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Dialogue, Debate, and Discussion

Semiconductor Catch-Up Is Not Enough: Twigging the Context of China's Ambitions

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ABSTRACT The extensive narrative of growth and development of the information and communication technologies (ICTs) in China by Jiang and Murmann (2022) and the discussion of Chinese strengths and weaknesses portray the remarkable progress that China has made, especially in technology relative to advances in the basic sciences. In our response, we situate their contribution in the larger context of Chinese economic growth and the challenges it faces in transforming these accomplishments into an embedded national capability to become a leading innovation economy and thereby deliver prosperity to its enormous but aging population. The contexts for the successes and weaknesses in ICT that Jiang and Murmann (2022) describe so admirably are vital for a more comprehensive understanding of their place in the overall development of China.

KEYWORDS China, information and communication technologies (ICTs), innovation, semiconductors

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The sheer growth of China, which followed Deng Xiaoping's 1978 Economic Reforms, transformed a once impoverished country into the world's second largest economy and a powerful global competitor in a number of industrial sectors and, in particular, in commerce (information and communication technologies). It experienced the fastest most sustained economic growth in human history. However, the past may not be prologue. In the 2020s, while its ICT industries continued to prosper, overall China experienced a gradually slowing GDP growth rate consistent with predictions that the fast economic growth of middle-income economies inevitably experiences diminishing returns to infrastructure investment (Eichengreen, Park, & Shin, 2013; Prescott, 1988). Thus, while its ICT industry grew precipitously fast and innovated particularly in terms of its commerce and gaming platforms, other important sectors of the economy may be reaching their limits to growth.

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The evidence points to such a productivity slowdown. Between 2007 and 2020, the growth rate of China's GDP declined from 14.6% to 5.9% in 2019. In 2020 (the COVID-19 pandemic year), the growth rate declined to 2.9%. This cumulative decline of 8.7% suggests that China's model that led to its economic miracle may have reached its limit. If this decline continues, it may threaten China's common prosperity social contract that secures the political legitimacy of the Chinese Communist Party (CCP) and its long-term political survival. In fact, in the pursuit of common prosperity and greater income equality, the CCP has cracked down on e-commerce and social networking platforms and their billionaire entrepreneurial founder owners.

Importantly, China is being challenged by a real estate debt crisis, fall in housing sales and land purchases, double-digit declines in the output of steel and cement, and recently electricity shortages that have disrupted manufacturing. China has been coping with the economic consequences of rolling lockdowns (due to a strict, but thus far successful, zero-COVID policy, in part, enabled by advanced surveillance ICTs). How China will evaluate and respond to the challenges that it faces will be of significance not only for China but also for the rest of the world.

More consequential may be the cumulative impact of three long-term dynamics that Lewin and Witt (2022) identify as potentially undermining the Chinese development model. The first is an irreversible decline of the population that traces back to the one-child policy. This is already manifested in the rapid societal ageing and corollary prediction of a shrinking population. Second, China is already experiencing poor and decreasing returns to infrastructure capital investments and an attendant overcapacity. Third, this is the disappointing results of previous national technological upgrading initiatives (Hammer & Yusuf, 2020).

Since 2010, China has experienced a steady decline in the working-age population (World Population Review, 2022a) with total population expected to peak this decade (Powell, 2022; World Population Review, 2022b) and then decline by half by the end of this century (Vollset et al., 2020), thus, transforming China's demographic dividend into a demographic liability. The rapid aging of the population is indicated by the steady rise of the old-age dependency ratio, which is predicted to reach at least 25% by 2030, up from 8.6 in 1990 and 17.0 in 2020 (United Nations, 2019). The growing aging population is bound to increase the social welfare burden on the working-age population.

Labor costs are expected to continue to rise as the manufacturing workforce steadily shrinks. The relatively poor quality of education in rural China is already affecting the employability of the working-age population in higher value-added jobs (Rozelle & Hell, 2020) and is expected to become more critical as the value increasingly accrues to innovation and creativity. Not only are these developments likely to adversely affect GDP growth but have also contributed to increasing economic inequality which has required the CCP to introduce policy initiatives meant to rebalance common prosperity.

