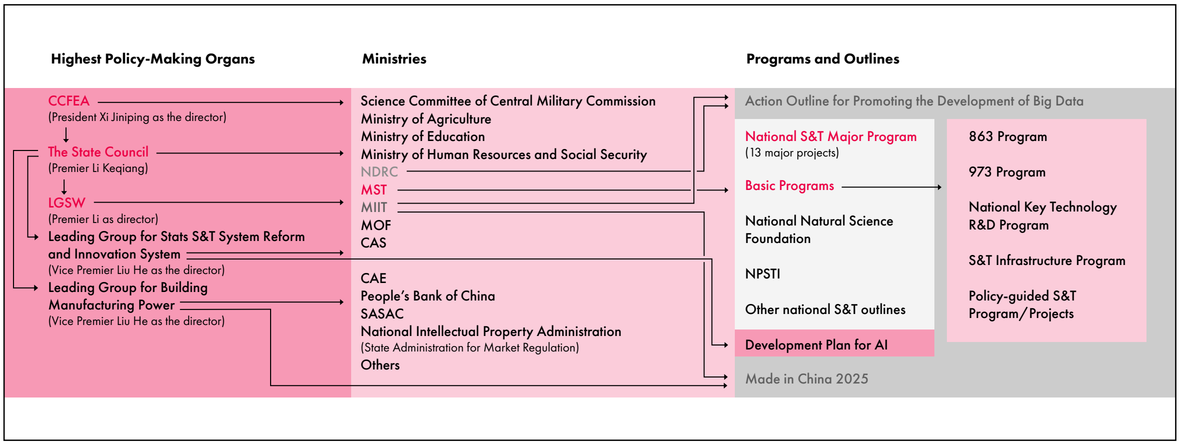
China's economic decision making has been experiencing institutional changes since the reform and opening up at the end of the 1970s. President Xi's emphasis on and the practices of the top-level design — a new top-down approach in policy making with its systemic conceptualization and overall viewpoint — constituted the most important institutional change that has cemented the party's control over the government in economic policy making. Through the leading groups and commissions within the party system, Xi himself supervises almost every area of policy making, including national security, major foreign and economic policies, government restructuring, cybersecurity and information. The leading group or commission in each area is given more authority in initiating policy proposals and guidelines and forming a general policy outline (He 2020).

Increasing relevance between S&T development and economic growth in the digital age has pushed China's top leaders to put more emphasis on technology and the escalation of innovation-based manufacturing. Policy making in techno-industrial development has been incorporated into the big picture of economic and financial works. The Central Commission on Financial and Economic Affairs (CCFEA), as the highest economic and financial policy-making body, extended its authority into the State Council over the S&T policy making and related strategic industrial development plans. The MST, the NDRC, the Ministry of Industry and Information Technology (MIIT), CAS and the Chinese Academy of Engineering (CAE) in the State Council were debriefed at the second meeting of the CCFEA in July 2018, which focused exclusively on enhancing the capacity for core technologies and innovation and providing a scientific guarantee for China's growth.

Due to the path dependency, however, Xi's institutional innovation did not bring critical change to the state bureaucracy's central status for specific policy formulation and enforcement in China's economic policy-making process. In general, the CCFEA provides guiding principles and instructions for S&T and industrial development while specific policy making is in the hands of relevant government departments. In terms of specific technical and industrial policy, the MST and the MIIT at the State Council are the two major departments that dominate policy specification and implementation. Other related departments and agencies that have a say in techno-industrial policy making include the NDRC, which provides support for policy planning and project approval; the CAS and the CAE, which provide crucial intellectual support and expert opinion; and the MOF, the department that oversees fiscal appropriation. Other relevant but lower-level government agencies and institutions include the National Natural Science Foundation and the National Intellectual Property Administration (see Figure 1 for the institutions and process of China's techno-industrial policy making).

Before the 2018 government restructuring, the Leading Group on Scientific Work (LGSW) at the State Council was the highest body in science and education policy making. Although it has

Figure 1: Techno-Industrial Policy-Making Institutions and Process in China



Source: Author.
Note: NPSTI stands for the National Plan for Scientific and Technological Innovation for the 13th Five-Year Plan (2016–2020).

become the second-tier institution after the CCFEA in techno-industrial policy making, the LGSW remains the central unit for policy making and coordination in the S&T field. After stripping off the responsibility of education in the government reshuffling in 2018, the newly restructured LGSW has three major responsibilities: mapping out strategies, outlines and major policies in scientific areas; planning major tasks and projects; and coordinating major scientific affairs among different central government departments and local governments. Government agencies such as the MIIT, the Ministry of Human Resources and Social Security, the People's Bank of China, the State-owned Assets Supervision and Administration Commission (SASAC) and the Central Military Commission's science committee have been added to the LGSW since 2018.

Although it seems the LGSW at the State Council keeps charge of S&T policy making, the overall governance style imposed by Xi — tighter control of every aspect of policy making — has already strengthened the party's power over the cabinet and the responsible agencies, including the MST, the MIIT, the NDRC and CAS, pushing them to become more obedient, and following and executing more closely (but blindly) the goals Xi raised. The unprecedented concentration of power can be seen in Liu He's unique roles in economic policy making. Premier Li Keqiang hosts the position of director of the LGSW, as his predecessors did. However, Liu He, as the trusted senior economic adviser of President Xi, assumes the director of office for the CCFEA and has more of a say in China's economic and S&T policy making.

Promoted to the position of vice premier, who traditionally oversees finance and industry,[12] and handed a new duty in managing S&T affairs in 2018, Liu He is regarded as an extension of Xi's power and control over China's economic and financial affairs and S&T and industry policy. Liu He holds the directors of other coordinating groups for S&T and industrial policies in the State Council, including the Leading Group for State Science and Technology System Reform and Innovation System with responsibility for coordinating reform and innovation-related science issues such as the introduction of an AI development plan and the outline of the National Strategy of Innovation-Driven Development. As the vice premier overseeing finance and industry, Liu He has resumed the position of the Leading Group for Building Manufacturing Power to coordinate the implementation of Made in China 2025 (see Table 1 in the appendix for details on Made in China 2025).

The convergence of power may have negative impacts on policy making and indicate some connection between Xi's top-down governance style and problems in China's S&T and industrial development. Under Xi's top-level approach, unprecedented emphasis on discipline and loyalty

12 The job duties of the four vice premiers in each Chinese government remain basically the same but usually vary slightly based on the individuals' expertise.

reinforces the party's tight control of both policy making and policy implementation. The party's deeper involvement in economic policy making and economic management intensified China's model of government intervention in the economy (He 2020). In the area of S&T policy making, it intensified the trend and eagerness of bureaucrats to prioritize short-term projects (so as to be seen as achieving required goals) but not long-term R&D and innovation, which are more necessary to drive real technological progress and sustainable growth. Breakthroughs in S&T innovation and techno-industrial advancement require long-term accumulation of R&D, a market-oriented approach and close academic-industry links, but Xi's unparalleled tight command-and-control model would give responsible bureaucrats more incentive to try a campaign-style and short-cut approach for short-term ornamental technological progress instead of real market-oriented innovation.

China's Techno-Industrial Development in the Past Decade

Major Strategies and Outlines

A review of the major strategies and outlines released since the introduction of the MLP shows there are three clear priorities for China's techno-industrial growth (see Table 1 in the appendix for major policies and strategies for China's techno-industrial development, and Table 2 in the appendix for China's priority projects for techno-industrial development).

The first priority is implementing the 13 major special projects under the National S&T Major Programs and its follow-up strategic plans. The MST, with the support of the State Council, led the implementation of the MLP and updated the advancement and achievement in each of these projects in its annual report. This consistency has been kept and developed into the five-year plans since then. Among them, the National Plan for Science and Technological Innovation (NPSTI) for the 13th Five-Year Plan (2016–2020)[13] marked another significant strategic plan that updated the MLP. It also constitutes the implementation plan and road map for the Outline of the National Strategy of Innovation-Driven Development (NSID) issued in May 2016.

13 It was issued by the State Council in July 2016 (State Council 2016a).

The second priority is developing the so-called strategic emerging industries. The Science and Technology Development for the 12th Five-Year Plan (2011–2015) listed six strategic emerging industries, including energy conservation and environmental protection as an industry, next-generation information technology, biology, high-end equipment manufacturing, new energy, new materials and new energy automobiles.[14] The National Development of Strategic Emerging Industries for the 12th Five-Year Plan[15] specified the road maps for realizing goals in each of these strategic emerging industries and listed 20 priority projects related to these industries (see Table 1 in the appendix). The National Development of Strategic Emerging Industries for the 13th Five-Year Plan[16] continued the focus on these strategic emerging industries, with more emphasis on five industries and sectors associated with innovation and the knowledge economy.

The third priority is establishing another 15 S&T innovation projects that target the strategic S&T goals by 2030. The 15 projects, which were detailed in the NPSTI, upgraded the previous 13 major projects and included some new emerging frontiers such as quantum communication, big data, smart manufacturing and robotics (Ling 2016). They were included in the Major Projects for Science and Technology Innovation 2030 (Projects 2030, hereafter) announced in 2017. One other project, next-generation AI, was added in 2018. Projects 2030 indicated China's high attention to and ambition on frontier technologies and industries that could lead the next phase of S&T revolution. Before this, the State Council had released strategic plans for the development of big data and the next generation of AI.

Made in China 2025, issued in 2015, aroused unprecedented attention worldwide and great criticism from leading Western powers such as the United States and Germany. The unique focus it has on advanced manufacturing seems to be the main reason for the attention and criticism. Furthermore, unlike the outlines issued in the previous decades, Made in China 2025 included specific goals for self-reliant supply — for instance,

14 The new energy in the plan refers to renewable energy, including nuclear power, wind power, solar power and bioenergy (made from biomass or biofuel). New energy automobiles refers to electric vehicles.

15 It was issued by the State Council in 2012 (State Council 2012).

16 It was issued by the State Council in 2016 (State Council 2016b).

40 percent by 2020 and 70 percent by 2025 — in fundamental components (electronic components) and core fundamental materials. It also listed enhanced financial and fiscal policy support for these advanced industries (State Council 2015). In addition, it proceeded as a well-organized national strategy, coordinated by the Leading Group for Building Manufacturing Power that was headed by the vice premier and implemented by the MIIT.

However, these are not the only reasons for the strong criticism Made in China 2025 received. The core industries it focused on are not different from the outlines issued in previous years, such as the MLP and the NPSTI. Similar policies for financial and fiscal support are also seen in other outlines. Perhaps the most important reason for the great attention Made in China 2025 received lies in the bigger background of the increasingly worsening trade and economic relations between China and the United States when Trump came to power in 2017. Made in China 2025 was issued in 2015 but only began to receive fierce criticism from the United States and the European Union in 2017.

Progress

By the end of the 12th Five-Year Plan (2011–2016), a series of major achievements in R&D and strategic high technologies listed in the MLP had been made, including a manned space and lunar exploration program, manned deep-sea submersibles, deep drilling, supercomputing, quantum anomalous Hall effect, quantum teleportation, neutrino oscillation and induced pluripotent stem cells. Major breakthroughs have been achieved in advanced manufacturing in the fields of high-speed rail, hydropower equipment, ultra-high voltage (UHV) power transmission and transformation, fourth-generation (4G) mobile communication technology, Earth observation satellites, the BeiDou Navigation Satellite System, electric cars and hybrid rice (State Council 2016a).

As of 2019, China had made further progress and became a leading country in a few of the above-mentioned fields, including 5G technology in mobile networks, big data, supercomputers, AI applications such as facial recognition, quantum teleportation, biotech, and space and lunar exploration. Among these substantial achievements in China's S&T and innovation, the rise of China's digital economy since 2015 drew worldwide attention. Internet giants such as Alibaba, Tencent, Baidu and JD.com, as well as Huawei, the world's largest telecommunication equipment manufacturer, bolstered the rise of China's high-tech sector.

The rapid digitalization of traditional agriculture, manufacturing and the service industry in China constituted the main engine for the rise of China's digital economy (Chinese Academy of Information and Communication Technology [CAICT] 2019). As a result of the rapid growth, the size of China's digital economy accounted for 34.8 percent of its GDP, based on a broad definition of digital economy (ibid.).[17] China's internet industry has maintained dramatic growth during 2014–2017, with an annual revenue growth rate of 44.7 percent (Thomala 2019). Its revenue growth still increased by 20.3 percent in 2018 and by 15.6 percent in 2019 (CAICT 2019; 2020),[18] while the Chinese economy was under downturn pressure facing continued domestic economic restructuring and the trade war waged by the United States.

China has emerged as a global leader in some key industries, such as e-commerce and fintech (mobile payment). With the explosive growth of online banking — mainly operated by Alibaba's Alipay and Tencent's WeChat pay — e-commerce, together with online banking per se, has evolved into a main driver for China's economic growth in its transformation from investment and export driven to domestic consumption driven. The power of mobile payment, with the wide use of smartphones in daily life, was explored and developed in China at a maximum level. The powerful propaganda machine of the CCP portrayed the tech boom as a symbol of China's national rejuvenation, creating for the Chinese public an illusion that the country has risen as a technology powerhouse that parallels the United States and Japan.

