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The Question of Comparative Advantage in Artificial Intelligence

Enduring Strengths and Emerging Challenges for the United States

CSET Policy Brief

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Who is leading in artificial intelligence (AI) and machine learning (ML)? How should leadership in AI be evaluated or measured? Which aspects of comparative advantage in AI possess the greatest strategic importance? These questions are critical to address as nations around the world embrace the potential of AI through a range of policy initiatives.

None of these questions yields easy answers. Leadership and comparative advantage in artificial intelligence are difficult concepts to measure. There is no one formula to determine who may be "winning" or will be leading in the long term across various aspects of the field. On some fronts, the United States remains in a relatively favorable position in AI, but its centrality in the ecosystem should not be assumed or taken for granted. The scope and scale of Chinese research in AI are rapidly increasing. Careful evaluation of relative strengths and weaknesses can generate more useful and actionable insights to assess policy choices.

The United States possesses distinct strengths in top AI talent and research. U.S. comparative advantages reflect its dynamic innovation ecosystem and capabilities in semiconductors. Such advantages can take decades to build and appear to be difficult to buy or quickly duplicate. While the People's Republic of China (PRC) excels in commercial applications, American prominence in foundational elements and enablers of AI, including hardware, talent, and basic research, are important. Despite considerable progress in AI research in recent years, breakthroughs rarely occur in single moments. The latest advances are the product of decades of refinements to deep learning's conceptual architecture. Future progress in AI will look less like the space race and instead require dynamic research environments that create and sustain synergies among government, industry, and academia.[1]

China's future trajectory in AI remains uncertain. The development of AI in China will depend on the evolution of its overall environment for innovation. The Chinese government is devoting billions to AI through R&D initiatives and government guidance funds, which are stimulating private investments and expenditures by leading companies. These investments may prove effective despite likely inefficiencies in allocation, but also run the risk of introducing

new distortions in the market through the surge in funding. The inflated valuations of China's "AI unicorns" could be a symptom of an "AI bubble." Looking ahead, the state of AI in China will be hard to disentangle from the broader macroeconomic environment.

This policy brief examines a number of potential strengths for the United States and PRC in AI. Our analysis identifies both areas of U.S. comparative advantage and those where it risks falling behind a rising China.[2] Success in AI research, development, and applications will be shaped by the three building blocks of AI: hardware (e.g. AI chips that enable the underlying computing capabilities), the availability of data, and continued advances in algorithms. On the policy and commercial fronts, enablers of AI development include the workforce of AI researchers and engineers, availability of funding for basic and applied research, and private sector investments. Overall, competitiveness in AI will reflect the dynamism of national innovation ecosystems, which we consider in terms of educational opportunities, access to global talent through immigration, and networks of research collaboration.[3] The creation of norms and frameworks for governance of AI are equally imperative, while the application of AI to enable a range of military capabilities could affect the future balance of power among nations.[4]

The state of AI as a field is dynamic and rapidly evolving. In summary, this brief can draw some initial conclusions about the state of play between the United States and China.

Core Elements of AI Capabilities

- **Proficiency in semiconductors to create AI chips and hardware**: American leadership in semiconductors is a major strength in the near term, but Chinese initiatives to catch up and develop indigenous capabilities will present a challenge in the long term. The United States needs to keep pace with new directions in the development of semiconductors, particularly AI chips.
- **Access to sizable amounts of data with depth and diversity**: Neither the United States nor the PRC possesses a definitive or generalized advantage in data. Relative strengths can only be assessed for specific sectors and applications or for particular enterprises. The availability of data may be less important than policy and bureaucratic initiatives that make data more available and

facilitate its integration.[5] The impact of long-term research that enables AI/ML to progress beyond the current reliance on massive amounts of data, such as the use of synthetic data, will be a critical trend to monitor and exploit.

- **Advances in research and underlying algorithms**: Since AI as a field remains fairly open and inclined toward open-source toolkits and platforms, advances in algorithms are unlikely to provide any durable advantage to the United States or China. However, the influence of policy choices, such as decisions about the allocation of research funding to academia, could contribute to divergence or specialization in different countries.

Critical Enablers of AI Development

- **Workforce of AI researchers and engineers**: The United States possesses notable strengths in its current workforce, particularly highly skilled AI researchers. However, China's educational initiatives and recruitment of AI talent appear to be scaling up at a pace the United States may not be able to match in the years to come. Immigration will be all the more critical to sustaining American competitiveness.
- **Funding for basic and applied research in AI**: The United States has been slow to increase funding for AI R&D relative to its potential and the opportunities. Present trends show that China is catching up in overall support for R&D. Despite current deficiencies in basic research, PRC S&T plans indicate that Chinese leaders intend to ramp up investments for research from the central and local governments.
- **Commercial investments and applications**: The U.S. venture capital ecosystem is more sizable and dynamic, but Chinese AI start-ups attract funding comparable to or exceeding that of their U.S. counterparts. Chinese government mechanisms, such as guidance funds, seek to combine state support with the proficiency and resources of a growing venture capital ecosystem.

Systemic Drivers of National Competitiveness in Science and Technology

- **Dynamism of economy and innovation ecosystem**: The American innovation ecosystem has been a key enabler of the U.S. lead in S&T,

but its dynamism will require sustained investments. China's innovation ecosystem is overcoming long-standing weaknesses to achieve progress in indigenous innovation.

- **Strength of education system and leading universities**: The American education system has been a traditional strength, but suffers from critical weaknesses, particularly in primary and secondary education. The failure of U.S. STEM education and of technology companies to embrace diversity and inclusion has further undermined the creation of a pipeline of trained scientists and engineers. Meanwhile, the Chinese education system faces major disparities of opportunity between urban and rural schools. Chinese universities remain uneven in the quality of education provided, but are moving up the rankings internationally in terms of their strength in research and education.
- **Access to global talent through openness to skilled immigration**: Immigration has been a critical determinant of American advantage that is now imperiled by adverse trends in politics and restrictive policies. China's demographic advantages in the near term will likely become a liability because of its aging population, and it may struggle to attract immigrants.
- **Centrality in networks of research collaboration**: The United States is in a more favorable position when it is able to leverage the benefits of collaboration with allies and partners. However, China is becoming more central in global science, including pursuing new collaborations through the Belt and Road Initiative.

Core Elements of AI Capabilities

1. Strength in Semiconductors for AI Chips and Hardware

U.S. Strengths and Weaknesses

The United States maintains considerable strengths in the research, design, and manufacturing of advanced semiconductors, which constitute the basic building blocks of all major advances in modern computing, including in AI. In 2018, U.S. semiconductor companies commanded nearly half of the $469 billion global semiconductor market.[6] This market share means that U.S.

companies have a first-mover advantage in harnessing the advanced silicon powering innovation.

The U.S. advantage extends not only to semiconductors, but also to the equipment used to manufacture them. Almost all semiconductor manufacturing equipment (SME) firms, such as Applied Materials and Lam Research, are from the United States, the Netherlands, and Japan, and nearly all high-end AI chips are fabricated by firms headquartered in Taiwan, the United States, and South Korea.[7] Given the extreme costs of high-end fabs and SME, the field has narrowed to a select few players in the United States or allied nations.

