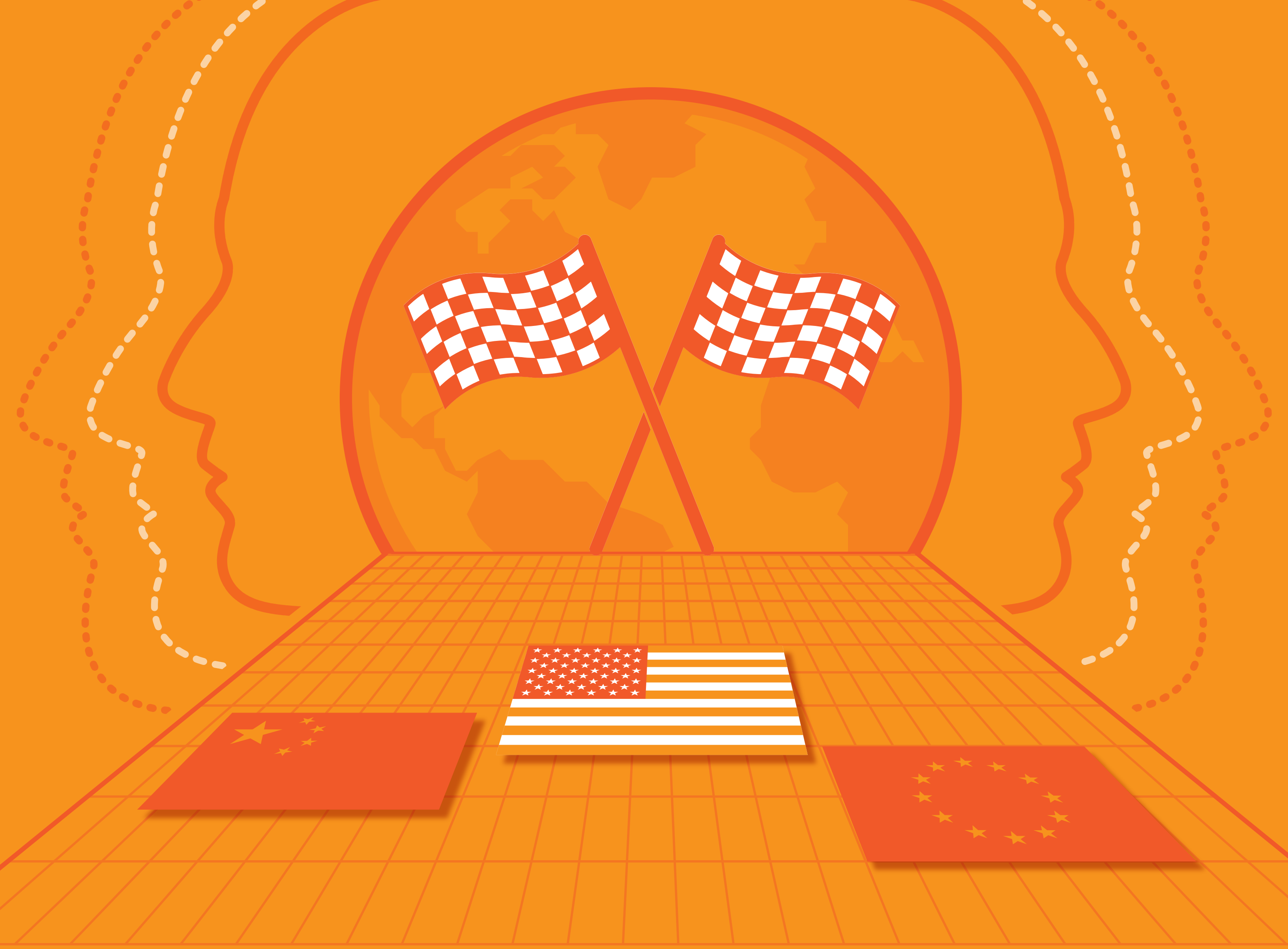

WHO IS WINNING THE AI RACE:

CHINA, THE EU OR THE UNITED STATES?

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Who Is Winning the AI Race: China, the EU or the United States?

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Many nations are racing to achieve a global innovation advantage in artificial intelligence (AI) because they understand that AI is a foundational technology that can boost competitiveness, increase productivity, protect national security, and help solve societal challenges. This report compares China, the European Union, and the United States in terms of their relative standing in the AI economy by examining six categories of metrics—talent, research, development, adoption, data, and hardware. It finds that despite China's bold AI initiative, the United States still leads in absolute terms. China comes in second, and the European Union lags further behind. This order could change in coming years as China appears to be making more rapid progress than either the United States or the European Union. Nonetheless, when controlling for the size of the labor force in the three regions, the current U.S. lead becomes even larger, while China drops to third place, behind the European Union. This report also offers a range of policy recommendations to help each nation or region improve its AI capabilities.

The United States leads in AI. However, China is catching up and leads in some areas. In contrast, the European Union is behind both the United States and China in most areas.