Looking through the lens of a global innovation landscape, China has grown in technology and knowledge and made its way into the group of leading nations in innovation in recent years. China has steadily risen upward in rankings in

17 By the same standard, the digital economy in the United States, Britain and Japan account for 59 percent, about 57 percent and 46 percent, respectively. According to the International Monetary Fund, the narrow definition refers to the information and communications technology (ICT) sector only, including telecommunications, internet, IT services, hardware and software. The broad definition includes both the ICT sector and parts of traditional sectors that have been integrated with digital technology (Zhang and Chen 2019).

18 According to Statista, the figures are 29.3 percent in 2018 and 26.8 percent in 2019 (Thomala 2019).

the Global Innovation Index issued by the World Intellectual Property Organization (WIPO), moving to fourteenth in 2019 from twenty-sixth in 2016 (Cornell University, INSEAD and WIPO 2019). China remains the only middle-income economy in the top 30 in the index (see Tables 3, 4 and 5 in the appendix for further information). China's total number of scientific and technical journal articles ranked number one in the world as of 2018 (World Bank 2021) and its number of scientists cited ranked number two in 2020 (Clarivate 2020).

China's Sputnik Moment: A Prosperity Built on Sand

Despite the noticeable S&T progress since 2006 and rapid surge of the digital economy over the past few years, China still falls far behind in most of the fields that Chinese leaders have defined as core technologies, such as advanced manufacturing in high-end chips, basic software, industrial software, operating systems and high-end precision manufacturing equipment, including machine tools. Within the 13 major special projects, major breakthroughs have not been achieved in nine fields, in particular core electronic devices, high-end general-purpose chips and basic software, that constitute the core technologies in the most cherished sectors of information industries and high-end manufacturing.

Among these core fields, there is one crucial sector that is an Achilles' heel in China's endeavours to catch up and seek a prominent position in global high-tech and advanced manufacturing. It is the integrated circuits (IC) — also known as computer chips and semiconductors — industry, in particular high-end chips that constitute key components of core electronic devices, such as central processing unit (CPU) and graphic processing unit (GPU) chips, and key equipment in the semiconductor industry, such as lithography, wafer-level chip-scale packing, wafer engraving and key materials for industrial use. The very first major project under the National S&T Major Program in the MLP has included high-end general-purpose chips. However, after decades of efforts to catch up in this area, China's semiconductor industry still lags far behind its major foreign competitors.

The ZTE incident in April 2018 acted as a wake-up call for China's key weak point in core technologies. Chinese telecom equipment manufacturer ZTE was put on the verge of collapse by the US government sanctions that banned the company from buying American-made microchips, software and other tools. The ZTE incident became China's sputnik moment, in which many Chinese elites and policy makers realized that the prosperity boosted by China's tech boom since 2015 is vulnerable. As commented by Pony Ma, the founder of Tencent, at a science forum in Shenzhen in May 2018, "the ZTE event made us realize clearly that no matter how advanced our mobile payment is, it is a building on sand and will be easily pushed down without microchips and operating systems" (Ma 2018). Starting from April 19, 2018, *Science and Technology Daily*, the official newspaper of the MST, published a series of articles revealing 35 core technologies that China lacks in many fields of the techno-industry (*Science and Technology Daily* 2018), and its editor-in-chief made a sensational speech reminding citizens of the fact that China falls far behind and is not that "amazing"[19] in the S&T field (Liu 2018).

After that, the US Huawei ban that forbid the Chinese telecom giant to use US technologies, including the supply of some key high-end chips, and prevented it from using basic operating systems, such as the Google Android system installed in its smartphones, hit the company hard. The Huawei ban further underlines China's weakness due to a lack of core technologies in high-end chips, operating systems and basic software.

The ZTE incident and Huawei ban by the US government created a "critical juncture,"[20] at which China has further determined the need to put more effort on "indigenous innovation" over "market for technology" for achieving breakthroughs in core technologies. Policy makers in China further realized that it seems unavoidable for China to transition toward depending on more indigenous innovation rather than importing foreign advanced technologies if China wants to move up the value chain from the low end to high end in core sectors such as the semiconductor industry under the circumstances of ongoing US restrictions or, even worse, the US "decoupling" with China in terms of technology and innovation.

19 The speech echoed in a sarcastic way the popular 2018 Chinese documentary film *Li Hai Le Wo De Guo* (*Amazing China*), which displays China's achievements in S&T, industry and poverty alleviation since the president came to power in 2012.

20 Or a notable diffusion of new ideas, a concept that caused key institutional changes in the historical institutionalism (Hall and Taylor 1996; Peters, Pierre and King 2005).

President Xi placed unprecedented emphasis on "core technologies" and "key technologies" immediately after the ZTE ban in April 2018 (Xinhua 2018a). Xi's speech at the congress of the CAS and the CAE one month later even included intense language such as "core technologies cannot be acquired by asking, buying, or begging" in a separate paragraph highlighting the desperate need to strive for "independent and controllable core technologies" (Xi 2018). The Chinese top leader's emphasis on grasping core technologies was not something new, but Xi's focus on the immediate urgency for owning core technologies was unparalleled. Xi's speech in May 2018 created a strong response. Senior officials from the MIT, the CAS and the CAE took the lead following Xi's talk, asking officials to work harder for China's progress in technological innovation (Xinhua 2018b).

In terms of the manufacturing sector, which relies heavily on technological progress, senior MIIT officials had, before the ZTE event and Huawei ban, reiterated China's status as a relatively low-level technological and industrial country. Miao Wei, the current minister of the MIIT, had stated in 2015 that China ranks in a quite low position in the techno-industrial area in the world. He assessed that China, along with other emerging economies, is in a third tier of the global manufacturing industry, while the United States maintains a predominant position, followed by second-tier economies such as the European Union and Japan. It would take a pretty long period of time for China to develop into a leading advanced manufacturing powerhouse, a goal China hopes to achieve by 2049, the one-hundreth anniversary of the founding of the People's Republic of China (Chen 2015, 5; Deng 2015).[21] Vice Minister of the MIIT Xin Guobin pointed out in early January 2019 that the Chinese manufacturing industry is big but not strong, and still lags substantially behind that of the international advanced level in terms of labour productivity, efficiency of resource use, return on investment and total factor productivity (Xinhua 2019a).

Why the Lag behind in Core Technologies?

Premier Li Keqiang pointed out that the deep-rooted reason for China falling behind in core technologies lies in weak fundamental R&D (Xinhua 2019b). The 13th Five-Year Plan admitted that the contribution rate of S&T to economic growth in China is still not high enough (State Council 2016a). These official opinions gave some hint of the main obstacles that stand in the way of China's S&T innovation.

The first and biggest barrier lies in China's bureaucracy-dominated research system and research culture.[22]

The so-called bureaucracy standard in China's research system means that bureaucrats, instead of scientists and experts, supervise and make crucial decisions on research, including determining research guidelines, project funding, and grants management and assessment. The bureaucracy standard in China's research system comes with two significant features that have stifled academic freedom and innovation. First, the bureaucracy standard in China's research system means research findings mainly serve to improve bureaucrats' performance and then their opportunities for promotion. Second, having connections with bureaucrats, not scientific merit, is the most important factor for a researcher to get project funding. Specifically, the problems in China's research system include:

- Prioritizing short-term projects while neglecting R&D and innovation. Short-term projects featuring greater certainty of achieving desired results can easily attract attention. R&D is time-consuming and has a high risk of failure. Scientists and researchers have less motivation to carry out innovative R&D than short-term projects with more certainty. This leads directly to the second problem.

- A huge amount of investment in S&T has been wasted on low-level, redundant and worthless research findings.

21 Miao mentioned this ranking when he explained the introduction of Made in China 2025 at the 13th Plenary Session of the 12th Standing Committee of the Chinese People's Political Consultative Conference in 2015.

22 For more about the problems in China's research culture, see Shi and Rao (2010), an opinion piece by two prominent Chinese scientists.

- Focusing on the quantity instead of the quality of research findings, as the former provides straightforward support for bureaucrats' performance.
- Strict on project selection but lax on authenticity and originality of research findings, which, to a large extent, explains the large amount of redundant and worthless research findings.
- Researchers invest most of their time and attention on building connections with bureaucrats instead of doing research, attending academic workshops and participating in discussions.
- For the same reason, China's research culture could not produce innovative researchers and failed to attract and keep talented scientists and top scholars and experts.
- The spirit in scientific research — the credibility of researchers — is perverted, and widespread academic cheating and faking of research findings is happening and is difficult to eradicate.

The second type of problem that exists in China's research system is the low quality of research in universities and the weak link between academics and industries.

In China, the quality of research in universities is generally low, and talented young researchers are scarce due to the problems that exist in China's S&T research system. "The key role of universities so far centers not so much on cutting edge innovation but on adaptation and redevelopment of existing foreign technology and products" (World Bank and the Development Research Center 2013, 171). The latest annual assessment and research report on the world's first-class universities and first-class academic disciplines for 2019–2020 by China's Wuhan University concluded that China's universities made significant progress in terms of S&T research level but still have a big gap with universities in the United States. The rankings in the report are based on the performance of disciplines at each university using Essential Science Indicators (ESI). The top two universities in China, Tsinghua University and Peking University, ranked twenty-second and twenty-seventh, respectively, on the comprehensive competitiveness list of world universities but their rankings for highly cited scientists, number of ESI disciplines, number of times cited for each paper and number of ESI highly cited papers[23] are not very impressive compared to universities with a similar position on the comprehensive competitiveness list (Qiu et al. 2020).

Among the academic achievements that have received awards, the disconnect between these academic findings and industries means that it is frequently difficult for them to be commercialized and they end up being mothballed. In general, "the effects of university-industry links on technological change have been minimal" (World Bank and the Development Research Center 2013, 171). The data released by the China National Intellectual Property Administration (CNIPA 2018b) showed that, as of November 2017, only five percent of patents held by universities have been industrialized. Most of the achievements among the 13 major projects under the National S&T Major Programs, such as a manned space and lunar exploration program, manned deep-sea submersibles, deep drilling and supercomputing, are not commercially viable or product-oriented and not aimed to achieve commercial success in the market.

Third, a lack of coordination between government-supported indigenous innovation and the free-market approach for technology progress has had a negative impact on China's techno-industrial growth.

For decades, China's ambition as a techno-industrial power has been built on two pillars: indigenous innovation and import technologies for advanced manufacturing industries. A swing from one extreme to the other between the two pillars in different periods led to a policy inconsistency in China's techno-industrial development. For example, policy makers kept switching between embracing a liberal approach and introducing and buying technologies overseas, to indigenous innovation since the reform and opening up at the end of the 1970s. Under President Xi, indigenous innovation on core technologies and advanced manufacturing are further emphasized and received stronger state support in terms of financial subsidies and other preferential policies. The establishment of the National IC Industry Development Fund in 2014 and the introduction of Made in China 2025 in the following year are the two cases showing this trend.

23 According to Clarivate (2020), highly cited papers are papers that rank in the top one percent by citations for a field or fields and publication year in the Web of Science.

Fourth, a solid foundation for innovation in China's research institutions and industries is lacking.

As a newcomer in modern S&T, China lacks a solid foundation for innovation. The capacity of original innovation has been weak for years. The years-long, widespread disconnection between innovation and absorption of import technologies has led to China being stuck in a vicious circle of technology acquisition — import, falling behind, re-import and falling behind again — while neglecting indigenous innovation. China's highest honours in technology and innovation, the First Class of the State Technological Innovation Award, was vacant during 1998–2003. Nationwide, only 34 technological innovation items were awarded the highest honour during 2004–2018 (Chen 2015, 5). Another top award in science, the First Class of the State Natural Science Award, has been vacant in many years, including in 1999–2001, 2004–2005, 2007–2008 and 2010–2012.[24]

The MLP defined three types of innovation China should pursue: original innovation, integrated innovation and innovation on the basis of absorbing advanced overseas technology. Problems exist in all three types of innovation, but China has long neglected integrated innovation and focused mostly on separated technologies due to limited resources and investment and has only begun to emphasize the importance of integrated innovation in the last decade.[25] China still faces a steep learning curve for transforming from a fast follower to a leader in innovation in S&T, particularly in major high-tech fields.

An in-depth look at China's development in patents and other forms of IP casts a light on the reasons for China's slow progress in making breakthroughs in core technologies.