This dynamic creates potential chokepoints throughout the semiconductor supply chain that the United States could leverage against strategic competitors.[8] In October 2018, the United States sanctioned Chinese chip national champion Fujian Jinhua, starving the company of vital equipment and virtually forcing it to halt production.[9] The prevalence of PRC intellectual property theft and technology transfer tactics in this sector indicates the degree to which Chinese challengers have struggled to compete, despite billions in spending to date.[10]

In the near term, the United States has the option and possesses the leverage to hamper the growth of China's tech industry through exploiting chokepoints in the semiconductor supply chain. Yet the collateral damage from an aggressive containment strategy of Chinese technology capabilities to U.S. companies, which depend on the Chinese market for revenue, would be considerable. Longer term, an overuse of export controls may advantage foreign competitors or lead U.S. companies to move their operations abroad.[11] For these reasons, leveraging U.S. advantages in semiconductors through export controls requires policymakers to calibrate policies and balance the risks and rewards of chokepoints.

Even as the United States maintains its lead in semiconductors, cutting-edge fabrication increasingly happens elsewhere—mainly in East Asia. The rise of globalized supply chains and the "fabless" business model allow U.S. semiconductor companies to focus on chip design and outsource production to foundries like Taiwan Semiconductor Manufacturing Company (TSMC), the world's largest dedicated foundry for semiconductors. As a result, U.S. control over the flow of cutting-edge chips is weakening.[12] Chinese companies like Huawei can also outsource chip production to TSMC and

other leading-edge foundries, allowing them to compete with U.S. chip companies and evade U.S export controls.[13] In response, the U.S. Department of Commerce has considered reducing the threshold of "U.S. content" that subjects U.S. re-exports to a licensing requirement from 25 percent to 10 percent, a potential measure that has provoked concern among industry stakeholders. Reshoring this manufacturing capacity and reasserting U.S. control over semiconductor production, while not impossible, would be difficult and require concerted effort on the part of government and industry.

PRC Strengths and Weaknesses

Recognizing this risk, China has attempted to build domestic capacity to manufacture semiconductors. Its progress has been slow because of the immense complexity involved in designing and manufacturing semiconductors; each stage of the supply chain requires unique knowhow and specialized expertise that take time to master. China's leadership has elevated semiconductors as a priority and will reportedly invest over $100 billion within the next decade to close the gap with the United States.[14] Since Chinese companies like Huawei and ZTE were added to the Department of Commerce's Entity List,[15] China's determination to pursue indigenous innovation has only intensified.[16]

In cases where the United States has stymied Chinese advances with unilateral export controls but substitute options remain available, China has typically managed to find workarounds or substitute components within a short timeframe.[17] The challenge will be for China to replicate core innovations in semiconductor technology where no comparable substitute exists.

China's model of development through state subsidies appears ill-suited for the semiconductor industry, which is fast moving and requires both business acumen and sizable technical expertise.[18] Nearly 20 years after PRC science and technology leaders set out to develop a competitor to the x86 processor, Chinese alternatives remain limited and significantly behind U.S. counterparts. State-led pushes in the 1990s to establish a foothold in the chip fabrication market failed to produce commercially viable firms capable of keeping up with foreign leaders. China's most successful fab, the Semiconductor Manufacturing International Corporation (SMIC), kept PRC's S&T officials at arm's length during its early development.[19] The current state drive, led by the

National Integrated Circuit Fund, attempts to learn from prior mistakes and introduces more market mechanisms than in the past. However, many experts are skeptical that this state-led push will be sufficient to wean China off foreign chips.[20]

Regardless of the Chinese model's efficiency, the reality is that China is building its manufacturing capacity to compete in semiconductors as the United States loses indigenous capability and outsources semiconductor manufacturing to foundries elsewhere.[21] Technological trends may also play out in China's favor. As Moore's Law reaches its end, squeezing additional computing power out of chips will require new materials and specialized AI chip architectures.[22] The United States enjoys a dominant market share in leading-edge GPU (Graphics Processing Units) and FPGA (Field Programmable Gate Array) design, as well as many of the top AI-relevant ASICs (Application Specific Integrated Circuits). For the time being, China's leading AI chip designs often incorporate U.S. and allied designs. Yet as technological progress slows and evolves, China may have an easier time catching up.

Chinese players are starting to break into the AI chip space on some fronts. China's AI chip unicorns Cambricon and Horizon Robotics, for example, have attained multi-billion-dollar valuations within just a few years.[23] Huawei has launched its own AI chip, Ascend 910, designed to process efficiently the massive amounts of data often required to train algorithms.[24] Alibaba has also created a new AI chip, known as the Hanguang 800, which it claims possesses the computing capabilities of 10 GPUs.[25] Alibaba's chip subsidiary Pingtouge (平头哥) open-sourced its microcontroller design platform on GitHub in order to make chip design more accessible.[26] So far, however, PRC AI chips have primarily achieved successes in "inference," the process of running existing neural networks; the process of training continues to rely primarily on GPUs produced by NVIDIA.[27] Whether Chinese companies like Huawei can compete with NVIDIA in the AI training space remains to be seen.

2. Quantity, Quality and Diversity of Data

U.S. Strengths and Weaknesses

The United States and its allies benefit from the geography of the internet and the fact that most fiber-optic cables run from or terminate in U.S. and allied territories. The United States benefits, as well, from greater cloud storage capacity, widespread use of business analytics software, and access to business-specific data, which can be valuable for training machine learning systems. The U.S. government has launched initiatives to make data more available and improve accountability, an objective of the 2019 Executive Order on Maintaining American Leadership in AI.[28]

Beyond the quantity of data, the quality and diversity of data are important determinants of its value in AI/ML. The most valuable American tech companies gain the bulk of their revenue outside the United States; by contrast, Chinese counterparts gain nearly all of their revenue from the Chinese market. U.S. tech companies therefore have as many or more users of different nationalities than comparable Chinese companies.[29] Companies with a greater international presence may also enjoy a comparative advantage because of their capacity to access more diverse data. However, the relative dominance of major technology companies, which command a significant proportion of data, may tilt the playing field. As scholar Tim Wu observes in his account of the origins and evolution of the American information industry, "History shows a typical progression of information technologies: From somebody's hobby to somebody's industry; from jury-rigged contraption to slick production marvel; from a freely accessible channel to one strictly controlled by a single corporation or cartel."[30] The tendency toward consolidation by American technology companies with established advantages could impede innovation in the long term, which has provoked debates on new directions in antitrust.[31]

As for militarily relevant data, the United States benefits from an array of remote sensors and collection platforms with global reach. These platforms generate more data, in more locations, with greater precision than comparable platforms of near-peer competitors. By some accounts, the U.S. military has collected more granular information on the forces of potential adversaries than on its own forces.[32] The U.S. government may benefit from more diverse and higher quality data in some use cases, but its ability to access that data, particularly that of commercial enterprises, is often limited. Much of the data the U.S. military collects is siloed, poorly integrated, or in an unusable form. This "dirty data" presents a serious challenge.[33] Because of bureaucratic politics, reliance on legacy software and systems, and a lack of enabling infrastructure for cleaning and integrating data, policymakers often

lack access to high quality and labeled data that can be widely shared and leveraged.

PRC Strengths and Weaknesses

By one account, China is on track to possess as much as 30 percent of the world's data by 2030.[34] Such crude estimates tend to be limited, making a more rigorous examination of the state of data in China essential.[35] China enjoys access to data from its more than 800 million mobile internet users, contributing to Chinese strengths in AI applications like ecommerce. Chinese super-apps such as WeChat collect data uniquely granular in coverage, and Chinese technology companies are integrating AI to capitalize on that data.[36]

At the same time, new policies and regulations are addressing issues of data privacy and protection in response to public concerns and cyber security incidents.[37] The ambiguity of these policies can impede both Chinese and foreign companies.[38] For the Chinese government, the integration of datasets across enterprises and levels of government remains challenging, and big data is the focus of a number of plans and policy initiatives.