INTRODUCTION

The United States reaped tremendous economic benefits from the last wave of digital innovation, becoming home to some of the world's most successful tech companies, such as Amazon, Apple, Facebook, Google, Intel, and Microsoft. Meanwhile, many parts of the world, including the European Union, paid an economic price staying on the sidelines. Recognizing that missing the next wave of innovation—in this case, AI—would be similarly problematic, many nations are taking action to ensure they play a large role in the next digital transformation of the global economy.

China, the European Union, and the United States are now emerging as the main competitors for global leadership in AI. Indeed, China, which achieved success in the Internet economy in part by shutting out U.S. firms, has clearly stated its ambition of achieving dominance in AI—both to increase its competitiveness in industries that have traditionally been vital to the U.S. and EU economies, and to expand its military power.[1] Moreover, the EU's coordinated plan on AI states that its "ambition is for Europe to become the world-leading region for developing and deploying cutting-edge, ethical and secure AI."[2] The outcome of this race to become the global leader in AI will affect the trio's future economic ouput and competitiveness, as well as military superiority.

FINDINGS

Overall, the United States currently leads in AI, with China rapidly catching up, and the European Union behind both. The United States leads in four of the six categories of metrics this report examines (talent, research, development, and hardware), China leads in two (adoption and data), and the European Union leads in none—although it is closely behind the United States in talent. Out of 100 total available points in this report's scoring methodology, the United States leads with 44.2 points, followed by China with 32.3 and the European Union with 23.5.

The United States leads for several reasons. First, it has the most AI start-ups, with its AI start-up ecosystem having received the most private equity and venture capital funding.[3] Second, it leads in the development of both traditional semiconductors and the computer chips that power AI systems.[4] Third, while it produces fewer AI scholarly papers than the EU or China, it produces the highest-quality papers on average.[5] Finally, while the United States has less overall AI talent than the European Union, its talent is more elite.[6]

China is ahead of the European Union in AI and appears to be quickly reducing the gap between itself and the United States. It has more access to data than the European Union and the United States, which is important because many of today's AI systems use large datasets to train their models accurately. In venture capital and private equity funding, Chinese AI start-ups received more funding than U.S. start-ups in 2017, but not in 2016 or 2018.[7] China, however, is clearly behind both the United States and the European Union in high-quality AI talent. Several European Union member states, including Italy, had more AI researchers ranked in the top 10 percent internationally than China as of 2017.[8] Nonetheless, China has made clear progress relative to the United States in most metrics, and significantly outpaces the European Union in funding and AI adoption.

The European Union has the talent to compete with the United States and China. Indeed, it has more AI researchers than its peers, and typically produces the most research as well.[9] However, there is a disconnect between the amount of AI talent in the EU and its commercial AI adoption and funding. For example, AI start-ups in the United States and China both received more venture capital and private equity funding in 2017 alone than EU AI start-ups received in the three years covering 2016 through 2018.[10] The European Union's laggard position reduces its ability to not only enjoy the economic and social benefits of AI, but also influence global AI governance, which is a goal of the European Commission.[11]

Table 1: Rankings, absolute metrics

Category	China	European Union	United States
Talent	3	2	1
Research	3	2	1
Development	3	2	1
Adoption	1	2	3
Data	1	3	2
Hardware	2	3	1

To get a sense of each region's AI strengths in relation to their size, we also calculated scores for each metric by adjusting for the size of their labor forces. Controlling for size, the U.S. lead grows (58.2 points), the European Union ranks second (24.3 points), and China comes in third (17.5 points).

As this report demonstrates, China, the European Union, and the United States each have different areas they can improve to become more competitive in the AI economy. For example, China should expand its capacity to teach AI-related subjects at the university level, encourage research quality over quantity, and foster a stronger culture of promoting open data. Meanwhile, the EU should focus on developing policies that incentivize talent to remain in the EU, help transfer research successes into business applications, encourage the development of larger firms that can better compete in a global market, and reform regulations to better enable use of data for AI. Finally, for the United States to maximize its lead, it should focus on policies that grow its domestic talent base, enable foreign AI talent to immigrate, and increase incentives for research and development (R&D). More detailed recommendations are enumerated at the end of this report.

On the following pages, we examine the metrics and scores, by category.

Table 2: Talent metrics and scores, absolute values

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2017	Number of AI Researchers	5	18,232	43,064	28,536	1.0	2.4	1.6
2017	Number of Top AI Researchers (H-Index)	5	977	5,787	5,158	0.4	2.4	2.2
2018	Number of Top AI Researchers (Academic Conferences)	3	2,525	4,840	10,295	0.4	0.8	1.7
2018	Educating Top AI Researchers	2	11%	21%	44%	0.3	0.6	1.2
	Total Scores	**15**				**2.1**	**6.2**	**6.7**