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The CCP and policy makers are well aware of the above realities and their potential to stall China's national aspiration to exit the middle-income trap (MIT) (Lewin, Kenney, & Murmann, 2016). The previous policies of relying on ever-increasing debt-financed infrastructure and capital investment are unlikely to reverse these trends because increasingly this investment is unproductive. The phenomenal China growth from 1978 was fueled by a national infrastructure investment. According to the OECD, in 1993 one dollar of additional GDP required an investment of about 1.5 dollars. By 2017, 5.9 dollars were needed to generate one dollar of additional GDP (OECD, 2022: 42). According to Bradley et al. (2020), of the total US$11.8 trillion of capital invested from 2015 to 2017 in Chinese companies that ranked among the world's 5,000 largest, 80% went to sectors that earned below their cost of capital. However, new infrastructure capital investment is having a diminishing impact on economic growth (Lewin & Witt, 2022). Unfortunately, immediate consequences of scaling back infrastructure spending are even greater overcapacity and excess labor in key industries such as steel, cement, aluminum, and construction machinery. New sources of growth must be developed. The ICT sector does offer one important path forward. However, the Solow productivity paradox does call this into question (Krishnan, Mischke, & Remes, 2018).

In 2015, China unveiled the Made in China 2025 (MIC 2025) initiative that was intended to upgrade and transform the huge Chinese manufacturing sector to world-class levels (i.e., tier-1 in global manufacturing). As Jiang and Murmann (2022) observe, an important part of the initiative was to catch up with the West in semiconductors and software – however, it also caused the US, in particular, to adopt policies to cut China off from key electronics technologies and exclude Chinese ICT exports, especially in communication technologies where firms such as Huawei and ZTE have developed global-class technologies. MIC 2025 was a major national initiative to redirect economic development and escape the MIT.

The MIC 2025 setback also recognized that one of the greatest challenges involved upgrading the huge and intensely competitive manufacturing sector, mostly dominated by small- and medium-sized family enterprises. According to China's Vice Chairman of the CPPCC National Economic Committee and former Minister of Industry and Information Technology, China is ranked third in the four-tier global manufacturing pyramid (*Global Times*, 2021) and will require about 30 years to achieve global tier-1 status. Key weaknesses include low innovation in manufacturing, lack of essential key technologies for significant upgrading of the manufacturing value chain (much equipment does not match global standards), and heavy dependence on imported basic components and technologies such as integrated circuits (80%), large-scale and high-quality castings, and forgings (90%), and high-end hydraulic parts and seals (100%). In short, 'Made in China 2025' revealed 'a low absorptive capacity for investments in, and adoption of, the technological capabilities crucial for achieving status of tier-1 manufacturer in global rankings' (Lewin & Witt, 2022).

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Despite successes in high-speed computing, space exploration, 5G, hypersonic missiles, high-speed trains, drones (but not in civil aviation), and other apex sectors and increasingly massive investments in technology and science (T&S), Chinese productivity growth has slowed. In terms of total factor productivity, Hammer and Yusuf (2020) conclude that it has been trending downward and is in the 1% range or less, which is unchanged since 1981 at about 40% of the US level. Recent estimates of China 2022 real growth of annual GDP are predicted to grow about 5% (Kihara, 2022). A Lowy Institute report by Rajah and Leng (2022) concludes that 'China will likely experience a substantial long-term growth slowdown owing to demographic decline, the limits to capital-intensive growth, and a gradual deceleration in productivity growth' and they predict 'annual economic growth will slow to about 3% by 2030 and 2% by 2040, while averaging 2–3% overall from now until 2050'. Despite the slowing growth rate, China will become the world's largest economy. And yet, it 'would remain far less prosperous and productive per person even by mid-century' (Rajah & Leng, 2022: 1).

Another major initiative, and perhaps the most important response to the MIC 2025 setback, was the launching, in late 2013, of the Belt and Road Initiative (BRI). It was framed as a global infrastructure development strategy and as a way of globalizing the Chinese infrastructure industries, thus, postponing the impact of a severe overcapacity in China infrastructure sector that could lead to significant levels of unemployment and restructuring. Lewin and Witt (2022) provide a detailed analysis of the antecedents and evolution of the BRI since its inception. The BRI has boosted Chinese GDP growth. Zhai (2018) predicted a 1.1% increase of GDP by 2030. A World Bank study estimated a long-term GDP gain between 9.0 and 11.2% (de Soyres, Mulabdic, Murray, Rocha, & Ruta, 2019); and Cebr, a consultancy, estimated an increase in Chinese GDP of 4.2% by 2040 (Cebr, 2019). From its launch in 2013–2020, China has invested over $80 billion in 70 partner countries (Dossani, Bouey, & Zhu, 2020), of which about 89% were awarded to Chinese contractors (Lew, Roughhead, Hillman, & Sacks, 2021). Ferdinand (2016) documented that the BRI also serves to counteract overcapacity in steel, aluminum, construction, and telecommunication infrastructure industries.