The Chinese government seeks to open up public data in order to promote AI industry. For instance, an initial work plan in Beijing aims to overcome current shortcomings through a municipal data resource network enabling public applications, including in financial services, healthcare, and autonomous driving.[39] China's national strategy for military-civil fusion encompasses an integrated approach to managing data resources in such tasks as national defense mobilization.[40]

China's AI policy and research communities may also possess an asymmetric information advantage: Chinese AI experts track U.S. AI developments closely, translating and analyzing key research and strategies in the United States and worldwide. By contrast, the community of U.S. AI experts who study and translate Chinese AI developments is relatively small.[41]

3. Advances in Research and Algorithms

U.S. Strengths and Weaknesses

By most estimates, the United States commands the preponderance of highly cited research in AI.[42] It continues to lead China in AI citations, but this lead is

shrinking.[43] In the past couple of years, the majority of algorithms have been discovered and pioneered by U.S.-owned companies. For instance, DeepMind pioneered unique advances in AI reinforcement learning through AlphaZero by enabling learning based entirely on "self-play" with no actual data involved.[44] AI has also developed the capability to beat humans in poker.[45]

In addition to these advantages, American companies have developed the primary toolkits and software frameworks—such as TensorFlow, Pytorch, and Caffe—commonly employed in AI research. They remain far more dominant than their nascent Chinese equivalents.[46] The prominence of these platforms contributes to the centrality of American leadership in artificial intelligence, including in the accumulation of data.

PRC Strengths and Weaknesses

China has emerged as a global powerhouse in AI. An evaluation of AI paper trends from the Allen Institute for Artificial Intelligence estimates that "China is poised to overtake the US in the most-cited 50% of papers this year, in the most-cited 10% of papers next year, and in the 1% of most-cited papers by 2025."[47] As of 2018, China also commanded a significant proportion of global scientific and engineering publications with a share of 21 percent relative to 17 percent for the United States.[48] The strength of Chinese research varies across different subfields of AI, however, and the rates of in-country versus external citation are disproportionate. As of mid-2019, China ranked first in the world with more than 280,000 patent applications,[49] and Chinese institutions were prominent in deep learning patenting.[50] Yet these quantitative indicators can be limited or even misleading, and the influence of state policy, such as financial incentives for publications, can distort advances.

Chinese companies have emerged as serious contenders in AI, rivaling or arguably surpassing U.S. AI companies. Several leading Chinese companies have been branded as China's "national team" in AI, including Baidu, Alibaba, Tencent, and Sensetime. Chinese start-ups and tech giants are particularly strong in applications including facial recognition and natural language processing.[51] For instance, in June 2018, a team from the Chinese People's Liberation Army National University of Defense Technology was at the top of a competition organized by Apple and Google for "robust vision."[52] Baidu's advances in natural language processing, particularly ERNIE (Enhanced Representation through Knowledge Integration),[53] have

overtaken most competitors and achieved the highest score to date in one assessment.[54]

By a range of metrics, China's research in AI has become increasingly prominent in terms of quality. For instance, its participation in leading international conferences has rapidly increased, drawing closer to parity with the United States.[55] The 2017 annual meeting of the Association of the Advancement of Artificial Intelligence (AAAI) marked a milestone, involving a nearly equal number of accepted papers by researchers from China and the United States respectively.[56] Since then, the representation of Chinese researchers at top conferences, including the International Joint Conferences on Artificial Intelligence (IJCAI) and the Conference on Neural Information Processing Systems (NeurIPS), continues to rise.

Critical Enablers of AI Development

4. AI Workforce and Talent Cultivation

U.S. Strengths and Weaknesses

Measuring the AI workforce is challenging. As the 2019 AI Index notes, "Traditional statistics and labor force surveys do not yet include AI and related occupations. Thus, online jobs platforms function as proxy indicators to assess the evolution and growth in AI labor market indicators, and largely demonstrate the demand side of labor market outcomes."[57]

The United States enjoys a significant advantage in talent, drawing AI researchers with its world-class universities and companies, higher standards of living, relatively higher compensation, and commitment to human rights, liberty, equality, and openness. It remains dependent on foreign-born talent. The majority of computer scientists and electrical engineers employed in the United States are foreign-born, and the figure rises to roughly two-thirds of those employed in Silicon Valley.[58] As for the future AI workforce, more than two-thirds of graduate students in computer science and electrical engineering are foreign-born, while the domestic pool of AI graduate students has remained relatively flat since the early 1990s.[59]

The demand for AI talent in the United States exceeds the supply for many reasons. These factors include burdensome student debt and a lack of

diversity and investment in STEM education at all levels. With lucrative opportunities in the private sector, faculty shortages at the graduate level are becoming especially problematic for PhD programs. For the U.S. military and government, particular difficulties have arisen because of inadequate mechanisms for recruiting and retaining AI talent. At the same time as U.S. immigration policies grow more restrictive, international competition for AI talent is rising.[60]

PRC Strengths and Weaknesses

Talent remains a significant bottleneck, which Chinese policymakers recognize and seek to address through new policy initiatives. China produces more science and engineering graduates than the United States, though the quality of their education may not be necessarily comparable.[61]

To date, a high proportion of Chinese graduates in AI have opted to work overseas rather than in China or with Chinese research institutions. Some recent examples and anecdotes, however, suggest a number of top Chinese scientists are starting to return, such as Jia Yangqing's departure from Facebook to join Alibaba's DAMO Academy.[62] Moreover, a significant proportion of China's workforce in the field has prior experience abroad, either studying (24.2 percent) or working in a foreign university or company (19.8 percent).[63] It is worth underscoring there is not yet a clear trend toward more Chinese graduate students returning to China, relative to the proportion opting to remain in the United States.[64]

While estimates vary, AI talent in China is sizable and growing. As of late 2017, China had an estimated 18,232 individuals in its AI talent pool, second to the United States' 28,536, according to a study from Tsinghua University.[65] With regard to "top" AI talent, measured in terms of the H-Index, China fared less well, ranking only 8th in the world, with 977 individuals relative to 5,518 for the United States.[66] Moreover, a high proportion of AI graduates and researchers from Chinese universities have been leaving China to date.[67] This limited talent pool is concentrated in major cities, such that smaller cities and more rural provinces may struggle to attract adequate expertise despite the optimistic ambitions often expressed in their AI plans.

The Ministry of Education's "AI Innovation Action Plan for Institutions of Higher Learning" (高等学校人工智能创新行动计划), released in April

2018, calls for Chinese universities to become "core forces for the construction of major global AI innovation centers" by 2030.[68] To bolster its AI talent training system, China seeks to improve the discipline's structure, strengthen professional development, improve the construction of teaching materials, enhance personnel training, launch universal education in AI, support innovation and entrepreneurship, and expand international exchanges and cooperation. China aims to establish at least 50 AI academic and research institutes, while also pioneering an interdisciplinary "AI+" approach. As of mid-2019, 196 universities in China had reportedly established a big data and data science major, 101 had established programs in robotic engineering, and 96 had introduced the new major of intelligent science and technology.[69]

5. Funding for Basic and Applied Research in AI

U.S. Strengths and Weaknesses

The United States still leads the world in R&D spending.[70] While this lead is narrowing relative to China, the United States benefits from a network of allies and partners that collectively account for an estimated two-thirds of global R&D spending, possessing comparative advantages and niche capabilities.[71]

The history of postwar U.S. innovation suggests a plurality of models for stimulating cutting-edge research and development. The United States can harness the bottom-up creativity and freedom of the private sector with federal support for long-term investments in basic and applied research, greater transparency, and a strong intellectual property system.