China's number of patent filings has topped the world since 2011 (WIPO 2020, 12). The latest WIPO data showed that China's patent filings amounted to 1.4 million in 2019, accounting for 43.4 percent of world total patent applications. This is more than twice the number of filings in the United States. China accounts for even larger portions in terms of world total filings in utility models (96.9 percent), trademarks (51.7 percent) and industrial designs (52.3 percent) (ibid., 6). However, only 10 percent of these patent filings have market value and 90 percent of them are probably useless and subsidy driven, according to Dong Yunting (2019),[26] a top expert in this area. The high number of patent filings were the result of a great leap in patent applications boosted by all provinces, which recklessly followed the central government's instructions to improve both the quality and quantity of China's patents. Data from the Chinese patent office, i.e., the CNIPA, revealed the truth about China's patent boom. Among the three types of patents — invention, utility model and design — in China, 81–89 percent of patents granted belong to the last two categories, and only 11–19 percent of the granted domestic patents belong to the invention type between 1985 and 2020 (CNIPA 2018a), which is the key indicator to evaluate the level of science and innovation in a country (see Figures 1 and 2 and Table 6 in the appendix). Most of the patents of utility model and design are low quality and useless. According to a statistic by Bloomberg, 91 percent of design and 61 percent of utility model patents became invalid during 2013–2017 due to failure to pay the annual fee (Chen 2018).

From the research perspective, a statistic by Clarivate Analytics based on data from Web of Science Group provides an assessment of the status of China's S&T development (see Figures 3 and 4 and Tables 7 and 8 in the appendix). The ratio of Chinese researchers accounting for the total number of highly cited researchers in each of the 21 fields of sciences (those used in the ESI) is lower than the world average number; however, Chinese researchers rank highly in the percentage of highly cited researchers in the fields of chemistry, computer science, engineering, materials science and mathematics — even better than the American researchers in the five fields (Clarivate 2020). This finding may help explain the fact that China made progress in certain areas but falls behind in most of the other S&T fields.

24 There were more first-class awards given in recent years, though, in both the State Technological Innovation Award and the State Natural Science Award, indicating some progress in China's original innovation. See the full lists of state science and technology awards at the website of the National Office for Science & Technology Awards: www.nosta.gov.cn/english/index.html.

25 The Large Aircraft Program, one of the 13 projects under the National S&T Major Programs, and its final output, the COMAC C-919 narrow-body jet, is a rare example that demonstrated China has made progress in the field of integrated innovation in recent years.

26 Dong Yunting is the director of the expert committee at the China Information Technology Industry Federation.

The low level of innovation among the patents granted in China manifested problems in China's bureaucracy-standard research system, such as prioritizing quantity instead of quality of research findings to demonstrate bureaucrats' performance and wasting money on low-level redundant and worthless research findings. It indicated that there may be a long way to go before the country can achieve advanced progress in sectors in which a great deal of R&D expenditure, lots of talent and a long-term accumulation of invention and innovation are needed.

A case in point is China's semiconductor industry. As the crown jewel in modern industry, the process of design and manufacturing of high-end chips is enormously complicated and involves thousands of millions of components in a necessarily automated production process. It requires collaboration among teams of thousands of researchers, sky-high costs of trial and error, a tremendous amount of R&D investment and long-term accumulation of techniques and experiences. Confronting the highly stringent requirements and conditions in the chip industry has fully exposed the weaknesses and obstacles in China's S&T and innovation system; they have effectively prevented China from achieving a breakthrough during the development of its chip industry.

New Efforts in Frontier Technologies: The Role of the Private Sector

Facing the long-standing problems that have slowed down China's rise to a real technological and economic powerhouse, Xi has sought to harness the digital economy for China's new engine of economic growth since 2015. A major policy initiative, "Internet Plus," and Xi's series of talks on building a "digital China" (Xi 2015; Xinhua 2016) showed new efforts for China's techno-industrial development. China put more focus on frontier technologies such as 5G, AI, the IoT, blockchain, big data and related IP and standards to support China's transition into a real powerhouse in the age of the digital economy. Xi has emphasized the importance of these new technologies as the main factors in China's new infrastructure-building plan more frequently since 2018.

In line with the state's strategic initiatives and efforts in building fundamental infrastructure through its state-owned enterprises (SOEs) to support digitalization, S&T innovation in private companies is driving China's digital economy. Over the past two decades, the private companies Tencent, Alibaba, Baidu and JD.com have risen as China's internet giants, along with other technological start-ups, such as Xiaomi and ByteDance, and telecom equipment giant Huawei. Before the government's major initiatives for promoting China's high-tech and advanced industries, these private internet companies had already begun to invest in new frontier technologies and transform themselves into technological companies. Major breakthroughs in frontier technologies, for instance, AI, big data, the IoT, cloud computing and blockchain, are pushed mainly by these private internet giants and start-ups.

In the digital age featuring rapidly evolving technologies, private companies have the advantage of the flexibility to make quick responses and adjustments to the constantly changing world. BAT (Baidu, Alibaba and Tencent), JD.com, Xiaomi and Huawei are all transforming into China's leading AI companies. In the areas of big data, BAT, JD.com and Huawei developed into leading companies based on their vast accumulated data on users' behaviours, relationships and social interaction, transactions and credit and their capacity in data analysis. In the blockchain field, Alibaba, Baidu, JD.com, Xiaomi and Huawei first realized the coming tide in 2017 and began to deploy their research and market, especially in the application of blockchain in financial areas.[27] In the area of the IoT, Huawei, Alibaba, Baidu, Xiaomi and JD.com are the major general providers and platform providers, along with SOEs such as China Mobile, China Telecom and ZTE, and foreign companies such as Qualcomm and Ericsson become the leading companies (Zhao and Dang 2018). Huawei is the key equipment provider for the 5G supply chain in both China and the world.

The Chinese government has turned to relying on these private companies to strengthen China's

27 See the column by Sina Tech on technological companies' involvement in the blockchain industry at: http://tech.sina.com.cn/zt_d/kejiqkl/.

status in these technological frontier areas. For example, the MST chose Baidu, Alibaba, Tencent, iFlytek and SenseTime as the first group of companies cooperating with the government on China's national open AI innovation platform (Chen and Liu 2017). Huawei, JD.com, Xiaomi and other private companies and SOEs were chosen as the second group of companies for the same purpose in 2019 (Yang 2019). In June 2020, China's power giant SOE State Grid announced the signing of a cooperation agreement with private giants Huawei, Alibaba, Tencent and Baidu for building a new type of digital infrastructure in the energy sector (Xinhua 2020).

At the same time, the government also made huge investments and created policies to encourage its government institutions and SOEs to make breakthroughs in what it defined as core technologies, such as semiconductors, basic software, operating systems and high-end computer numerical control machine tools. The problems existing in China's research system and techno-industrial development, however, still hinder the government-sponsored digitalization in these frontier areas.

Can China achieve its goals of becoming a real technological powerhouse to sustain its economic growth and a "great national rejuvenation"? It depends on whether China can overcome its weakness and shortcomings in the rigid S&T research system, which is deeply rooted in its political structure, as well as the problematic techno-industry connection to release the power of China's potential capacity in S&T innovation. It may also depend on whether China can continue to support and further encourage confidence in the country's private companies to fulfill its goals of developing into a technological powerhouse. China was also increasingly constrained by the growing "splinternet"[28] on the global stage. China's high-tech and internet companies face more geopolitical hinderance from plans such as the Clean Network proposed by Secretary of State Mike Pompeo under the Trump administration. The rapid growth of Huawei and ByteDance (TikTok) has been delayed by the consequences brought by the splinternet effect.

28 Splinternet refers to a characterization of the global internet that used to be free and open as splintering and dividing due to political agenda, technology, commerce and various other factors — for example, a bifurcation into a Chinese-led internet and a non-Chinese internet led by the United States. It is also called cyber or internet balkanization.

In the era of the digital economy, chips are crucial to all cutting-edge, high-tech devices, such as next-generation mobile networks, AI, supercomputers and self-driving cars. The capacity for chip design and manufacturing represent, to some degree, a country's comprehensive strength in S&T and determine its industry and military capacity. The following case study on China's semiconductor industry illustrates the country's techno-industrial development in recent decades and discusses the implications of the answers to the question above.

Case Study: From Paper Tiger to Real Tiger? The Development of China's Semiconductor Industry

A Short History of China's Semiconductor Industry (1960–2014)

1960–1978

China began to develop its semiconductor industry around 1960, at about the same time as Japan started its semiconductor industry. During 1960–1978, although the state-supported indigenous R&D and industry model helped establish China's semiconductor industry and made a few technological achievements, low-level industrialization during the chaotic period of the Cultural Revolution meant China's semiconductor sector fell further behind that of the United States and Japan. The total products made by more than 600 Chinese semiconductor factories only accounted for one-tenth of the products made by one large Japanese factory in one month (Li 2014).

1978–2000

During the first two decades of reform and opening up (1978–2000), the gap between the Chinese semiconductor industry and the advanced US and Japanese semiconductor sector became even wider. China's semiconductor sector even fell behind newly risen semiconductor industries in Taiwan and South Korea. Market-oriented reform and the opening-up policy allowed high-quality and cheap imported chips to dominate the domestic market supply, and Chinese semiconductor enterprises suffered great losses because of low profits and loss of market share. A large proportion of production lines relying on imported semiconductors were operating at a low technical level due to technology blocks by Western countries and fell into a vicious circle: technology acquisition, building a production line, manufacturing, falling behind and importing again.

Top policy makers during this period were aware of the backwardness in China's semiconductor industry and were determined to make changes. President Jiang Zemin was shocked by the rapid growth of South Korea's semiconductor industry and expressed the need to "develop China's semiconductor industry at all costs" after visiting Samsung's semiconductor factory at the end of 1995 (Jia and Song 2020). Project 908 and Project 909 were the main projects implemented after Chinese leaders announced their resolution to develop China's semiconductor industry. Project 908 was centred on Wuxi Hua Jing's foundry production line and supplemented with a number of firms and research institutions and universities on fabless design. It took seven years before the factory was established. The bureaucratic process of approving and building the production line killed the project as the slow process made its semiconductor products obsolete when it began to produce. Taking the lessons learned from Project 908, nationwide resources were mobilized to support Project 909 and all bureaucratic barriers and red tape policies were streamlined. It took only two years to establish the flagship semiconductor company Shanghai Hua Hong, which began to profit in the following years. The nationwide support did not last for too long, however — Hua Hong suffered huge losses as a result of the global recession's impact on the semiconductor sector around 2000 and lost its lustre, and as well as national support, after that.[29]

Although top leaders gave decent attention to developing the semiconductor industry and as well as related policy and financial support, China's semiconductor sector failed to narrow the gap with its foreign counterparts during the period. The government-dominated model of investment for the semiconductor industry revealed some fatal problems that restricted China's catch-up strategy in the semiconductor sector. The rigid bureaucratic system would kill the state-sponsored projects, as Project 908 showed. Even with a huge amount of investment and privileged policies from the top to clear the bureaucratic red tape, these state-sponsored projects could fail due to fierce global competition and fast-evolving semiconductor technology, as Project 909 indicated.

The policy and financial support from the government were not consistent, demonstrating that the policy makers did not fully understand the very significance of semiconductors to a country's technological power and economic growth in the future, nor did they comprehend the features of the semiconductor industry in terms of its high investment and risk and long-term accumulation of technologies and talents. It was reasonable for the leaders to think and act in this way as the development of the semiconductor industry was not a "life or death" issue at the time. China's economy continued its rapid growth and the imported semiconductor products could meet the domestic demand. In addition, technology backwardness and lack of talent constricted China's capacity for technology acquisition, adaptation and innovation. Chinese technicians and workers could hardly understand the advanced semiconductor technologies, let alone carry out adaptation and innovation based on them.

2000–2014

The arrival of the internet era and rapid growth of information technology in the late 1990s refreshed Chinese elites and leaders' realization of the significance of the semiconductor industry. In 2000, the State Council issued the Circular of Several Policies on Encouraging the Development of Software and Integrated Circuit Industries (State Council 2000). Ushering in policies on investment and financing, taxation, industry and technology, export and so on to promote the IC industry, the circular signalled a wave of chip enterprises in the first few years of the 2000s.

Encouraged by the Chinese government's policies, both state-owned and private IC enterprises were established in great numbers and some of them survived and developed into flagship companies in China's IC sector. For example, Semiconductor Manufacturing International Corporation (SMIC) in IC foundry and HiSilicon and Spreadtrum

29 Project 909's flagship enterprise, Hua Hong, barely survived the global semiconductor sector recession around 2000 but has developed into a heavyweight player in China's current foundry arena.

Communications Inc. in fabless design, as well as other top Chinese IC enterprises were established during the period. Overseas returnee talents in semiconductors became the leading entrepreneurs in China's emerging chip companies.

However, even with the rapid growth of Chinese IC in the 2000s, the industry, facing cutthroat global competition, again failed to catch up. The growing company SMIC lost a case of IP theft and patent infringement against Taiwan Semiconductor Manufacturing Company (TSMC) during the period, symbolizing a heavy blow to the fledgling Chinese IC industry, which has experienced a mediocre period since then. The technological gap between SMIC and TSMC in chip manufacturing and between China's IC industry and the world's advanced IC level has been even wider. China's IC industry has stalled in the making of low-end chips with a low profit, and the market for high-end chips relied heavily on foreign supply.