The BRI has enabled China to manage its excess infrastructure industrial capacity through internationalizing the construction sector. As Lewin and Witt (2022) discuss, the BRI served to maintain and deepen political legitimacy of the CCP. It laid the foundation for an increased dependency of BRI partner states by creating new markets for Chinese companies (Layne, 2018). Furthermore, the BRI infrastructure investments in Africa opened certain countries (e.g., Zambia) for Chinese investments requiring access to large supply of cheap labor and raw materials. There is a basis for rebuilding China's factory to the world in Africa. It also has strengthened and deepened political ties to a number of African nations.

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The BRI opens many regions around the world that are expected to experience the greatest growth in the future (e.g., Africa). Already, Chinese telecommunication firms are building wireless infrastructure throughout the developing world and also introducing internet-based applications such as TikTok and the online fast-fashion firm, Shein. Ultimately, this has the potential to advance China's foreign policy objectives relating to decoupling of China's economy from existing trade arrangements controlled by the US and international organizations such as the WTO, IMF, and World Bank. The BRI initiative seems to have successfully addressed important negative dynamics that were threatening the social legitimacy of the CCP and the mantra of common prosperity.

The designation of China as a national security threat by the US and countries aligned with it has the potential to slow economic growth, as China is denied access to key technologies. As Jiang and Murmann (2022) point out, this reduces Chinese access to cutting-edge semiconductors and related state-of-the-art manufacturing technologies and software for building them. Most likely, this will continue and extend to other capital goods and advanced materials and will sorely test China's lack of supply chain depth. Second, the US, in particular, is already restricting access by Chinese students to US universities, in particular, to STEM research and thus training-based technology transfer. Third, the US and the EU are implementing new controls on Chinese funding of joint research projects at US and EU universities. Finally, the US and its western allies are already blocking access to their markets.

CHINA RESPONDS TO THE NEW REALITIES

The CCP is cognizant that overcoming the MIT will require a redoubling of national efforts to accelerate quality improvements of manufacturing sector, deepen Chinese supply chain capabilities, and most important, increase China's participation and leadership in advancing technological innovations. This will require going beyond its dominance in online platform-based industries, such as gaming, social media, online retailing, payment systems, and block chain applications – all of which are far up in the ICT software stack. In the following sections, we explore these new efforts to break out of the MIT and achieve the national goal of an advanced economy comparable to the US, Japan, South Korea, and the EU.

Beginning in the late 1990s, China encouraged the development of a venture capital/entrepreneurship ecosystem that was concentrated in the internet and software industries. Stimulated by government policies and direct investments almost all of which were highly concentrated in the four cities, such as Beijing, Shanghai, Hangzhou, and Shenzhen. Early in his term as President, Xi Jinping favored Alibaba and Tencent, based in Hangzhou and Shenzhen, respectively, as visible engines of consumerism. Later, and simultaneously, with the renewed emphasis on common prosperity and decreasing income inequality, the CCP reined in high-tech platforms such as Alibaba (Taobao Market Place, TMALL, Alipay), ByteDance (TikTok), Tencent (Games, WeChat, WeChat.Pay), Didi, and JD.

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com. However, this also had the consequence of many western investors reconsidering investment in China.

Although it was initiated in 2019, the tilt away from consumer-internet tech, or soft tech, was formalized in 2021 with the release of the Fourteenth FYP that directed attention to investments in such areas as artificial intelligence (AI), semiconductors, industrial software, and cloud-based information technologies. *The Economist* (April 16, 2022) described it as hoping for the development of 'lots of Huaweis'. Specifically, the plan has already greatly expanded central and local governments targeted investments in AI (Hefei and Zhuzhou 8,000 + new venture registration), robotics (Wuhu, Shenyang 4,800 + new venture registrations), and internet of things (Chengdu and Zhuzhou 3,000 + new venture registrations). In these and other ICT sectors, government success in mandating winning technologies has been mixed. Of course, the 14th and 15th FYP are taking place at a time when the US government is also targeting same priorities for the US (White House, 2022).