However, there are reasons for concern about the possibility of an innovation deficit. The U.S. government has sustained only modest increases in AI R&D in recent years.[72] As the National Security Commission on Artificial Intelligence notes in its interim report, "Requested FY 2020 federal funding for core AI research outside the defense sector grew by less than 2 percent from estimated FY 2019 levels. Over the past five years, federal R&D funding for computer science (which includes AI) increased by 12.7 percent, barely sustaining a field in which tenure track positions grew by 118 percent over the same period."[73]

The scope and scale of research funding has failed to keep pace with the opportunities and challenges of today's emerging technologies.[74] American innovation remains relatively concentrated in a limited number of high-tech clusters, while other locales with favorable preconditions have not yet emerged as successful.[75] The networks so critical to the success of American innovation have frayed, as the once highly productive relationship between state support and scientific advancement has attenuated. The profile of the federal government as a primary funder and enabler of innovation has declined and many private sector actors have adopted a go-it-alone mentality toward innovation. Over the long-term, these trends, if not reversed, could undermine the strength of U.S. R&D in emerging technologies.

PRC Strengths and Weaknesses

Since 1991, China increased R&D spending by an estimated 30-fold and intends to continue ramping up funding.[76] Today, it is second only to the United States in total funding of R&D. In 2018, PRC R&D funding reached nearly 2 trillion RMB, or about $292 billion, and the intensity of R&D spending relative to GDP increased to 2.19 percent.[77] For 2019, R&D was set to 2.5 percent of GDP.[78] PRC funding for basic research has remained a smaller share, leading to calls for greater investments in basic research.[79] Robust state support for research from both the central and local governments will facilitate the dynamism of China's AI research. Although central funding for basic research is limited, there are plans to increase it,[80] and a high proportion of funding is disbursed through local governments for both research and applications.[81]

The history of state-supported AI research in China dates to the 1980s, contemporaneous with and in response to the U.S. Strategic Computing Initiative and Japan's program for Fifth-Generation Computer Systems. As of the late 1980s, the 863 Plan incorporated major projects involving intelligent robotics, intelligent computing, and intelligent information processing.[82] In September 1990, the Ministry of Science and Technology (MOST) approved the "Outline of the Development Plan for '863/306'," which funded research on intelligent computing for decades to come.[83] Launched in 1997, the National Key Basic Research and Development Plan/Program (国家重点基础研究发展计划, "973 Plan") also included plans and policies involving semiconductors.[84] Replacing and incorporating these prior initiatives, the National Key R&D Plan has launched major projects in

intelligent robotics and transformative technologies, which will receive 2.93 billion RMB or $421 million in 2020.[85]

The National Medium- and Long- Term Science and Technology Development Plan Outline (2006-2020) (国家中长期科学和技术发展规划纲要) provided a more cohesive agenda for innovation with the goal of China becoming an "innovation-oriented country" by 2020.[86] This plan emphasized new categories of information technology, such as intelligent sensing, ad hoc networks, and virtual reality technology, as well as intelligent and other advanced materials. It is noteworthy that PRC research in AI started to ramp up within that time frame.[87] When this plan is updated in its next iteration for 2021-2035, AI will likely be positioned as a major focus.[88]

Chinese leaders at the highest levels consider AI a "strategic technology."[89] According to the New Generation AI Development Plan, China aspires to develop a $21.7 billion AI industry by 2020 and lead the world in AI by 2030. The 2020 benchmark would represent "a tenfold increase of the AI industry" over the 2018 to 2020 period, underscoring China's ambitions.[90] The "New Generation Artificial Intelligence Development Plan" and the "Three-Year Action Plan for Promoting Development of a New Generation Artificial Intelligence Industry" underscore China's intent to leverage AI to enhance and upgrade its economy. Chinese leaders seek to achieve this by building up a domestic AI industry and integrating it with the real economy, while promoting indigenous innovation of "key and core" (核心关键) technologies to reduce external dependence on foreign technologies.[91]

The Chinese government continues to launch new funds and initiatives in basic research. The National Key Research and Development Plan funds a series of "key projects" (重点专项) on AI-related research, including big data and intelligent robotics.[92] In October 2017, the National Development and Reform Commission (NDRC) launched the Artificial Intelligence Innovation and Development Mega-Project (人工智能创新发展重大工程),[93] which will fund research on deep learning intelligent chips, open-source platforms for deep learning applications, and highly reliable intelligent unmanned systems.[94] In January 2018, the National Development and Reform Commission announced nearly 50 AI and "Internet Plus" projects it would fund, including CAS Sugon's platform for deep learning applications, Cambricon's project on a cloud deep learning processor chip, and Zhongdun Security's high accuracy facial recognition system.[95]

It is too soon to evaluate the success of these initiatives. PRC programs will support interdisciplinary research at the nexus of AI with brain science, biotechnology, and even quantum information.[96] The government is developing its AI ecosystem and making significant investments in AI ventures, including through "government guidance funds" amounting to estimates in the tens of billions of dollars.[97] These investment mechanisms deserve continued analysis.[98] According to the fourth plenum work report, Chinese leaders aim to "intensify investments in basic research; perfect the institutional mechanisms to encourage and support basic research and original innovation."[99]

6. Commercial Investments and Applications

U.S. Strengths and Weaknesses

America's commercial ecosystem in AI is vibrant and growing. In 2013, AI startups in the United States attracted $1.1 billion in venture capital funding. By 2018, VC funding for AI startups in the United States increased eight-fold to $9.3 billion.[100] While mostly concentrated in California, New York, and Massachusetts, AI startups across 42 states are attracting a broad range of support and investment, including 16 startups with more than $100 million in equity funding and nine unicorn startups in areas such as robotic process automation software, autonomous vehicles, and healthcare.[101] As of September 2019, AI startups had raised an estimated $6.6 billion in VC funding relative to $6.7 billion in VC funding for startups internationally.[102]

The scope and scale of commercial investment in AI inverts a paradigm in which the U.S. federal government traditionally provided the majority of investment in basic research for emerging technologies, particularly those technologies with military applications.[103] This inversion has created friction between the U.S. government and commercial enterprises. Despite the relative advantages of the U.S. tech ecosystem, the Department of Defense still struggles to tap into the success of start-ups and emerging commercial enterprises.[104] There is not only a gap in culture, but also a critical issue of incentives. Legal and regulatory burdens and questions of transparency, business practices, outlook, and speed pose obstacles for closer partnership between the federal government and commercial sector in AI.