The Chinese government sponsored a series of projects focused on achieving technological breakthroughs in the field of CPU chips, such as Arca CPU, Loongson CPU and MPRC CPU under the support from national projects such as the 863 Program,[30] the 973 Program and the "Core, High and Basic" (*HeGaoJi* in Chinese) Project.[31] These state-sponsored catch-up projects, featuring a quick-success and campaign-style strategy, basically failed, with a few exceptions, including the Sunway CPU for the supercomputer Sunway TaihuLight, which was the fastest supercomputer in the world from June 2016 to June 2018.

Arca CPU had once secured state support and government procurement from the Beijing municipal government but eventually failed to pass the basic test for being a commercially viable product (Fuller 2016, 167). Arca developed its Arca-1 CPU and related hardware and used the Linux operating system to evade Intel's CPU-centred ecosystem[32] and Windows' operating system. However, Arca-based PCs and network computers (NCs) relied on the Linux system and related software, which were incompatible with dominant Windows software products such as Office. Many government agencies and institutions boycotted or bluntly refused to use NCs that installed the Linux system and were supported by Arca CPU because of the awful user experiences. In the end, the lousy user experience led to Arca-based PCs and NCs being abandoned in the market, which signalled the failure of the quick-success strategy in building China's own independent Arca CPU-based ecosystem.

The notorious Hanxin digital signal processing (DSP) microchip scandal[33] in 2006 destroyed the reputation of indigenous CPU chips and the IC sector in China. It is a typical case that revealed some serious problems existing in China's bureaucracy-standard S&T research system, such as lax standards for assessing the authenticity and originality of research findings and widespread academic cheating and fake findings. This explains, in a way, why the catch-up strategy for quick success would not work in the IC field. Impacted by the Hanxin scandal, the indigenous innovation in China's IC sector was questioned and many projects were suspended. The government's financial and policy support was severely reduced accordingly.

To sum up, China's strategy during 2000–2014 changed to encourage both private companies and SOEs to invest in the IC sector instead of state direct investment for developing flagship IC enterprises. This change of strategy had both positive and negative repercussions. On the one hand, the wave of enterprise establishment in the first half of the 2000s laid the foundation for China building its IC industrial chain. Many of them have become pillar enterprises in China's IC industry since then. On the other hand, some observers argued that a nationally coordinated, consistent strategy is still crucial for cultivating China's flagship enterprises and accomplishing

30 It added a special project for very large-scale integration design under the 10th Five-Year Plan in 2001.

31 The development of "core electronic devices, high-end general-purpose chips and basic software" was listed as the top one in the 13 major projects under the National S&T Program in the MLP and also the number one priority in China's definition for strategic emerging industry for the 12th Five-Year Plan (2011–2016). It was known as the "Core, High and Basic" Project for short.

32 Ecosystem in the ICT sector means technological platform and supply chain (industrial chain). The global IT industry is basically built on two ecosystems: Wintel (Windows operating system plus Intel CPU) and AA (ARM CPU and Android operating system).

33 Hanxin 1, the so-called first DSP chip wholly developed in China, turned out to be a totally fake one. It is a Motorola DSP 56800 chip made by Freescale, the semiconductor sector of Motorola, with the original identifications and logo of "Motorola" sanded away and replaced with "汉芯一号" (Hanxin 1 in Chinese).

key progress in IC technology and innovation. The fiscal support from the government, such as the special major projects 863, 973, and "Core, High, and Basic," is not providing enough consistent financial support for China's IC sector to catch up.[34] This, once again, demonstrated a lack of realization of the importance of the IC sector.

The most important reason for the failure to make breakthroughs in the IC industry during 2000–2014, however, lies in a disconnect or a conflict between government support and the market-oriented approach. Given the features of the IC industry, such as being highly competitive, the high costs of trial and error, and rapidly evolving technologies, an approach that separated the forces of government and the market weakened both. The clash is deeply rooted in China's state-controlled model of technological development, in which the government-sponsored projects could not produce commercially viable products while also failing to provide the needed financial and policy support to encourage private companies to develop and catch up.

Latest Developments since the Introduction of the Fund in 2014

The year 2014 represented a new era for China's IC industry. The establishment of the National Integrated Circuit Industry Investment Fund (the fund) and the release of the Outline of the Program for National Integrated Circuit Industry Development (the outline) by the State Council in that year marked a great leap forward in the government's financial and political support for China's IC industry. The establishment of the fund showed Xi's endorsement for the elite's idea of strong and consistent government support for latecomers to pursue a catch-up strategy in key technological areas and industries.

Organized and supervised by the MIIT and the MOF, a fund of 138.7 billion yuan was finally set up in 2014 with multiple government and SOE sponsors, including the MOF, China Development Bank Capital (CDB Capital), China National Tobacco Corporation (CNTC), Beijing E-Town International Investment & Development Co., Ltd. (E-Town Capital), China Mobile and Unigroup (Zhang 2014; Fan 2018). Phase two of the fund got under way in 2018 when phase one finished its investment. It had an even bigger goal of fundraising a total of 200 billion yuan. The MOF and CDB Capital remained as the top two shareholders, with further capital input of 22.5 billion yuan from the MOF (11.02 percent) and 22 billion yuan from CDB Capital (10.78 percent). CNTC and four other SOEs invested 15 billion yuan each and more private companies and local governments from Yangzi River economic zones purchased the shares (*China Securities Journal* 2019).

A crucial question needed to be answered when China's support for the IC industry reached a new level in 2014: does China need to build the whole chip industrial chain, which includes design, fabrication, packaging and testing, equipment, materials, and core IP, for the sake of industrial security and national security? Some experts indicated that no country could develop the whole IC industrial chain, and China should hold an open-minded attitude and follow the route of global cooperation for its IC sector growth (Li 2019). This meant China focused on certain links of the IC industry, such as design and packaging and testing, and relied on imported chips manufactured overseas.

The outline made it clear that China was aiming to achieve an advanced level at each link of the whole IC industrial chain (MIIT 2014a). The fund investment behaviour followed the same spirit. China realized that in the era of the internet and information technology revolution, the IC industry has strategic significance for both economic growth and national security. Theoretically, a lack of any core technologies in IC design, fabrication, packaging and testing, equipment and materials, and IP core could risk China's industrial and national security. This way of thinking is getting more and more attention under the circumstances of the tech war and decoupling that have evolved between China and the United States since 2018.

The fund greatly boosted the financing for China's IC sector, and China started a serious restructuring to advance the whole IC supply chain, but with an emphasis on fabrication. The 138.7 billion yuan raised in the fund's phase one leveraged financing amounting to 500 billion yuan by 2018 (Li and Lai 2019). Through equity investment, the fund put most of its capital in IC fabrication, in particular, memory chips manufacturing. The promised investment in fabrication, design, packaging and testing, equipment and materials account, respectively, for 63 percent, 20 percent, 10 percent and seven percent of the total investment by the fund (*People's Posts and Telecommunications News* 2017).[35] Seventy percent of the fund investment went to the top three enterprises in each category and sub-category to make

34 The national IC fund approved in 2014 demonstrated, in their eyes, a substantive support from government for the IC sector.

35 According to the statistics by the Institute of China Merchants Bank report, these number were 67 percent, 17 percent, 10 percent and six percent by the end of 2018 when the fund's phase one finished (Institute of China Merchants Bank 2019).

these companies stronger and better, with 5–10 billion yuan going to each one: Yangtze Memory Technologies Co., Ltd. (YMTC), SMIC and Hua Hong Semiconductor Limited in foundry; Unisoc and Sanechips Technology Co., Ltd. (Sanechips) in fabless; Jiansu Changjiang Electronics Tech Co. (JCET), Tongfu Microelectronics Co., Ltd. and Tianshui Huatian Technology Co., Ltd. in packaging and testing; Advanced Micro-Fabrication Equipment Inc. (AMEC) and NAURA Technology Group Co. Ltd. (NAURA) in equipment; and National Silicon Industry Group and Anji Micro Shanghai Co., Ltd. in materials (ibid.).

Focusing mainly on equity and fund investment in a market-oriented way, the fund changed the way the Chinese government directly subsidized the IC sector. The fund boosted a new round of investment in China's IC sector. The domestic sale of IC products kept an average rate of increase of 20 percent over 2014–2018, the period of operation for the fund's phase one (China Semiconductor Industry Association 2018, 2019). Another area the fund focused on is overseas M&A to acquire high-end technologies. A few successful acquisitions helped speed up China's rise in IC design and packaging. For example, under the support from the fund, Unigroup acquired Spreadtrum Communications and RDA Microelectronics, and JCET acquired STATS ChipPAC, the world's fourth-largest IC packaging firm, located in Singapore.

The thing is, however, that most of the technologies invested in and purchased are generations behind the international advanced ones, especially in IC foundry. For example, the outline set the goal of realizing mass production of 32/28 nm (nanometre) chips by 2015 and 16/14 nm by 2020 in foundry, which is still two–three generations behind the TSMC. In the field of memory chips, the fund invested in the YMTC's 64-layer 3D NAND, which is generations behind the international advanced 128-layer chip produced by Samsung and Micron. As for the approach of M&A for technology, the failed attempt to purchase Micron in 2015 symbolized the end of this investment strategy by the fund.

China's IC industry has long been restricted by the lack of huge investment, the low level of technology and the reliance on foreign core technologies. It is understandable that the fund supported companies building IC factories or improving technological capacity through M&A for a quick rise. However, it seems incomprehensible that the fund did not specify any investment in indigenous innovation and long-term R&D, which are fundamental issues in the IC industry.

The primary reason for the lack of investment is the impact of the bureaucracy standard, under which the same short-cut approach for quick success still dominated China's IC development, and most of the fund investment went to low-end IC fabrication, packaging and testing for domestic market supply to make quick money. Although it was announced that it would follow market rules for equity investment, the fund is still dominated by the government agencies in charge (the MIIT and the IC leading group). The chairman of the board, Wang Zhanfu, is the director of the finance department of the MIIT, and the president of the fund, Ding Wenwu, is the director of the electronic information department of the MIIT. Possible accomplishments caused by the R&D expenditure and technological innovation would take 10–20 years to achieve and accumulate; no government officials in charge are willing to invest in fundamental R&D and technological innovation as the results would not be seen in the short term.

The bureaucracy standard created the long-standing institutional restrictions that obstructed the fund from following market rules for investment. In general, the institutional restrictions mean the fund must follow officials' instructions and intentions to choose projects for investment. As a government investment, the fund is supposed to have a similar rigid standard for assessment of "maintaining and adding value of state-owned assets," under which the fund would not tolerate loss and failure of its investment. In the approval process for the capital investment by the fund, financial indicators such as profitability and market value of a company have significant sway. This explains why the fund invested in top "dragon head"[36] enterprises in the fields of foundry packaging and fabless design, but provided far less capital for R&D, in order to assure that visible profit and solid accomplishment can be achieved in each year the fund is operating.

That being said, the fund did provide some promising prospects for China's IC industry. A catch-up strategy in 5G chips, AI chips, the IoT, autonomous vehicles and smart cities will be the focus of the fund's phase two, in particular, AI chips and the IoT. In the field of AI chips,

36 "Dragon head" is a term that is literally translated from Chinese. It means flagship enterprises or national champions enterprises.

which consists of GPUs, field-programmable gate arrays (FPGAs) and application-specific ICs, many Chinese start-up companies have been at the forefront in terminal chips, and Cambricon Technologies has developed into one of China's most valuable AI chip start-ups and the flagship company in China's AI chip industry. The fund's phase two could help accelerate the promising trend in the development of China's AI sector.

The Status of China's Semiconductor Sector

The outline gave an official assessment of China's IC sector in 2014: in general, there is still a big gap between China's IC industry and advanced countries, although rapid growth of the IC industry in China has been achieved in the past decade (MIIT 2014b). In line with the outline, the MIIT emphasized in June 2014 that the IC sector was too weak and small to support China's economic growth and meet the demand of state information security and national security (MIIT 2014a).

In its 2014 review of the IC sector, the MIIT admitted that the technology of IC fabrication in China lags at least one–two generations behind the international advanced level, IC design was in its fledging stage with a single product structure, and IC packaging and testing still has a wide technical gap with the prominent international enterprises. Most importantly, R&D intensity (the ratio of expenditures on R&D by a firm to the firm's sales) among China's IC flagship companies, such as SMIC, falls far behind the international IC tycoons, such as Qualcomm, TSMC, Intel and SK Hynix. The MIIT warned that lack of investment and low R&D expenditures could further widen the technical gap between China's IC companies and prestigious international enterprises (MIIT 2015).