Chinese R&D and Universities

To become an innovation nation requires massive investments in human capital. China has experienced a huge expansion of the 985/211 intiatives aimed at upgrading university research capabilities (Zhang, Patton, & Kenney, 2013). The simplest measure of this effort is that China's R&D investment is approaching that of its North Asian competitors. For example, in 2021, China allocated $441 billion to R&D (2.44% of GDP), only 0.6% less than its Asian neighbors (*Global Times*, 2022). In terms of purchasing power parity (PPP), Chinese R&D investment had almost overtaken the US. Merely increasing investment in R&D does not guarantee innovation, as building the context (Autio, Kenney, Mustar, Siegel, & Wright, 2014) and absorptive capacity (Cohen & Levinthal, 1990; Lewin, Massini, & Peters, 2020) are perhaps even more important.

To upgrade and build the human capital necessary for this massive increase in R&D expenditures, a vast cadre of specialized scientists and engineers will be required. In other words, a university system capable of preparing global-class human capital. In the 1980s, R&D was largely confined to government-funded research institutes – the most technically advanced of which were in national defense and were largely divorced from the larger economy. Universities were largely teaching institutions conducting minimal research and graduating students with scant research experience (Zhang et al., 2013). Simply put, China showed little promise of becoming a global-class T&S pace setter.

To become a technologically innovative society, it is necessary to invest in and increase the pool of researchers with advanced degrees to staff research universities, government institutes, national laboratories, and corporate R&D groups. In 2021, China had more university graduates with STEM degrees than any other nation, in line with Chinese government policy to create a globally competitive scientifically literate human capital.

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China already graduates more domestic STEM PhDs than the US, and the US National Science Foundation predicts that over the next decade China will further increase the graduation rates of advanced degree holders. The sheer number of graduates is impressive, but when it comes to exploring technological frontiers, the quantity of researchers is important but is unlikely to be as important as scientific or technology innovativeness which is more difficult to measure. Since 16% of all STEM PhD students in the US are Chinese, it is clear that Chinese undergraduate programs are matriculating some high-quality students capable of learning global-class research skills (Feldgoise & Zwetsloot, 2020). And yet, there are questions about the quality of Chinese students. For example, a large cross-national study of computer science and electrical engineering university students in China, India, Russia, and the US found that Chinese and US students were, upon entering the university, the most capable. However, upon being retested at graduation, researchers found that the test scores for the Chinese engineers not only had not improved in terms of critical thinking skills, but actually decreased (Loyalka et al., 2021).

In terms of PhD students, the measurement of quality and innovativeness is, if anything, more challenging than for undergraduates. One measure of PhD graduate quality would be university research ranking. As a measure of research quality, the Shanghai Jiaotong Academic World Research University (AWRU) shows that Chinese universities have not yet entered the global elite research universities. When the analyses are limited to the Top 500 research universities, the data suggest that China is building an increasingly broad and deep research university system. However, despite the significant improvement, even the most highly ranked Chinese universities are far below the quality of the top US and European universities. And yet, the sheer volume of R&D investment or the number of publications has not translated into increased innovation or GDP growth commensurate with the investment.

Contest for Commanding Heights of Technology and Science?

The recognition by the US government that China will become the largest consumer market in the world and that it is rapidly improving its technological capabilities in nearly every STEM field has galvanized a dramatic awakening of efforts to sever China's access to US technology. The US government is significantly increasing R&D investment and efforts to upgrade and build a US high-technology manufacturing base. Beginning under President Trump and greatly reinforced under the Biden presidency, the US has significantly increased R&D investments in technologies such as quantum computing, robotics, and AI.

The Biden administration 2023 budget signals a dramatic national investment in science and technology. It includes, for example, a massive 24% increase for the National Science Foundation. Most importantly, $880 million would

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support the newly created Directorate for Technology, Innovation, and Partnerships with a clear mandate to speed up technology transfer and adoption. Another Biden priority involves manufacturing. The National Institute of Standards and Technology funding is budgeted to more than double, increasing from $206 million to $372 million. The goal is to support both Manufacturing USA, which creates government industry–academia partnerships in key areas, and NIST's Manufacturing Extension Partnership program, which supports technology innovation for small- and medium-sized businesses. NIST is also budgeted for an extra $187 million to support standards development for key technologies, such as AI, quantum science, and advanced biotechnologies.