Increasingly, the Department of Defense works with a diverse array of suppliers, including early stage, VC-backed AI startups. The Joint Artificial

Intelligence Center and the Defense Innovation Board are spearheading a range of initiatives to engage private sector innovation, but challenges remain. Large programs of record continue to favor traditional players.[105] Acquisition processes need to be reformed and adapted to the speed at which emerging technologies are designed, developed, and deployed. And the Department of Defense will need to continue to explore ways to incentivize prime contractors to partner with technology startups and incorporate nontraditional players into large programs of record.[106]

PRC Strengths and Weaknesses

China's commercial ecosystem in AI has proven highly dynamic and competitive. In 2017, China's AI start-ups reportedly received a record financing of about $7.3 billion,[107] amounting to 48 percent of the world's total AI funding.[108] To date, financing has been concentrated in the disciplines of natural language processing and intelligent robotics, in which Chinese start-ups appear to have special proficiency.[109] In 2018, total financing for AI in China reportedly more than doubled relative to 2017, reaching 383.2 billion RMB ($55.8 billion) across 577 companies, again first in the world.[110] In that year, overall venture capital financing in China also reached a record high.[111] For 2019, AI funding decreased slightly, potentially indicating the start of a recalibration of expectations and enthusiasm.[112]

The emerging strength of China's commercial enterprises will be critical. Baidu, Alibaba, Tencent, iFlytek, and Sensetime, among others, have been designated as the "national team" of champions in AI. These enterprises promote the development of open innovation platforms.[113] Baidu is responsible for autonomous vehicles, Alibaba Cloud (Aliyun) for smart cities, Tencent for medical imaging, and iFlytek for smart voice.[114] The platforms will be piloted in the Xiong'an New Area, a development southwest of Beijing intended to become a futuristic demonstration of Chinese innovation, showcasing AI technologies and applications. The companies also contribute significantly to the ecosystem through investing in other start-ups.[115]

Systemic Drivers of Competitiveness

7. Vitality and Dynamism of Economy and Innovation Ecosystem

U.S. Strengths and Weaknesses

The United States nurtures an open, decentralized economy. It protects individual and property rights, and it is committed to the rule of law. America has benefited from the relative robustness of its institutions of governance. However, we lack good metrics or evidence that U.S. markets are more competitive than Chinese markets. The United States has seen large increases in monopolization and profit margin in multiple industries in recent decades, to an extent that may undermine long-term competitiveness.[116]

The United States also benefits from social networks that connect its science and technology labor force with the private sector. Academic research on national innovation indicates that these networks contribute to long-term technological advances and science and technology competitiveness.[117] Dynamic ecosystems, such as Silicon Valley and the tech hubs of Route 128 in Massachusetts, epitomize the strengths of this system. America's innovation advantage has emerged under unique historical and institutional conditions that have proven difficult to replicate elsewhere.[118] The confluence of labor and capital can promote technological advances and enable entrepreneurship, which requires a tolerance for risk and failure. Even more important is the ability to harness labor and capital around fresh ideas and innovative thinking.[119] The U.S. research ecosystem has benefited not only from talented entrepreneurs, but also from a state that pursues policies that are highly entrepreneurial.[120]

The United States remains a hub of innovation, but the U.S. government cannot directly leverage the fruits of that innovation. Rather, it must build bridges and partner with academics and companies that may have divergent or conflicting priorities. Considering these unique characteristics of the U.S. innovation ecosystem, the United States benefits from an open international environment that plays to its strengths. By contrast, an environment in which nations turn inward, admit fewer foreign researchers, and compete via appointed national champions seems to play to China's strengths.

In the United States, it has become more challenging for entrepreneurs to enter into high-risk sectors, such as the life sciences and biomedical applications. Although venture capital is readily available, some successful start-ups whose technologies are innovative but do not possess near-term viability from a commercial standpoint lack sufficient investment to bring their products to market.[121]

PRC Strengths and Weaknesses

China's approach to innovation combines state support with market mechanisms, but it suffers from several weaknesses. These include inefficient planning and allocation of capital, weak arbitration between government and business, insufficient protections for IP, and information bottlenecks resulting from closed decision-making processes. The limits of China's top-down approach to innovation are evident in lackluster results to date from its semiconductor fund, preferential funding for state-owned companies in the management of S&T projects, and the use of party committees and "special management shares" to increase party control over the tech sector.[122]

China has been less committed to individual and property rights, but is starting to implement reforms, mindful of the necessity of IP protection to enable and promote innovation.[123] The Chinese government has studied and sought to replicate innovation ecosystems comparable to prominent American counterparts. Only a small proportion of the cities and tech parks in China that aspire to become "China's Silicon Valley" are likely to succeed.

The Party-state sees data and artificial intelligence as important instruments for governance. Despite a heavy-handed approach, the creation of tech parks and campaigns to promote "mass innovation and mass entrepreneurship" is starting to yield some dividends.[124] For instance, Beijing's Zhongguancunhas has emerged as a major center for AI start-ups and research. As of early 2019, there were an estimated 745 "AI enterprises" in China, according to the MOST's research institute for AI strategic research, ranking second and amounting to 21.67 percent of the total number of such enterprises in the world.[125] China's model of innovation can be highly inefficient, given the often-poor allocation of investment, but it could also prove effective in the long term. In particular, the combination of state support and the dynamic, fiercely competitive commercial ecosystem in China may create and accelerate synergies.

In AI research, China has lagged behind in the development of open-source toolkits and software, resulting in dependence on foreign—typically U.S.—frameworks for AI development.[126] The government has established a growing number of dedicated open innovation platforms that involve prominent commercial enterprises.[127] These platforms are intended to promote innovation, while providing basic capabilities to foster a healthy ecosystem of start-ups. As platform guidelines describe, their development "is

a move aimed at making AI technical R&D resources publicly available" in order to "export AI technology service capability to society, promote industrial applications for AI technology, nurture leading companies in the industry, and support the growth of medium-, small-, and micro-size companies."[128]

The relative weakness of open-source software has been a major concern for PRC S&T leaders.[129] Initial efforts are underway to promote indigenous alternatives to U.S. options. For instance, Baidu's framework PaddlePaddle has grown more prominent, experiencing a significant increase in downloads. Its EasyDL tool has become popular given its ease of use.[130] Alibaba has also produced an open-source machine-learning platform known as Alink, which provides algorithm libraries and facilitates machine learning.[131]
At the same time, the ideological imperatives informing Xi Jinping's leadership and decision-making have encouraged tighter control over the tech sector, driven in part by a perception that their capabilities may pose a threat. A tension between the need for innovation and the ever-more intrusive imposition of Chinese Communist Party (CCP) control mechanisms has led to interference in corporate matters that may distort or compromise the culture of competition contributing to much of China's economic success. The Party's confidence in this model of state involvement in the economy may prevent reforms needed for course-correction or adjustment.

8. Education and Leading Universities

U.S. Strengths and Weaknesses

The U.S. education system, particularly at the university level, is a crucial advantage. America boasts more than half of the world's top 10 universities for computer science, more than half of the top 20, and more than half of the top 50.[132] The availability of resources for innovation is important, particularly funding and infrastructure, but the creation of enabling environments is also critical. The best universities in America took decades to grow and develop,[133] and these universities continue to attract the best and brightest. According to one evaluation, computer science graduates from American universities tend to outperform those from other countries.[134]

Nevertheless, America's education system demands urgent reform. The United States prides itself on being a meritocracy, but stark disparities in opportunity remain.[135] By one estimate, a quarter of U.S. students fail to

complete high school; half fail to complete college on time; and the proportion of young Americans with graduate degrees is slipping relative to other countries.[136] Notwithstanding ongoing debates over whether there is a major STEM shortage in the United States,[137] it is worth noting that the scores have stratified: students who have been scoring in lower percentiles are performing especially poorly, dragging down the average.[138] The Pew Research Center finds that a majority of Americans consider K-12 STEM education in the United States as "average" or "below average" relative to other countries.[139]

A significant proportion of students in leading U.S. universities are from overseas, whereas U.S. students appear to have less interest and opportunity to pursue these fields of study and careers, despite the demands for talent. The number of American teenage boys who want to pursue a career in STEM declined from 36 percent in 2017 to 24 percent in 2018, while showing a modest uptick to 27 percent in 2019, according to *Junior Achievement*.[140] The number of teenage girls interested in careers in STEM declined from 11 percent in 2018 to 9 percent in 2019.[141] The rising costs of education, as well as an epidemic of student debt, render higher education unaffordable for many Americans. Meanwhile, the U.S. tech sector often fails to retain diverse talent and has made only halting progress toward embracing diversity and inclusion.