Compared to the relatively moderate tone in the official documents, experts from the IC sector were more blunt about China's backwardness and weakness in this field. In their view, China still falls behind in terms of technology in IC manufacturing, storage and packaging, five years after the 2014 outline was released. In particular, IC manufacturing still has a huge technical gap, equal to two–three generations behind. Most high-end IC design is still controlled by foreign enterprises and most domestic companies can only supply mid-to-low-end design (Zu 2018). The only exceptional case is Huawei's impressive achievements in 5G chips, including base station and baseband chips and smartphone SoCs (system on a chip) (see Table 9 in the appendix for market percentage of Chinese chips). In general, domestic IC enterprises can supply low-end products while high-end chips rely heavily on imports, with the value of IC products having become the single largest imported item since 2015 and the value of IC imports reaching as high as US$312 billion in 2018 (China Semiconductor Industry Association 2019) and US$305 billion in 2019 (China Semiconductor Industry Association 2020). The net import of IC products reached as high as US$227 billion in 2018, rising from $193 billion in 2017, and dropped to $204 billion in 2019 (China Semiconductor Industry Association 2018, 2019, 2020).

Specifically, the landscape of China's IC sector after two decades of development looks like this: Seen from the supply chain, Chinese enterprises have risen rapidly, and a few fabless enterprises such as Hisilicon and Unisoc have emerged into the advanced level in the global field of IC design. But Hisilicon is not supplying the external market and Unisoc is mainly designing low-end chips. Qualcomm and other foreign companies hold the high-end chips market. In the field of fabrication, there is still a two-generation technical gap (Ernst 2020). China's champion foundry company SMIC can manufacture 14 nm chips but lacks capacity for mass production, while TSMC has capacity for mass production of 7 nm and 5 nm chips. Chinese companies have achieved the advanced level in packaging and testing, which has a lower technical threshold. JCET and Shanghai Micro Electronics Equipment Co., Ltd. are two frontrunners in advanced packaging. In the area of IC equipment, China falls far behind in almost every link, such as lithography, etching, physical and chemical vapour deposition (PVD/CVD), thermal processors, ion implantation and chemical mechanical planarization. ASML monopolizes the field of lithography. Together with four other international companies, Applied Materials, Tokyo Electron Limited, Lam Research and KLA Corporation, the five top companies account for 80 percent of IC equipment fabrication and material engineering (China Securities 2020). Chinese flagship companies in this field, such as AMEC and NAURA, currently focus on low-end IC fabrication equipment, including etchers and PVD/CVD.

Looking at the categorized IC products, global integrated device manufacturer (IDM) companies dominate in the memory chip market, with

Samsung, SK Hynix and Micron accounting for 95 percent of the dynamic random-access memory (DRAM) market (Huang 2018) and Samsung, Toshiba, Micron, West Data, SK Hynix and Intel controlling 99 percent of the global NAND market (Roos 2017; Dongguan Securities 2020). There is almost no market space for Chinese enterprises. Wuhan Xinxin Semiconductor Manufacturing Co., Ltd. was incorporated into YMTC, a memory giant, with a huge investment of $24 billion by the fund and Unigroup in 2016 (Zheng 2017; Kim 2019).[37] YMTC is China's greatest hope in the memory market but its technological level is still falling behind. The newly established (in 2016) Jiangsu Advanced Memory Semiconductor Co., Ltd. focused on phase-change memory technology. In the area of microprocessors, including PC CPU, mobile phone SoC and other mobile terminal microprocessors and server chips, Hisilicon and Unisoc have stepped into the global advanced level, but Intel monopolizes PC CPUs and other top companies, such as Qualcomm, Broadcom, Apple, Samsung and Media Tek, dominate the mobile terminal microprocessors. In the area of analog IC, Chinese companies fall far behind. Chinese flagship enterprise SG Micro, with a smaller revenue scale and a huge technology gap, could not compete with top companies in the sector, such as Texas Instruments, Analog Devices, Infineon, Skyworks Solution, ST and NXP.

In respect of the commercial model of IC enterprises, China, as a latecomer, lacks the large-scale IDM enterprises such as Samsung, Intel, SK Hynix, Micron, Texas Instruments and so on. The most prominent IC enterprises in China include fabless companies HiSilicon and Unisoc, foundry company SMIC and packaging and testing company JCET. Chinese IC enterprises that follow the IDM model mainly focus on middle and low-end IC products due to the technological backwardness. Some of the typical Chinese IDM enterprises in the IC sector, including Tianjin Zhonghuan Semiconductor, Hangzhou Silan and Unigroup (the parent company of Unisoc), have proceeded to an IDM enterprise through large-scale international M&A in the whole IC supply chain supported by the fund. Some scholars have advocated that China should encourage the IDM model and indicated that this is the trend China should follow to develop its IDM enterprises to upgrade the entire supply chain of China's IC industry (Wei 2017; Mo 2017).

37 Phase one of the huge project kicked off at the end of 2016 and phase two began in June 2020 (Zheng 2017; Wallstreetcn.com 2020).

In terms of core IP, China's enterprises face a few "choke points" of key technologies that could substantively restrict the growth of the Chinese IC industry. These core IP technologies include licences for ARM architecture for microcontroller units (MCUs), SoCs, CPUs, GPUs and other advanced IP chip design; electronic design automation software for IC design, which is dominated by three American companies, Cadence, Synopsys and Mentor; the technology capacity for 7 nm and 5 nm chips manufacturing; and ASML's EUV lithography machine in foundry. Chinese business elites and policy makers fear that any of ban in the use of technologies based on these aspects of core IP would put China in a second-class status in the IC industry, in which China can only supply mid- and low-end products and relies on importing high-end chips for a long period of time — a reliance that is unstable because of US sanctions.

To sum up, China lags far behind in IC manufacturing equipment and materials, and fabrication but made some impressive progress in IC fabless, in particular HiSilicon's series of 5G chips, and is approaching the global advanced level in packaging and testing, seen from the perspective of the IC supply chain. In terms of IC categories, Chinese companies have the biggest technology gap in memory chips and analog IC, then logic IC and microprocessors. Accordingly, China relies heavily on imports of DRAM and NAND memory chips, analog/power chips, and PC CPU and server CPU chips. Memory chips is the single largest import category, accounting for 36 percent of China's total IC products import. Analog/power chips are the second-largest import category, accounting for 15 percent of the total IC imports, then, successively, 12 percent for mobile phone SoCs, eight percent for PC CPUs and four percent for microprocessors (Institute of China Merchants Bank 2019). China faces choke points in core IP technologies in the whole IC supply chain and will not catch up in the foreseeable future. China also lacks powerful IDM IC enterprises that can integrate the whole IC industrial chain to compete with foreign counterparts.

Problems in the Development of China's Semiconductor Sector

The history of China's semiconductor sector during 1960–2014 indicated the reasons for lagging behind, including lack of investment, talent, faulted development strategy and technological block by Western countries. The fund established in 2014 addressed the concern of lack of investment but not the absence of huge R&D expenditure and talent attraction that constitute the foundation of the IC industry.

Fundamentally, the long-existing bureaucracy standard in China's IC sector is to blame.

Under the bureaucracy standard, the government-dominated campaign-style catch-up strategy seeks a short-cut approach for quick success. This approach goes against almost every factor and requirement for a successful IC sector, including long-term accumulation of R&D input and talent dedicated to it, huge and consistent investment, and extremely high trial-and-error costs,[38] and is why China kept failing to narrow the gap with the advanced level in the global IC industry. Specifically, these problems include:

- No room for real innovation and no tolerance for failure in China's S&T research system, in which government officials in charge do not encourage investment in R&D that focuses on long-term innovation but instead focus on short-term projects with more certainty for success. This problem demonstrates the priorities of the fund, which basically excludes the most fundamental but time-consuming R&D and puts its main investment on IC foundry, packaging and testing, and fabless companies. The problem echoes the dominant philosophy or utilitarian mindset in current Chinese society that seeks a short-cut approach for quick success and holds a disrespectful attitude toward fundamental R&D and innovation.
- Related to the first problem, most IC investments followed the catch-up strategy and supplied the low-end domestic market, emphasizing quantity instead of quality. Under the strategy, achievements can be realized quickly, and companies can profit from it, although these productions are still generations behind the international advanced level. More importantly, it provides noticeable results, making the performance of supervising bureaucrats look impressive.
- A lack of talent and the absence of an environment that attracts talent to stay in the IC industry. This also echoes a long-existing problem in the bureaucracy-standard-dominated research culture in China, in which innovative researchers and talented scientists find it difficult to survive.

Widely cited data[39] shows that there is a huge talent gap between the demand and the reality in China's semiconductor industry, which needs 700,000 skilled employees to support its development but only has 300,000 qualified personnel serving in the industry (Gao 2018). There have been some positive changes in recent years, though. Overseas returnees — in particular some top Chinese experts from overseas — continue coming back, and the increase of qualified workers educated in China's universities and institutions would supply more reserve talent. China's top IC companies, such as HiSilicon and JCET, provided generous salaries for their engineers and technicians and attracted more skilled persons to join China's IC sector.

The second type of problem that exists in China's IC sector concerns the disconnection between research and commercially viable products, which is also a typical problem in China's techno-industrial field.

Similar to Arca CPU chips, the case of Loongson CPU chips demonstrated the importance of a market-oriented R&D model for commercially viable products. Government-sponsored and -subsidized IC R&D in state-affiliated institutions and universities, if disconnected with the market, is a dead-end for the development of the IC industry.

Following the national security requirement of "fully controllable" and indigenous CPU chips, the Loongson CPU chose the MIPS structure plus Linux system instead of the mainstream X86 structure by Intel and AMD plus Windows system at the beginning. Without the support of the Wintel (Windows plus Intel) ecosystem, there is a lack of supply-chain support from PC manufacturers and software companies in the market. As a result, Loongson had to develop its full ecosystem, consisting of the supply chain of PC manufacturers and software companies

38 Billions of yuan of investment could be for nothing and return on investment in the IC industry is quite disproportional in a relatively short period.

39 This data is originally from the White Paper on China IC Industry Talents (2017–2018), which was jointly released by China Electronics and the Information Industry Development Research Institute and the Software and Integrated Circuit Promotion Center of the MIIT.

based on the MIPS structure plus Linux system, which are almost non-existent in the market.

Under these circumstances, it seems Loongson was facing a mission impossible. Loongson's long-standing disconnection with the consumer market made it worse. Loongson's isolated research on general purpose CPU chips kept being refused by the market. Its CPU chips are low quality. Loongson 3B1000, 1A and 2I could not even boost the operating system (Hu and Song 2018). After waiting for Loongson's independent CPU chips for 12 years, the Chinese government gave up. In 2013, the "core, high, and basic" project under the National S&T Major Program cancelled its fiscal support for Loongson's independent CPU project and sought instead cooperation with foreign companies such as IBM, AMD and ARM for China's own CPU, based on authorization from these companies.

The third type of problem is that the lack of coordination between government-supported indigenous innovation and the market-oriented approach has constituted a significant obstruction in China's IC industry.

Government direct investment to cultivate flagship IC companies in the late 1990s, such as Project 909, failed due to the global IC market downturn around 2000. The government encouraged both the laissez-faire capitalism approach and state-sponsored projects to develop China's IC industry in the following decade. Government-dominated programs for CPU chips, such as Arca and Loongson, failed in the first few years of the 2000s as they sought an inflexible way for indigenous innovation, which overemphasized "fully independent" and "fully controllable" and rejected technological cooperation with Western companies. The idea of a fully independent controllable supply chain in the IC sector is a self-isolating, self-embargo strategy, in which China's IC industry had already decoupled itself prior to US actions. It goes against the trend of globalization in the IC industry.

During the same period, the market-oriented approach for boosting domestic investment and relying on the global IC supply chain met China's increasing demand for IC products, which prevented Chinese leaders from paying a consistent investment on indigenous innovation for a powerful IC sector after government-funded CPU chip programs failed. It is difficult for the fledging Chinese IC industry to catch up through a free-market competition without substantive and consistent government support in the highly competitive global IC industry with a high density of capital and technology. China's venture capitalists seldom invested in the IC sector before 2018 due to the huge financial risk posed by the long-term investment, huge cost and low return rate in the industry (China Business Network 2018).[40]

A comprehensive and coordinated approach should be encouraged, combining government financial and policy support, as well as a market-oriented approach for the long-term accumulation of technology and talent, aiming to produce commercially viable products and financing from the capital market. The problem is that government support (such as that provided by the fund beginning in 2014 and the promised full support at all costs from the government after the ZTE incident in 2018) again have the potential to go back to another extreme — with more focus on fully independent innovation and less on global cooperation.

The fourth type of problem concerns the lack of capacity for innovation in the IC sector.