Given US government investments and the massive investments by the US private sector, in the form of US leading electronics firms (e.g., Google and Apple), and ICT billionaires such as Jeff Bezos, Elon Musk, Eric Schmidt, Mark Zuckerberg, and others, China may find it difficult to compete in fields such as AI, robotics, space exploration, and quantum computing that many believe are critical for future innovation and growth. The US federal government is clearly committed to respond to the Chinese challenge across the T&S leading-edge research frontiers. These initiatives enjoy wide political support reflecting the US concerns with Chinese geo-political ambitions (Petricevic & Teece, 2019; Witt, 2019).

During the last decade, there has been increasing excitement and hype about the potentials of AI and this has prompted a competition between China and the US to become the AI leader – a race that has prompted accelerated investment. In 2021, across the entire US federal government, over $6 billion was invested in AI-related R&D (Wiggers, 2021). These government funds complement massive investments by US information technology firms such as Amazon, Apple, Facebook, Google, Microsoft, IBM, and others. Moreover, in 2020, US venture capitalists (VCs) invested $42 billion, while Chinese VCs invested $17 billion (OECD, 2021). Which innovation system will be more successful in developing AI, assuming that AI will be an important technology, is uncertain. Some observers such as Lee (2018) suggest that both countries could be successful in different ways.

The increasing investments by both nations have the potential to create tremendous T&S advances. The Chinese government investments appear to be far more focused and targeted (Prud'homme & Zhang, 2019) than those of the US. This makes the contest for the commanding heights of the Technology and Science knowledge frontiers interesting. What is certain is that over the last 70 years since World War II, the US and its innovation model have not been challenged by a peer or near-peer competitor. The growing Chinese R&D investment will test the US model's ability to maintain its leadership.

DISCUSSION

In 2022, China confronts some serious challenges as it tries to overcome the MIT and, in particular, it is venturing that ICT industries are crucial for future growth.

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There are ample opportunities for China to grow. However, there are significant structural issues including a weak domestic supplier base and dependence upon high value-added imported components.

These weaknesses will be especially problematic, if the geopolitics of collaborative coexistence and finding the 'middle way' deteriorate to national enmity. As Jiang and Murmann (2022) point out, in the ICT space, the Chinese situation is curious – they can design cutting-edge semiconductors, but they cannot make them. It lacks the capability to produce the sophisticated manufacturing technologies for producing cutting-edge semiconductors and producing the ultrapure gases, silicon boules, and photoresists that are necessary to build advanced leading-edge semiconductors. Without these inputs, a fabrication facility produces scrap. Paradoxically, China, the manufacturing superpower, can design a cutting-edge semiconductor, and it cannot make them. This becomes a problem when the inputs are not accessible available from abroad.

Of course, this is also an opportunity for China. Significant advances in the robustness of the supplier base could provide significant domestic productivity growth. Similarly, enduring and growing R&D investments seem to have had some success in terms of increased patenting, especially in the ICT sectors, but there has been less success in innovating new products that will be adopted outside of China. However, as Jiang and Murmann (2022) point out, an increasing number of Chinese ICT products (5G wireless technologies) and ICT-enabled services are global class. Most interestingly, the two greatest global internet successes of the last five years, TikTok and Shein, originated from China.

For China, pivoting to a new national innovation model that values deep, extremely specialized manufacturing skills, what might be thought of a PhD in physics-level craft skills will be very challenging, as it will require reinventing the current innovation model, which values 'good-enough' products for a mass market. China has developed important technological strengths in electric vehicles, drones, batteries, AI, and online services. And yet, as Jiang and Murmann (2022) recognize, China will have to deepen its capabilities in electronics materials and machinery for building semiconductors – the technology that drives all of these products. This is likely to require greater new to the world – and yet also highly specialized incremental – innovation capabilities necessary to transform the manufacturing sector to global tier one – none of which will be easy especially if China and the US inadvertently or by design end up in a global contest for T&S leadership.

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