PRC Strengths and Weaknesses

The Chinese education system is characterized by a high level of variability in quality and opportunity. Urban China—particularly in Beijing and Shanghai—has much higher quality education in STEM than rural areas, revealing striking disparities.[142] Yet in urban locales, education reforms have improved outcomes and enabled students to outcompete their peers around the world.[143] Chinese leaders have made improvements in STEM education a priority at all levels and seek to expand quality and quantity.

Chinese universities are producing a growing number of graduates in computer science and engineering, contributing to its overall goal of hosting globally competitive universities. As of summer 2019, there were more than 8.34 million graduates from Chinese universities. If an approximation of 30 to 40 percent graduating in science and engineering remains accurate, then the total would be an estimated 2.5-3.3 million.[144] The quality of Chinese university research and education varies, but leading institutions like Tsinghua

are considered among the best in the world in science and engineering.[145] Chinese industry experts and policymakers have expressed concerns that this education does not inculcate the creativity necessary for original, cutting-edge research.[146]

Meanwhile, China's spending on STEM is increasing. Its STEM learning industry is forecast to grow to $15 billion by 2020.[147] Beyond formal educational programming, a growing number of Chinese students are turning to online platforms reportedly becoming the primary channel for AI courses.[148] The use of AI to enable adaptive learning is an emerging industry rapidly growing as a means of improving and expanding learning outcomes.[149] For instance, iFlytek has expanded its "smart education" products and programming into a growing number of classrooms at the middle school and high school levels in order to improve efficiency in teaching and learning.[150]

9. Access to Global Talent through Openness to Skilled Immigration

U.S. Strengths and Weaknesses

The United States remains demographically vibrant, and its working-age population is forecast to grow over this century, largely because of immigration.[151] Immigration is especially critical for the U.S. AI workforce. The majority of students with graduate degrees in computer science employed in the United States are foreign-born, as are the majority of computer science and mathematics professionals in Silicon Valley and teaching and research staff in computer science and engineering at major U.S. universities.[152] As of 2011, 87 percent of top university patents awarded for semiconductor device manufacturing included at least one foreign-born inventor.[153]

Harsh rhetoric and restrictive policies risk driving away students and talented researchers.[154] At the same time, heightened politicization of immigration issues has undermined attempts to implement necessary reforms, such as raising caps on permanent residence and expanding options for recent graduates.[155] The difficulty and uncertainty of immigrating to the United States appear to be driving researchers away from the United States toward more welcoming countries, including Canada.[156] The United States faces a major talent shortage in AI, but its current policies on immigration risk turning away the foreign-born talent America needs to advance U.S. scientific and technological progress for the long term.[157]

PRC Strengths and Weaknesses

Although China is aging, the size of its population constitutes an advantage for the time being.[158] China faces large inequities in education and opportunity, as well as major gaps in the distribution of talent between urban and rural areas. To offset these disadvantages, China is implementing national- and local-level programs to support domestic AI researchers and creating AI institutes and laboratories overseas to engage foreign talent.[159] The Belt and Road Initiative is driving science and technology cooperation with other countries, which could be an important source of talent for China in the future. China has also developed multiple vectors for technology transfer out of the United States.[160]

China's state-directed talent recruitment plans, such as the "Thousand Talents Plan" (千人计划), may help mitigate the current human capital bottleneck.[161] By some estimates, dozens and perhaps even hundreds of overseas talent bases engage in recruitment of top tier talent to China. A significant majority of Chinese students and researchers with experience in top overseas programs, particularly in the United States, choose to remain abroad. Although a number of foreign scientists have been recruited through talent plans, China struggles to become a more welcoming destination for immigration.[162] It remains to be seen what combination of factors or incentives, if any, may be required to tip that balance more decisively, given that many of the barriers to competitiveness are political.[163]

10. Centrality in Networks of Research Collaboration:

U.S. Strengths and Weaknesses

The United States is bordered by friendly neighbors and has maintained a network of alliances and partnerships worldwide. Many of the countries neighboring China are U.S. allies. America's allies provide important comparative advantages in mobilizing manpower, facilitating power projection, conferring legitimacy, deterring adversaries, and spurring political, economic, and technological cooperation.[164] The United States can leverage its vast network of allies and partners to promote safe and reliable AI through smart investments in AI R&D, sharing non-sensitive data while protecting privacy, controlling semiconductor supply chains, and developing norms and standards.

In a networked world, the country with the most connections enjoys a crucial advantage.[165] This new global environment calls for a "systems integrator" approach to international relations and technological development.[166] Leadership need not entail dominating the network; rather, it involves shaping the network in ways that achieve common objectives and foster collaboration in research and development.[167] As scholars have noted, it's about turning complex zero-sum problems into positive-sum solutions.[168] The ability of the United States to orchestrate networks that drive scientific and technological discovery will prove an enduring strength.

Historically, America has been successful in mobilizing international action through its alliances because it articulated a broader vision of leadership that embraced the interests of its liberal democratic allies. That strategic vision is increasingly at risk. American relationships with allies and partners have frayed and weakened. Alliances pose coordination problems and can prove time-consuming to leverage. Allies can also create vulnerabilities to foreign intelligence. Beyond these potential inefficiencies and risks, U.S. policy in recent years has created new fissures and eroded trust in America's credibility as a reliable ally and partner. AI will introduce major challenges in terms of interoperability and will require the United States and its allies to step up efforts to coordinate policy, share information, pool capabilities, and promote greater coherence and complementarity in capability development. By weakening its alliance commitments and creating uncertainty around U.S. security guarantees, the United States risks frittering away a key asset and undermining its ability to benefit from collaborating with allies in R&D and the creation of norms and standards for AI.

PRC Strengths and Weaknesses

Given the sector's relative openness and the Chinese government's efforts to leverage international innovation resources, a fairly high proportion of AI research— 42.64 percent by Tsinghua's estimate—has involved international collaboration.[169] There are strong network ties between American and Chinese researchers, and China has stepped up its scientific investments in Europe and Israel, concentrating on emerging technologies.[170]

Chinese investment in U.S. AI companies increased from $1.5 million in 2010 to $514 million in 2017,[171] but has since declined, in part because of the impact of reforms to the Committee on Foreign Investment in the United States.[172] Chinese venture capital investments in U.S. AI companies facilitate

their access to AI technologies with both civilian and military applications.[173] As the United States imposes constraints and safeguards against PRC access to U.S. technology, China has looked to diversify its access to technology and global collaborations.