Years of catch-up based on the approach of introduction, assimilation and innovation, and market for technology can at best make China a close follower but never a real innovator in the global IC industry. This echoes the lack of sufficient capacity for innovation in China's industries and research institutions. As the case of Project 909 in the 1990s showed, it is impossible to get the up-to-date or core technologies using the market for technology strategy. Generally, most technology acquisitions were out of date and the introduction, assimilation and innovation approach did not translate in practice into indigenous innovation in core technologies. Even if it succeeded after a few years of effort, it would fall behind again as China's competitors did not stop innovation. Innovation in frontier technologies based on existing ones is the only way for China to become a leading country in the IC industry.

In summary, all of these problems contributed to the failure to make breakthroughs in core IC technologies and to narrow the technological gap in China over the past four decades. Under the short-cut approach for quick success, a market-oriented

40 More venture capitalists are investing in China's IC industry, stimulated by the government fund-led investment spree since 2018. See Wu (2020).

Box 1: Reasons for HiSilicon's Rise

First, there was huge R&D investment for technological innovation. HiSilicon started as an R&D section of Huawei's IC department and evolved into an IC design subsidiary of Huawei. In the highly competitive IC sector, featuring fast-evolving technological innovation, prestigious global IC companies put R&D expenditure as their top strategic priority for future growth (KPMG 2019). With full support from Huawei, HiSilicon's huge amount of R&D investment and high R&D intensity lays a solid foundation for its success. HiSilicon's R&D expenditure is among the top 10 in the world, ranking ninth with a figure of US$2.4 billion, an R&D intensity of 21 percent and an annual growth rate of 44 percent in 2019 (*Chip Insights* 2020). The absolute number of R&D expenditure of HiSilicon is much higher than other Chinese IC companies, such as Unigroup, SMIC, ZTE and Hua Hong (Qiu 2020),[41] and its R&D intensity is one of the highest among all the Chinese ICT and top internet companies (see Table 10 in the appendix for R&D expenditure and intensity of Chinese ICT and internet companies). Lack of consistent and high investment on R&D is the crucial reason why most of China's IC enterprises fall further technologically behind their foreign peer companies.

Second, HiSilicon's R&D research has a very close connection with the market. As Huawei's IC design subsidiary, it has an important advantage and supplies SoC for Huawei smartphones. This provided a convenient playground for HiSilicon to test the water of user experiences of its chips and a stable market for its SoC. The big orders from Huawei play a crucial role in HiSilicon's success. In 2018, Huawei's order for chips from HiSilicon amounted to US$21.1 billion (Ouyang and Xu 2019). In 2012, SoC designed by HiSillicon began to supply Huawei's new-generation smartphones. From Kirin 910, its first SoC, until Kirin 970, its latest, HiSilicon supplied its parent company's flagship smartphones for each generation. Huawei's smartphone products use ARM architecture and are supported by the Android system. It was convenient to use the existing ARM plus Android system to provide hardware and software and applications support, which created a favourable environment for HiSilicon to design compatible products and to be accepted more easily in the market.

Third, technological innovation in IC frontiers based on existing technologies constitutes another key factor for HiSilicon's success. HiSilicon's business and products cover four key areas in the IC industry: Kirin series SoC for smartphones and other devices; Kunpeng series server CPU chips for cloud computing at data centres; Ascend series SoC for AI processors; Balong terminal chips and Tiangang base station chips for baseband chips; and other specialized chips for surveillance, mobile cameras, the IoT, set-top boxes and routers. Among them, Kirin series SoCs are a concentrated display of HiSilicon's achievements. With the support from powerful Balong baseband chips, Kirin chips developed into globally advanced SoCs that support 5G communication. For example, HiSilicon's Kirin 980 SoC released in 2018 consists of ARM v8-A ISA (Instruction Set Architecture), ARM Cortex-A76 CPU, ARM Mali-G76 MP10 GPU, baseband chips by Balong 750, TSMC 10 nm FinFET+ fabrication technology and so on. With the solid support of parent company Huawei, HiSilicon's advanced chips, such as Kirin series SoC, are used in its main new generations of smart devices and next-generation mobile communication products. These chips parallel similar products by Qualcomm and Samsung, which even Apple and Intel did not achieve.

Fourth, HiSilicon's huge amount of R&D expenditure make it capable of attracting high-quality talent from around the world for its research and technological innovation.

41 According to the annual report of SMIC, its R&D expenditure in 2019 amounted to US$687.4 million, with R&D intensity at 22 percent (2018 — US$663.4 million with intensity at 17 percent; 2017 — US$509.4 million; and 2016 — US$318 million). It has increased in recent years but is still far below the numbers of HiSilicon. Other companies, such as Hua Hong, are even lower (Qiu 2020).

investment model that prioritized foundry and M&A of IC companies, there were some achievements in a short period, but it would not help strengthen the most-needed R&D and indigenous innovation. The issue of disconnection between academic R&D and the IC industry has not been effectively addressed. Many self-proclaimed advanced, international-level research breakthroughs stopped on paper without any further movement after the researchers and institutions received the government's recognition and rewards. Other problems, such as inconsistent government support and lack of talent and capacity in innovation, all contributed to the slow progress in breakthroughs for core technologies in China's IC industry.

What is the way out for China's IC industry, then, facing all these problems? Huawei's HiSilicon stands out as a rare case of an advanced fabless company among a few successful Chinese IC enterprises. Box 1 describes the reasons for HiSilicon's rise, which acts as a stark contrast to the weaknesses and problems existing in the state-dominated IC development model and demonstrates some traits that may indicate a way forward for some encouraging prospects in China's IC industry.

In short, the huge and consistent investment on R&D research and technological innovation, the close connection between research and market, technological innovation into new frontiers of the IC industry, and qualified talent to support its research and innovation, explain the success of HiSilicon while serving as a foil to the failure of other state-sponsored IC enterprises. In a broad sense, the case of HiSilicon described in the box illustrates the fundamental problems that prevented China's IC industry from achieving breakthroughs in core technologies and narrowing down the technological gap with its advanced foreign peers.

Conclusion

China's decades-long techno-industrial development has primarily followed a government-dominated national campaign-style model through a catch-up approach for quick success. Government-sponsored major S&T programs such as the 863 Program, the 973 Program, the National S&T Major Programs and Made in China 2025, and government-subsidized R&D research carried out by institutions and universities played a major role in China's progress and breakthroughs in many sectors in China's techno-industrial development. In particular, this model helped achieve success in certain high-tech industries and sectors, including nuclear and satellite programs, a space and lunar exploration program and supercomputing, as well as in some advanced manufacturing fields, such as high-speed rail, hydropower equipment, and UHV power transmission and transformation.

However, this government-dominated catch-up approach did not work in the semiconductor industry and other sectors, such as automobiles. The reasons are complicated but, to a large extent, these failures in key technological breakthroughs can be attributed to the long-standing problems in China's S&T research system. The case of China's semiconductor industry showed that a market-oriented approach, close connection between research and the market, the support of a full industrial supply chain, and consistent and huge R&D expenditure and capital investment are necessary to achieve success in the sector, which features a highly competitive atmosphere, high talent and capital intensity, a high cost of trial and error, and fast-evolving technology. China's government-controlled S&T research system and correlated government-dominated campaign-style catch-up approach for techno-industrial development, however, restricted China's capacity to develop into a real technological powerhouse in the semiconductor industry and related sectors.

Technological innovation needs a flexible, relaxed and supportive systemic environment in which innovation is encouraged and failure is tolerated. A research system dominated by government officials instead of technological experts caused many deep-rooted problems that severely restricted S&T achievements and hampered findings. Disconnection between research and the market is another problem in China's government-dominated research system and state-sponsored projects. China's catch-up approach in technological innovation has proven to be ineffective for achieving supremacy in technological and scientific growth. Exploration in new frontiers based on existing technologies for leading innovation is supposed to be the right path. But China's government-dominated S&T research system, which frequently prioritizes short-term and noticeable projects with high certainty, does not provide favourable support.

After realizing the importance of what they defined as core technologies in sectors such as the semiconductor industry as early as the 1990s, top policy makers in China resorted to the government-dominated national campaign-style model for breakthroughs in techno-industrial development. However, the deep-rooted problems in China's S&T research system restricted China's capacity in innovation and technological breakthroughs. A swing between the market-oriented approach for technology acquisition and indigenous innovation for progress and breakthroughs in core technologies prevented a consistent attention from the government and restricted the required huge investment on strategic industries such as IC.

The critical juncture happened in 2018. The ZTE event and Huawei ban as a consequence of the US-China trade and technological war reminded Chinese leaders and elites, in a painful way, that China still faces the great possibility of being choked in core technologies. The forces in China today advocating strategies and approaches such as building the whole industrial chain and achieving breakthroughs in core technologies in many sectors, in particular in the IC industry and other advanced manufacturing sectors, have been reinforced since then. However, the goal of "fully controllable and independence" in a country's S&T field is not feasible, and policy makers should be cautious about government-dominated plans that develop core industries such as the IC industry "at all costs." Entrepreneurship and innovation in the market-oriented private sector should be encouraged in China's techno-industrial development.

The rise of China's digital economy since 2015 has been mainly built on the innovation in both the business model and technology of private companies, represented by the internet giants Tencent, Alibaba, Baidu and JD.com; ICT giant Huawei; and other start-ups such as Xiaomi and Bytedance. Private companies such as HiSilicon have made a few real breakthroughs in core technologies in the IC industry where China has lagged for decades. The Chinese government invested heavily in what it defined as core technologies, such as IC, through state-sponsored funds and by providing supporting polices while seeking cooperation with private companies on innovation in frontier technologies, such as AI, 5G, big data, blockchain and the IoT.

While the government-backed technological progress is still restricted by the deep-rooted problems in its S&T research system and the disconnect between academic research and industry, China's potential to become a real technological powerhouse depended on the continuing innovation and progress of leading private companies and on whether the Chinese government would continue to have confidence in the private sector and provide an encouraging environment for further development of the private sector in the age of the digital economy.

The ongoing US-China tech war created additional geopolitical risks and difficulties for Chinese enterprises attempting to compete in the global IC industry. Since it is "choked" on core technologies because of the US ban, China has no choice but to rely more on strengthened investment for indigenous innovation while resorting to the forces of market for possible cooperation with other advanced economies such as the European Union, Japan and South Korea, as well as on the American business community to counter the restrictions.

Appendix

Table 1: Major Strategies and Policies for Techno-Industrial Development

Strategy (Policy)	Strategy (Policy) in Chinese	Main Features	Issuing Department	Year Passed
Outline of the MLP (2006–2020)	国家中长期科学和技术发展规划纲要(2006-2020年)	→ Overarching strategic plan for China's S&T development in 2006–2020. → Selected 16 top priorities (13 priorities announced) and key areas in China's long-term S&T development.	State Council	2006
The Science and Technology Development for the 12th Five-Year Plan (2011–2015)	国家 "十二五(2011-2015)科学和技术发展规划	→ S&T part of China's 12th Five-Year Plan. → Implementing China's 13 top priority projects. → Nurturing China's strategic emerging industries. → Promoting breakthroughs in core technologies.	MST	2011
The National Development of Strategic Emerging Industries for the 12th Five-Year Plan (2011–2015)	十二五"国家战略性新兴产业发展规划	→ Specified the goals, policies and measures for strategic emerging industries: energy-saving and environmental protection, next-generation information technology, biology, high-end equipment manufacturing, new energy, new materials and electric vehicles. → Listed 20 priority projects related to these industries.	State Council	2012

Strategy (Policy)	Strategy (Policy) in Chinese	Main Features	Issuing Department	Year Passed
Made in China 2025	中国制造2025	→ Identified a three-step strategic goal: listed as a manufacturing power by 2025, middle manufacturing power by 2035 and leading manufacturing power by 2049. → Setting indicators for manufacturing in innovation capacity, quality and efficiency, green development, self-reliant supply, etc. → Identified five significant projects: establishment of manufacturing innovation centres; smart manufacturing; green manufacturing; intensifying industrial fundamentals in core electronic devices, advanced manufacturing technology and key basic material; and high-end equipment innovation and manufacturing. → Identified 10 priority areas for breakthroughs, largely overlapping with the 13 top priorities in 2006.	State Council	May 2015
Action Outline for Promoting the Development of Big Data	促进大数据发展行动纲要	→ Promote government data sharing, integration for better governance. → Big data for traditional and emerging industries for economic transformation to the digital economy. → Internet and big data for national security.	State Council	August 2015
Outline of the NSID	国家创新驱动发展战略纲要	→ Set the tone for a sci-tech-centred innovation-driven development for China. → Identified a three-step strategic goal: becoming an innovative country by 2020, moving to the forefront of innovative countries by 2030, and an innovative power by 2050.	Party Central, State Council	May 2016

Strategy (Policy)	Strategy (Policy) in Chinese	Main Features	Issuing Department	Year Passed
NPSTI for the 13th Five-Year Plan (2016–2020)	十三五”国家科技创新规划	→ Strategic plan for 2016–2020, based on and updated from previous overarching one released in 2006. → Further promoting the 13 top priority projects. → Establishing 15 other significant sci-tech innovation projects. → Implementation plan and road map for the NSID.	State Council	July 2016
The National Development of Strategic Emerging Industries for the 13th Five-Year Plan (2016–2020)	十三五”国家战略性新兴产业发展规划	→ Continued focusing on strategic emerging industries outlined in the 12th Five-Year Plan. → Emphasis on five fields: ICT and internet economy, high-end manufacturing, bioeconomy, green and low-carbon economy, and digital creative economy. → Listed 23 priority projects in the five fields, with new projects on AI, big data, and Internet Plus added, compared to the 20 projects in the 12th Five-Year Plan.	State Council	Nov. 2016
Major Projects for Science and Technology Innovation 2030	科技创新2030重大项目	→ Following the NSID and NPSTI, selecting 16* strategic sci-tech projects that are expected to be achieved by 2030. → Six projects have been initiated by 2018, including quantum teleportation and quantum computer, neuroscience, deep-sea space station, space-ground integrated information network, aeroengine and gas turbine, and next-generation AI.	MST	Jan. 2017
Notice on Issuing the Development Plan on the Next Generation of Artificial Intelligence	关于印发新一代人工智能发展规划的通知	→ Identified a three-step strategic goal: becoming an advanced country in AI technologies and applications by 2020, achieving major breakthroughs in AI theory of foundations and leading position in some AI technologies by 2025, and leading power in AI theory and technology by 2030.	State Council	July 2017

Strategy (Policy)	Strategy (Policy) in Chinese	Main Features	Issuing Department	Year Passed
China Standards 2035	中国标准2035	→ Setting and promoting standards in advanced high-end manufacturing and next-generation information technology, including blockchain, IoT, cloud computing, big data, 5G, AI, smart city, etc., as well as biotechnology. → Promotion of China's standards going global and in-depth participation in international standards organizations for international cooperation. → Promoting standards connectivity with other countries and regional governmental organizations, particularly with the Belt and Road Initiative countries. → Adopting more international standards in China.	Standard Administration of China	In progress

Source: The State Council.
Note: * The next-generation AI was added in 2018 to the previous 15 significant projects, making it 16 projects.

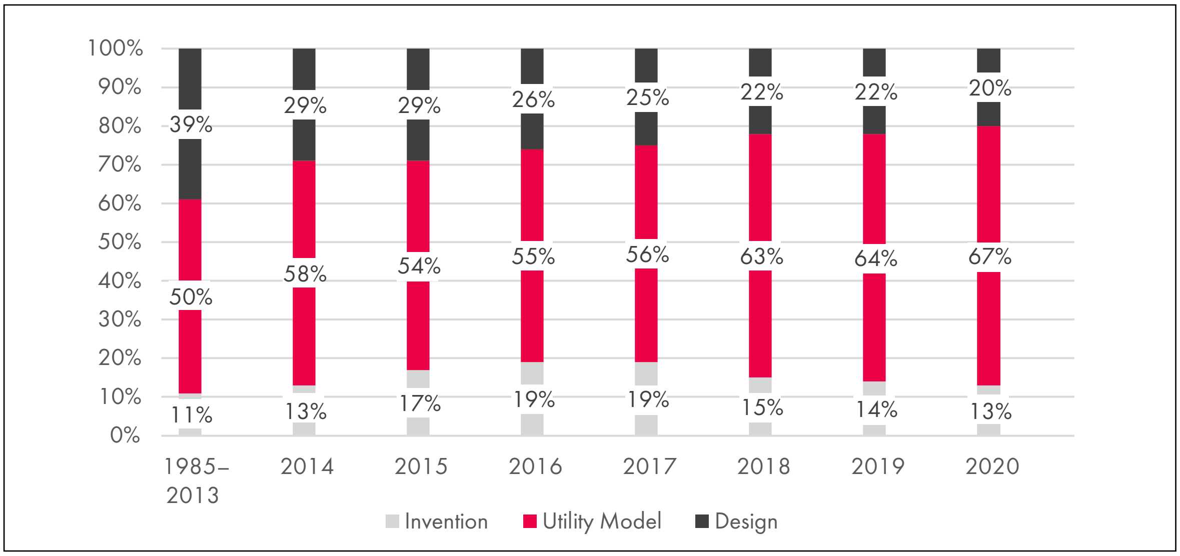
Table 2: China's Priority Projects for Techno-Industrial Development

<table>
<tr><th>Top 13 Priority Projects in National S&T Major Programs</th><th>10 Priority Areas in Made in China 2025</th><th>16 Significant Innovation Projects</th><th colspan="2">More than 20 Strategic Emerging Industries (Projects) in Five Fields</th></tr>
<tr><td>1. Core electronic devices, high-end general-purpose chips and basic software</td><td rowspan="5">1. Next-generation information technology, including IC and its equipment, information communication equipment, and operating system and industrial software</td><td>1. Aeroengine and gas turbine</td><td>1. Network infrastructure such as 4G, 5G and fibre optic network</td><td rowspan="5">Information technology</td></tr>
<tr><td rowspan="3">2. Complete set of technologies and processes for ultra-large-scale IC manufacturing</td><td rowspan="3">2. Deep-sea space station</td><td>2. Internet Plus</td></tr>
<tr><td>3. Big data</td></tr>
<tr><td>4. Core information technologies in IC, basic software, etc.</td></tr>
<tr><td>3. Next-generation broadband mobile wireless communication</td><td>3. Quantum teleportation and quantum computer</td><td>5. AI</td></tr>
<tr><td rowspan="2">4. High-end computer numerical control machine tools and basic manufacturing technology</td><td rowspan="2">2. High-end computer numerical control machine tools and robotics</td><td rowspan="2">4. Neuroscience</td><td>6. Smart manufacturing</td><td rowspan="6">High-end equipment and new materials</td></tr>
<tr><td>7. Aviation breakthroughs in aeroengine, large passenger aircrafts</td></tr>
<tr><td>5. Development of large-scale oil and gas fields and coalbed methane</td><td>3. Aerospace equipment</td><td>5. National cyberspace security</td><td>8. Satellite and its application</td></tr>
<tr><td>6. Large-sized advanced pressurized PWR and HTGR nuclear power stations</td><td>4. Ocean engineering equipment and high-tech ships</td><td>6. Deep-space exploration and in-orbit servicing and maintenance systems for spacecraft</td><td>9. Keep leading in advanced rail transportation equipment manufacturing</td></tr>
<tr><td>7. Water pollution control and treatment</td><td>5. Advanced rail transportation equipment</td><td>7. Seed industry indigenous innovation</td><td>10. Ocean engineering equipment</td></tr>
<tr><td>8. Large passenger aircraft manufacturing</td><td>6. Energy-saving and new energy automobile</td><td>8. Cleaner and more efficient use of coal</td><td>11. New materials</td></tr>
</table>

Top 13 Priority Projects in National S&T Major Programs	10 Priority Areas in Made in China 2025	16 Significant Innovation Projects	More than 20 Strategic Emerging Industries (Projects) in Five Fields	
9. Cultivation of new varieties of genetically modified organisms	7. Power equipment	9. Smart grid	12. Biomedicine	Biological industry
10. Invention and production of major new drugs	8. Agricultural machinery equipment	10. Space-ground-integrated information network	13. Biomedical engineering	
			14. Bio-agriculture	
11. Prevention and treatment of AIDS, viral hepatitis and other major infectious diseases	9. New materials	11. Big data	15. Bio-manufacturing	
			16. Bioenergy	
12. High-resolution Earth observation systems	10. Biomedicine and high-performance medical devices	12. Smart manufacturing and robotics	17. Biotechnology	
13. Manned space and lunar exploration program		13. Research and application of priority new materials	18. New energy automobile	New energy automobile, new energy, and energy-saving and environmental protection
			19. New energy	
		14. Comprehensive environmental improvement in Beijing, Tianjin, and Hebei Province	20. Energy-saving industry	
			21. Environmental protection industry	
			22. Resource recycling and utilization	
		15. Health care	23. Digital innovation industry	
		16. Next-generation AI		

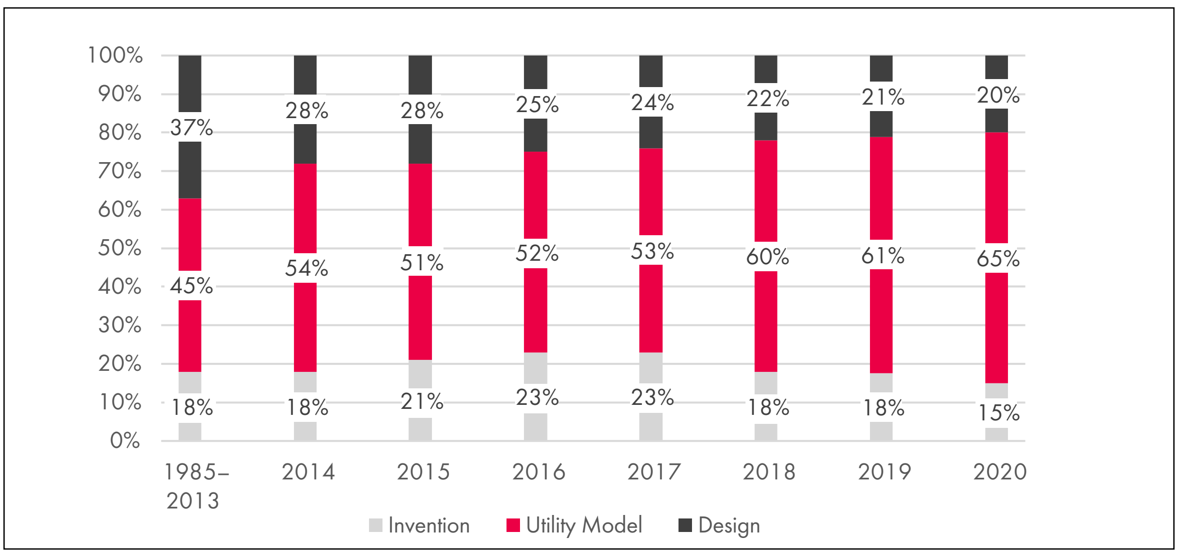
Source: The State Council.

Figure 1: Patent Breakdown in China (1985–2020), Excluding Grants to Foreign Applications



Source: CNIPA.

Figure 2: Patent Breakdown in China (1985–2020), Including Grants to Foreign Applications



Source: CNIPA.

Table 3: China's Rankings in the Global Innovation Index (2012–2020)

	GII Overall			GII Innovation Input Sub-Index			GII Innovation Output Sub-Index		
	GII	UM	SEAO	GII	UM	SEAO	GII	UM	SEAO
2020	14	1	4	26	1	7	6	1	1
2019	14	1	4	26	1	7	5	1	1
2018	17	1	5	27	1	7	10	1	1
2017	22	1	3	31	1	7	11	1	2
2016	25	1	7	29	1	7	15	1	2
2015	29	1	7	41	2	8	21	1	5
2014	29	1	7	45	4	8	16	1	2
2013	35	3	8	46	6	8	25	1	5
2012	34	3	8	55	12	10	19	1	3

Source: WIPO, Global Innovation Index 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019 and 2020.
Note: GII = Global Innovation Index; UM = upper middle-income economy; SEAO = South East Asia, East Asia and Oceania.

Table 4: China's Innovation Strengths in the Global Innovation Index (2020)

Indicator Name	Sub-category	Category	Rank
PISA scales in reading, math and science	Education	Human capital and research	1
Global R&D companies, average expenditure top 3, million US$	R&D		3
QS university ranking, average score top 3			3
Gross capital formation, % GDP	General infrastructure	Infrastructure	6
Domestic market scale, billion purchase power parity (PPP)$	Trade, competition and market scale	Market sophistication	1
Domestic credit to private sector, % GDP	Credit		6
Firms offering format training, %	Knowledge workers	Business sophistication	1
Gross expenditure on R&D (GERD) finance by business, %			4
High-tech imports, % total trade	Knowledge absorption		5
Patents by origin/billion PPP$ GDP	Knowledge creation	Knowledge and technology outputs	1
Utility models by origin/billion PPP$ GDP			1
Growth rate of PPP$ GDP/worker, %	Knowledge impact		2
High-tech net exports, % total trade	Knowledge diffusion		5
Trademarks by origin/billion PPP$ GDP	Intangible assets	Creative outputs	1
Industrial designs by origin/billion PPP$ GDP			1
Creative goods exports, % total trade	Creative goods and services		1

Source: WIPO, Global Innovation Index 2020.