China is also extending its political and strategic influence through the Belt and Road Initiative. The BRI enables China to access new markets, acquire strategic assets such as ports, secure reciprocal trade preferences, and build connections with governments eager for loans with few strings attached, while also expanding the development of digital infrastructure and internationalization of Chinese technology companies through the "digital silk road."[174] As part of the BRI, China will establish 50 new joint laboratories in partnership with member countries.[175]

America lacks an alternative vision to China's BRI, backed by sufficient resources and targeted at areas playing to U.S. strengths, such as digital infrastructure, sustainable urban planning, maritime domain awareness, and financing for connectivity initiatives.[176] The Chinese government, meanwhile, has concentrated on expanding international cooperation, while seeking to characterize the United States as paranoid and protectionist. For instance, in January 2018, leading universities in China and France created an "AI alliance" intended to promote research cooperation, including Tsinghua University, Zhejiang University, and Shanghai Jiao Tong University as partners.[177] China has also looked to increase cooperation in AI research with the United Kingdom.[178]

China is expanding research collaborations around the world and has deepened military and technological cooperation with Russia. This engagement can provide a source of valuable technical expertise, including human capital and access to new sources of data. For instance, these countries seek to expand the sharing of big data through the Sino-Russian Big Data Headquarters Base Project.[179] Another project will leverage AI technologies, particularly natural language processing, to facilitate cross-border commercial activities intended for use by Chinese and Russian businesses.[180] For China and Russia, artificial intelligence has emerged as a new priority in technological cooperation in 2020 and beyond.

Artificial Intelligence and Geopolitical Influence

Current advances in AI research and applications could enhance geopolitical influence, from the capacity to shape norms to emerging military capabilities. These dimensions are important to examine.

11. Capacity to Shape Global Norms, Technical Standards, and Governance

U.S. Strengths and Weaknesses

America's postwar leadership of the international order may endow it with advantages in promoting AI global governance. U.S. strengths have included its agenda setting, diplomatic acumen, and cultural appeal. The United States can leverage these strengths to further cooperation on AI safety and promote norms and standards that guide AI's development and deployment in service of the common good.[181]

U.S. withdrawal from multilateral institutions and agreements will diminish its ability to leverage these advantages. The risks of arms racing dynamics against the backdrop of an intensifying security dilemma could lead the United States and China to develop and deploy AI-enabled systems without adequate safeguards against brittleness, unpredictability, and systemic risks that will arise when algorithms interact at machine speed.[182]

The U.S. State Department has lost talent and capacity, particularly within the past couple of years. Current trends risk undermining American diplomacy and leadership on these critical issues at a time when deeper engagement with not only our allies and partners but also our competitors is important.[183] U.S. failures to live up to its values at home can also limit its influence and effectiveness on the global stage.

PRC Strengths and Weaknesses

The Chinese government invests heavily in soft power and "discourse power" (话语权) in particular, seeking to increase China's influence on the global stage.[184] For instance, the Chinese government exercises greater influence at the United Nations, including efforts to redefine traditional concepts of human rights to place economic development ahead of political freedoms.[185] It aims

to shape the debate in international institutions through greater participation in standard-setting organizations.[186]

China's New Generation Artificial Intelligence Development Plan calls for China to lead in AI ethics, standards, and global governance.[187] Initial frameworks for AI ethics could be welcomed, but should also be treated with some skepticism; the Chinese government's commitment to using AI "to benefit humankind" stands in stark contrast to its employment of AI for surveillance and censorship.[188] Despite genuine debates among Chinese academics on issues of AI ethics, the Chinese government will likely attempt to co-opt these conversations to assert its own centrality, in ways that advance Party-state priorities.[189]

Meanwhile, China has been engaged in a charm offensive on AI ethics, convening a growing number of AI conferences and inviting prominent individuals in the field.[190] The relative effectiveness of this approach has manifested so far in the promotion of the concept of cyber sovereignty and an authoritarian approach to internet governance gaining traction worldwide. In AI, the spread of surveillance technologies has heightened concerns about "high-tech illiberalism" and "digital authoritarianism."[191] Indeed, the Chinese Communist Party recognizes AI as an ideal instrument to increase its capacity for control.[192]

12. National Defense and Military Power

U.S. Strengths and Weaknesses

The U.S. military's technological superiority has been unparalleled in recent history. America excels in the 14 categories of systems believed to allow for command of the commons, from nuclear attack submarines to satellites and transport logistics.[193] It benefits from an array of sensors that can provide a militarily relevant advantage in data, which is important to training algorithms for defense applications.[194] The United States also enjoys a comparative advantage in developing, fielding, and deploying advanced weapons systems, which can take up to 15 to 20 years to build and require high levels of coordination to employ.[195]

By contrast, China has struggled to produce high-performance aircraft engines and compete in undersea warfare, despite recent progress.[196] Its state-owned defense industrial base has been sclerotic, but it is starting to

become more competitive. Innovations coming from the U.S. defense sector have driven advances in basic and applied research. America's defense industrial base benefits from decades of experience in managing complex defense projects. Orchestrating large-scale defense projects requires practical, on-the-ground experience that China and other powers cannot readily learn through cyber theft and industrial espionage.[197]

Notwithstanding these advantages, America's defense industrial base evolved to meet the demands of a previous era; it is not driving AI innovation in the United States. The U.S. companies and universities at the forefront of private sector innovation have an often-uneasy relationship with the U.S. defense establishment. Moreover, the U.S. military has encountered difficulties in its efforts to recruit, retain, and manage talent, particularly considering the rigidity and antiquated elements of its personnel system. The U.S. military has also suffered from the strains of war. The costs are mounting after 18 years and taking a toll on personnel and readiness alike.[198]

Despite persistent efforts to introduce reforms, the U.S. system for procurement and acquisitions remains cumbersome, to an extent that hampers innovation and can deter companies from working with the Pentagon. In addition, the commitment to costly legacy systems can create constraints that impede investments in emerging capabilities. For instance, even legacy information technology architectures can be difficult to modernize in a secure manner.[199] There are also reasons for concern that the U.S. defense industrial base has atrophied and lost critical capabilities in certain materials and expertise that may be difficult to recover.[200]

PRC Strengths and Weaknesses

China's military has been rapidly modernizing, outpacing American assessments and expectations. The PLA has been advancing a range of high-end capabilities that include integrated air defense systems, anti-ship ballistic missiles, stealth, and C4ISR, along with asymmetric capabilities, such as space, cyber and electronic warfare. The PLA has launched historic reforms that will be disruptive in the near term, but could produce far-reaching implications for the future of Chinese military power in the long term.

In the process, the PLA has pursued and sought to operationalize weapon systems designed to blunt U.S. advantages in the Western Pacific. So far, most metrics on total spending and aggregate military capabilities fail to

capture this asymmetry of investments and strategic objectives, not to mention the advantages geography could provide to the Chinese military. Meanwhile, the Central Military Commission (CMC)—particularly through its S&T Commission—is launching new programs to capitalize on China's national AI initiatives, promoting innovation in emerging technologies critical to operational advantage in future warfare.

Under Xi Jinping, military-civil fusion has been elevated as a national strategy.[201] This agenda is implemented through the Central Military-Civil Fusion Development Commission, which oversees the design and application of initiatives ranging from new platforms for procurement to local efforts to create new parks and zones to promote military-civil fusion enterprises. The Chinese military seeks to increase its access to commercial technologies and academia, including through new joint laboratories, such as in human-machine integration.[202]

The PLA's embrace of military innovation and attempts to leverage emerging technologies could enable it to compensate for current weaknesses and challenges. For instance, the PLA is interested in leveraging advances in AI/ML to enhance command and control. To prepare to fight and win wars without contemporary experience in combat, it is exploring advances in realistic training that exploit virtual reality and advanced simulations, while also exploring the employment of AI in war-gaming.

The Chinese government seeks to "leapfrog" the United States in innovation by developing concepts of operations and emerging capabilities that could be employed asymmetrically.[203] Today's research, development, and experimentation could produce tomorrow's weapons systems, including swarming, autonomy, decision support, improved intelligence, and information operations. For instance, the 2018 Zhuhai Airshow displayed a UAV command and control system intended to serve as the "strongest brain" to support unmanned operation, enabling integrated situational awareness, coordination in planning, and distributed combat operations.[204]
The Chinese military and defense industry have been recruiting AI engineers and researchers with an eye toward military AI applications and operations. Notably, the Academy of Military Science, which leads the PLA's military scientific enterprise, has established the National Innovation Institute of Defense Technology, including research centers focused on artificial intelligence and unmanned systems.[205] The Beijing Institute of Technology has also launched a program to train students in the development of intelligent

weapons systems.[206] The PLA's capacity to adapt and innovate will depend on a range of reforms currently underway.

Conclusions and Implications for U.S. Policy

No single answer exists for the question of comparative advantage in AI, and dynamics can only be evaluated through a series of lenses as complementary as they are contradictory. Chinese and American leaders have articulated parallel objectives to lead the world in AI, launching plans and policies to that end.[207] These ambitions merit serious attention, but they must be assessed relative to current advances and long-term potential. It is challenging to evaluate comparative advantage in AI, given that this discipline encompasses such a wide range of techniques and applications, from deep learning to generative adversarial networks. The pace of progress in the field raises questions about the enduring relevance of core elements of AI believed to confer an edge, such as access to large quantities of data.

American strategy must be informed by a careful evaluation of relative strengths in research, development, and applications across countries. The United States needs to recognize and reinforce its comparative advantages in order to sustain leadership in AI. In the process, American policymakers must also identify which elements of leadership are vital for U.S. national interests and objectives. The question of which data and metrics best capture progress in AI continues to be subject to debate and could evolve as the field progresses.[208]

In recent decades the United States has established leadership, even predominance, in science and technology. American advantages in innovation have resulted from the U.S. government's historical contributions as an engine for scientific progress. The ethos of science as the "endless frontier"—and government as the main driver of this exploration—has animated significant, and often successful, investments in basic research and education.[209] For all the contributions of Silicon Valley, the unique role of state support in driving innovation frequently remains unacknowledged, to the detriment of effective policy making.[210] With U.S. technological leadership increasingly contested, relying on previously accrued advantages will not necessarily translate into today's emerging industries and technologies, which rapidly evolve and feature new players and contenders.

American policymakers should consider the following core principles and general directions for policy to sustain U.S. comparative advantages:

Invest in core dimensions of U.S. AI capabilities.

- Provide long-term funding to high-risk, high-reward techniques to advance AI research, where there may be inadequate commercial investment.
  - Focus on AI safety and general techniques for testing and verification.
- Promote cross-disciplinary research in fields for which there are potential synergies, such as brain science and biotechnology.
  - Launch new institutes at national laboratories, and fund new programs at public universities.
- Recognize data as a critical strategic resource, and concentrate on ensuring its security and privacy.
  - Continue to expand the availability of data to pursue applications of AI in the public interest, and incentivize companies to make data more available for research purposes.
  - Promote initiatives for data sharing and open government, including for state and municipal governments.
  - Create regulatory frameworks that balance privacy and data security against the benefits of sharing.
- Invest in research on techniques, such as the use of synthetic data, evolutionary algorithms, and training in simulations, that are less dependent on the availability of large amounts of data.
  - Create an IARPA prize challenge involving the use of synthetic data or evolutionary algorithms.
- Sustain and expand initiatives to bolster American advantages in semiconductors, including DARPA's Electronics Resurgence Initiative.[211]
  - Support and fund research for next-generation materials and approaches to AI chips.

    - Bolster lead in next-generation manufacturing techniques, including prototyping capabilities at the discovery, application, and manufacturing scales.
- Expand public-private partnerships to advance next-generation research in semiconductors and to promote initiatives in talent and training.[212]
- Evaluate the risks that come with the globalization of U.S. supply chains and international dependencies in semiconductor manufacturing that could be disrupted by geopolitical contingencies.
    - Explore options to establish mission-critical foundries in the United States and, in collaboration with allies and partners, provide funding and support for the underlying equipment and infrastructure.

Promote critical enablers of AI development.

- Increase the quality of STEM education at all levels, including through the provision of support to public schools to hire and retain teachers.
- Provide incentives and opportunities for professors to continue to pursue cutting-edge research in academia; create new mechanisms to provide long-term grant funding for priorities in AI research.[213]
- Support the expansion of programs for training and retraining of the U.S. workforce, including through technical schools, apprenticeships, and certification of AI skills.
- Increase the affordability and accessibility of higher education, including through tackling issues of student debt.
- Create new scholarships in AI/ML, and promote pathways to military or government service through easing hiring requirements.
- Establish pilot projects and mechanisms to promote applications of AI that benefit society, including for education, healthcare, and environmental protection.
    - Provide federal grants to state and local governments to launch their own initiatives in AI for public good.

Sustain American competitiveness for the long term.

- Increase total U.S. R&D funding to at least the historical norm of three percent of GDP and consider going beyond that target, provided that investments are linked to a concrete end goal and strategy for engaging the primary sources of U.S. R&D funding and implementation, including the federal government but also other actors like industry and academia.[214]
    - Promote the emergence of new tech hubs throughout the United States.
- Explore options to collaborate more extensively with allies and partners on research and development.
    - Launch programs to fund joint research in AI and interdisciplinary applications among scientists and at major universities.
- Remain open to and welcoming of foreign students and high-tech talent through immigration.
    - Raise caps on permanent residence, expand temporary and permanent visa options for tech workers and entrepreneurs, and develop a clear path to permanent residence and citizenship for recent graduates.
- Refine, clarify, and strengthen mechanisms for screening foreign students and researchers seeking visas to better detect and deter the small number of bad actors in the system.
- Institutionalize mechanisms to increase awareness and engagement between academia and law enforcement.
    - Create an advisory board of prominent scientists to consult with and provide an independent perspective on issues of tech transfer in academia.
- Reevaluate force postures and concepts to sustain future military leadership, including expanding initiatives intended to promote innovation and experimentation.
    - Invest in an AI ready force through focusing on talent recruitment and retention and on training opportunities.[215]
- Create legal, ethical, and regulatory frameworks for the use of AI within the United States.

    - Respond proactively to mitigate the potential for abuses of AI by the U.S. government, law enforcement, or national security institutions.
- Explore options to promulgate favorable approaches to AI governance internationally, in coordination with allies and partners.
    - Explore opportunities to deepen engagement across a range of multilateral organizations and initiatives, including the Organization for Economic Cooperation and Development, the Group of Seven, and the Global Partnership on AI.
    - Create a consortium of likeminded democracies to address issues of human rights in AI.

Neither the United States nor China enjoys a clear or uncontested advantage in AI. Each country possesses distinct strengths and confronts potential weaknesses. It is too early to assess whether the United States or China is leading in AI from the perspective of long-term development in the field, but both nations are poised to transform and be transformed by AI. In the years and decades to come, relative progress and strengths across these dimensions will be important to continue to evaluate.

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[215] For an excellent overview of this issue, see "Campaign for an AI Ready Force," https://media.defense.gov/2019/Oct/31/2002204191/-1/-1/0/CAMPAIGN_FOR_AN_AI_READY_FORCE.PDF.