Table 5: China's Innovation Weaknesses in the Global Innovation Index 2020

Indicator Name	Sub-category	Category	Rank
Regulatory quality	Regulatory environment	Institutions	82
Rule of law			72
Cost of redundancy dismissal, salary weeks			109
School life expectancy, years	Education	Human capital and research	87
Pupil-teacher ratio, secondary			62
Tertiary inbound mobility, %			101
Tertiary enrolment, % GDP			58
ICT access	ICTs	Infrastructure	71
ICT use			53
GDP/unit of energy use	General infrastructure		94
Environmental performance	Ecological sustainability		98
Ease of getting credit	Credit	Market sophistication	74
Microfinance gross loans, % GDP			73
Applied tariff rate, weighted average, %	Trade, competition and market scale		68
GERD financed by abroad, % GDP	Innovation linkages	Business sophistication	81
Joint venture/strategic alliance deals/billion PPP$ GDP			76
ICT services imports, % total trade	Knowledge absorption		78
Foreign direct investment net inflows, % GDP			100
National feature films/million population 15–69 years old	Creative goods and services	Creative outputs	93
Printing and other media, % manufacturing			72
Generic top-level domains/thousand population 15–69 years old	Online creativity		74

Source: WIPO, Global Innovation Index 2020.

Table 6: Annual Distribution of Three Types of Patents Granted (Domestic and Foreign)

	Year	Total	Invention	Utility Model	Design
Total	1985–2013	7,426,010	1,318,659	3,385,236	2,722,115
	2014	1,302,687	233,228	707,883	361,576
	2015	1,718,192	359,316	876,217	482,659
	2016	1,753,763	404,208	903,420	446,135
	2017	1,836,434	420,144	973,294	442,996
	2018	2,447,460	432,147	1,479,062	536,251
	2019	2,591,607	452,804	1,582,274	556,529
	2020	3,639,268	530,127	2,377,223	731,918
Domestic	1985–2013	6,659,972	735,863	3,357,509	2,566,600
	2014	1,209,402	162,680	699,971	346,751
	2015	1,596,977	263,436	868,734	464,807
	2016	1,628,881	302,136	897,035	429,710
	2017	1,720,828	326,970	967,416	426,442
	2018	2,335,411	345,959	1,471,759	517,693
	2019	2,474,406	360,919	1,574,205	539,282
	2020	3,520,901	440,691	2,368,651	711,559
Foreign	1985–2013	766,325	582,796	27,973	155,556
	2014	93,285	70,548	7,912	14,825
	2015	121,215	95,880	7,483	17,852
	2016	124,882	102,072	6,385	16,425
	2017	115,606	93,174	5,878	16,554
	2018	112,049	86,188	7,303	18,558
	2019	117,201	91,885	8,069	17,247
	2020	118,367	89,436	8,572	20,359

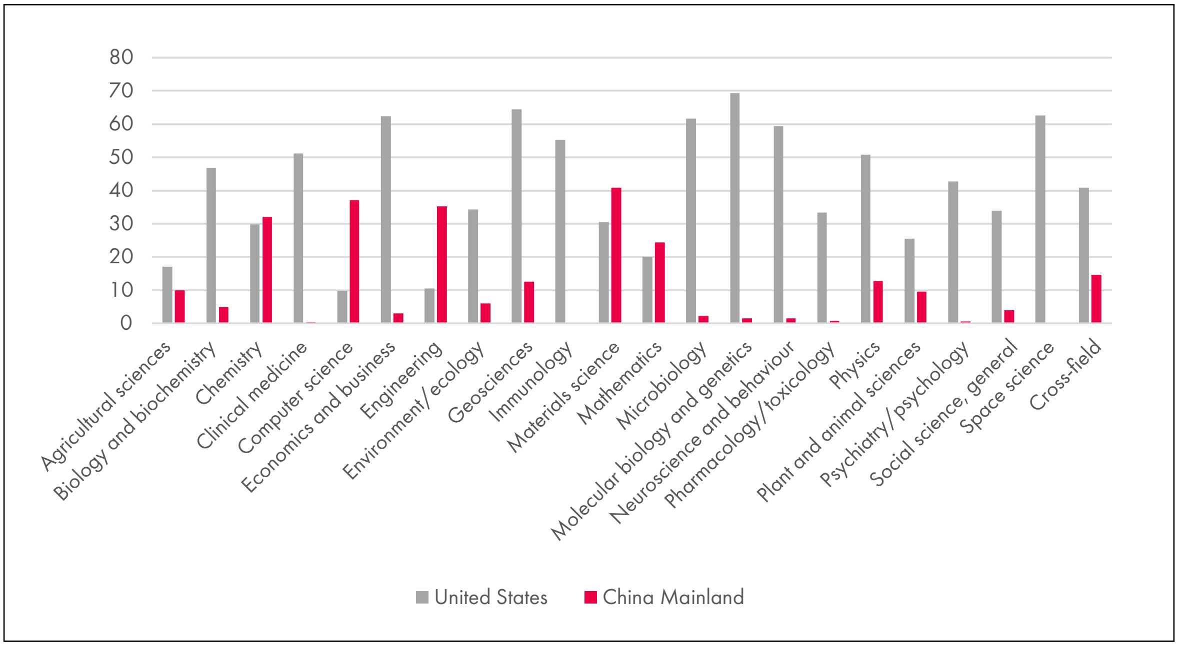
Source: CNIPA.

Table 7: Research Performance — A Comparison between the United States and China

Indicator		United States	China
Rank		1	2
Number of highly cited researchers		2,650	770
Percentage of highly cited researchers		41.5	12.1
Percentage of highly cited researchers of each ESI field	Agricultural sciences	17.1 (19/111)	9.9 (11/111)
	Biology and biochemistry	46.9 (114/243)	4.94 (12/243)
	Chemistry	29.7 (74/249)	32.1 (80/249)
	Clinical medicine	51.2 (247/482)	0.41 (2/482)
	Computer science	9.7 (12/124)	37.1 (46/124)
	Economics and business	62.4 (63/101)	2.97 (3/101)
	Engineering	10.4 (18/173)	35.3 (61/173)
	Environment/ecology	34.2 (69/202)	5.94 (12/202)
	Geosciences	64.4 (65/151)	12.6 (19/151)
	Immunology	55.3 (110/199)	0 (0/199)
	Materials science	30.5 (62/203)	40.9 (83/203)
	Mathematics	20 (14/70)	24.3 (17/70)
	Microbiology	61.7 (82/133)	2.26 (3/133)
	Molecular biology and genetics	69.4 (143/206)	1.46 (3/206)
	Neuroscience and behaviour	59.4 (126/212)	1.42 (3/212)
	Pharmacology/toxicology	33.3 (48/144)	0.69 (1/144)
	Physics	50.8 (91/179)	12.8 (23/179)
	Plant and animal sciences	25.5 (56/220)	9.5 (21/220)
	Psychiatry/psychology	42.7 (73/171)	0.58 (1/171)
	Social sciences, general	34 (68/200)	4 (8/200)
	Space science	62.6 (77/123)	0 (0/123)
	Cross-field	40.8 (1,017/2,493)	14.6 (364/2,493)

Source: Clarivate, Web of Science, Highly Cited Researchers 2020.

Figure 3: Highly Cited Researchers — A Comparison between the United States and China



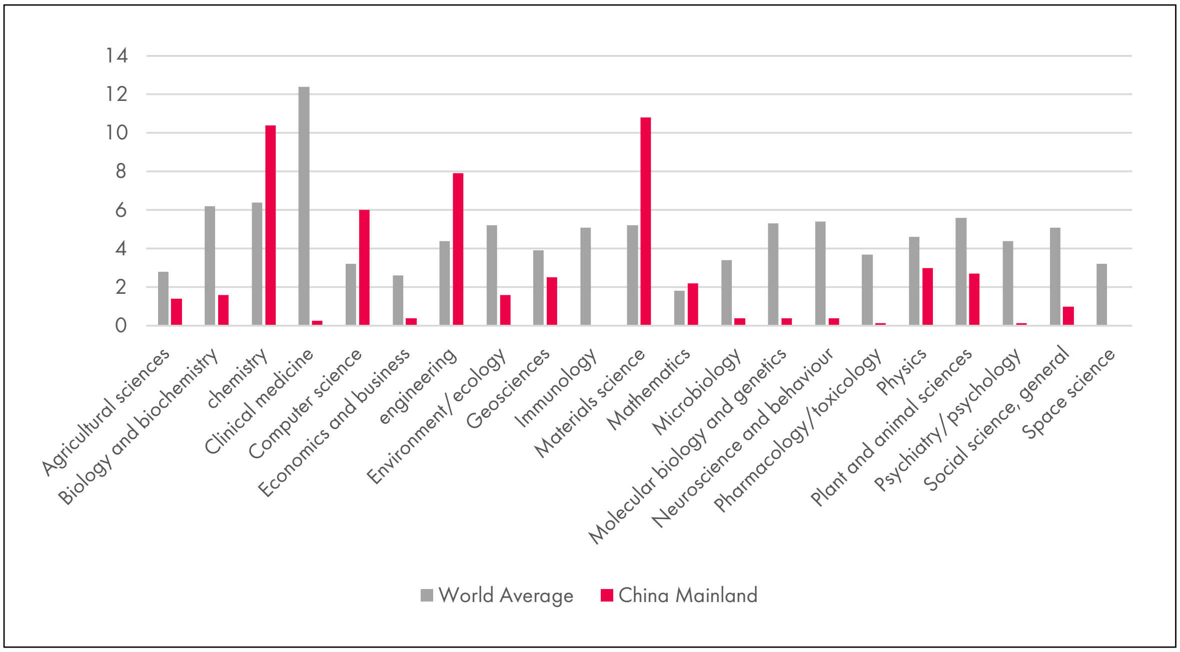
Source: Clarivate, Web of Science, Highly Cited Researchers 2020.

Table 8: Highly Cited Researchers — A Comparison between the World Average and China

Indicator		World	China
Percentage of highly cited researchers of each ESI field	Agricultural sciences	2.8	1.4
	Biology and biochemistry	6.2	1.6
	Chemistry	6.4	10.4
	Clinical medicine	12.4	0.26
	Computer science	3.2	6
	Economics and business	2.6	0.4
	Engineering	4.4	7.9
	Environment/ecology	5.2	1.6
	Geosciences	3.9	2.5
	Immunology	5.1	0
	Materials science	5.2	10.8
	Mathematics	1.8	2.2
	Microbiology	3.4	0.39
	Molecular biology and genetics	5.3	0.4
	Neuroscience and behaviour	5.4	0.4
	Pharmacology/toxicology	3.7	0.13
	Physics	4.6	3
	Plant and animal sciences	5.6	2.7
	Psychiatry/psychology	4.4	0.13
	Social sciences, general	5.1	1
	Space science	3.2	0

Source: Clarivate, Web of Science, Highly Cited Researchers 2020.

Figure 4: Highly Cited Researchers — A Comparison between the World Average and China



Source: Clarivate, Web of Science, Highly Cited Researchers 2020.

Table 9: Market Share of Domestic Chips in China

System	Device	Core Chips	Market Share of Domestic Chips
Computer system	Server	Microprocessor (MPU)	~0%
	PC	MPU	~0%
	Industrial PC	MCU	2%
General electronic system	Programmable logic device	FPGA/EPLD*	~0%
	Digital signal processor	DSP	~0%
Telecommunication equipment	Mobile communication terminal	Application processor	~18%
		Communication processor	~22%
		Embedded MPU	~0%
		Embedded DSP	~0%
	Neural network device	Neural processing unit	15%
Storage device	Semi-conductor memory	DRAM	~0%
		NAND flash	~0%
		NOR flash	~5%
Display and video system	HD/Smart TV	Image processor	10%
		Display driver	~0%

Source: Wei (2019).
Note: *EPLD stands for erasable programmable logic device.

Table 10: R&D Expenditure and Intensity of Chinese ICT and Internet Companies in 2019, in Millions of US$, unless Stated Otherwise

Rank	Enterprise	R&D Expenditure	Revenue	R&D Intensity	Notes
1	Huawei	18,852 (131,659)*	122,972	15.3%	World no. 5 R&D investor
2	Alibaba	6,085	71,985	8.45%	
3	Tencent	4,398 (30,387)	54,600 (377,289)	8.1%	
4	China Mobile	3,398 (23,481)**	107,947 (745,917)	3.15%	
5	Baidu	2,635	11,217	17.1%	
6	HiSilicon***	2,439	11,550	**21%**	No. 9 R&D investor among global IC companies
7	JD.com	2,100	82,865	2.5%	
8	ZTE	1,816 (12,548)	13,131 (90,737)	13.8%	
9	Unigroup	1,227 (8,478)	11,134 (76,938)	11%	
10	Xiaomi	1,084 (7,493)	29,789 (205,839)	3.64%	
11	SMIC	687	3,116	**22%**	
12	Hua Hong	63	933	6.77%	

Sources: 2019 annual reports from each company, unless stated otherwise. Data for Alibaba is from Alibaba Annual Report 2020, which covers data between March 2019 and March 2020.

Note: *The figures in brackets are the original numbers in millions of renminbi. The figures in US dollars are estimated based on CNY/USD average closing exchange rate in 2019, which is 6.91; **the figure is from "The Development Report on Top 500 Enterprises of China" [2020中国500强企业发展报告]; ***the data of HiSilicon is from Chip Insight (2020).

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