Table 3: Research metrics and scores, absolute values

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2017	Number of AI Papers	5	15,199	14,776	10,287	1.9	1.8	1.3
2016	Field-Weighted Citation Impact	4	0.9	1.2	1.8	0.9	1.2	1.8
2018	Top-100 Software and Computer Service Firms for R&D Spending	3	12	13	62	0.4	0.4	2.1
2018	R&D Spending by Software and Computer Service Firms in Top 2,500 (Billions)	3	$11.8	$10.1	$77.4	0.4	0.3	2.3
	Total Scores	**15**				**3.6**	**3.8**	**7.6**

Table 4: Development metric and scores, absolute values

Year	Metric	Weight	Metrics CN	Metrics EU	Metrics US	Scores CN	Scores EU	Scores US
2017–18	VC + PE Funding (Billions)	5	$13.5	$2.8	$16.9	2.0	0.4	2.5
2017–18	Number of VC + PE Deals	2	390	660	1,270	0.3	0.6	1.1
2000–19	Number of Acquisitions of AI Firms	2	9	139	526	0.0	0.4	1.6
2017	Number of AI Start-ups	4	383	726	1,393	0.6	1.2	2.2
2019	Number of AI Firms That Have Received More Than $1 Million in Funding	4	224	762	1,727	0.3	1.1	2.5
1960–2018	Highly Cited AI Patent Families	3	691	2,985	28,031	0.1	0.3	2.7
1960–2018	Patent Cooperation Treaty AI Patents	5	1,085	1,074	1,863	1.3	1.3	2.3
	Total Scores	**25**				**4.8**	**5.3**	**14.9**

Table 5: Adoption metrics and scores, absolute values[12]

Year	Metric	Weight	Metrics CN	Metrics EU	Metrics US	Scores CN	Scores EU	Scores US
2018	Number of Workers in Firms Adopting AI (Rank)	5	1	2	3	3.8	0.7	0.5
2018	Number of Workers in Firms Piloting AI (Rank)	5	1	2	3	3.9	0.6	0.5
	Total Scores	**10**				**7.7**	**1.3**	**1.0**

Table 6: Data metrics and scores, absolute values

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2018	Fixed Broadband Subscriptions (Millions)	4	394	176	110	2.3	1.0	0.6
2018	Number of Individuals Using Mobile Payments (Millions)	3	525	45	55	2.5	0.2	0.3
2018	Internet of Things Data (TB, Millions)	3	152	53.5	69	1.7	0.6	0.8
2018	Productivity Data (TB, Millions)	4	684	583	966	1.2	1.0	1.7
2019	Electronic Health Records (Rank)	2	3	2	1	0.3	0.7	1.0
2019	Mapping Data (Rank)	2	3	2	1	0.3	0.7	1.0
2019	Genetic Data (Rank)	2	2	3	1	0.7	0.3	1.0
2019	Regulatory Barriers (Rank)	5	1	3	2	2.5	0.8	1.7
	Total Scores	**25**				**11.6**	**5.4**	**8.1**

Table 7: Hardware metrics and scores, absolute values

			Metrics			Scores		
Year	**Metric**	**Weight**	**CN**	**EU**	**US**	**CN**	**EU**	**US**
2019	Number of Firms in Top 15 for Semiconductor Sales	2	1	2	6	0.2	0.4	1.3
2017	Number of Firms in Top 10 for Semiconductor R&D Spending	2	0	0	5	0.0	0.0	2.0
2019	Number of Firms Designing AI Chips	2	26	12	55	0.6	0.3	1.2
2019	Number of Supercomputers Ranked in Top 500	2	219	92	116	1.0	0.4	0.5
2019	Aggregate System Performance of Supercomputers Ranked in Top 500	2	30%	17%	38%	0.7	0.4	0.9
	Total Scores	**10**				**2.5**	**1.5**	**6.0**

Table 8: Talent metrics and scores, adjusted by number of workers[13]

			Metrics			Scores		
Year	**Metric**	**Weight**	**CN**	**EU**	**US**	**CN**	**EU**	**US**
2017	Number of AI Researchers per 1 Million Workers	5	23.2	172.9	173.1	0.3	2.3	2.3
2017	Number of Top AI Researchers (H-Index) per 1 Million Workers	5	1.2	23.2	31.3	0.1	2.1	2.8
2018	Number of Top AI Researchers (Academic Conferences) per 1 Million Workers	3	3.2	19.4	62.4	0.1	0.7	2.2
2018	Educating Top AI Researchers (Rank)	2	3	2	1	0.3	0.7	1.0
	Total Scores	**15**				**0.9**	**5.8**	**8.4**

Table 9: Research metrics and scores, adjusted by number of workers

			Metrics			Scores		
Year	**Metric**	**Weight**	**CN**	**EU**	**US**	**CN**	**EU**	**US**
2017	Number of AI Papers per 1 Million Workers	5	19.2	59.2	62.6	0.7	2.1	2.2
2016	Field-Weighted Citation Impact	4	0.9	1.2	1.8	0.9	1.2	1.8
2018	Number of Firms in the Top 100 Software and Computer Services Firms for R&D Spending per 10 Million Workers	3	0.2	0.5	3.8	0.1	0.4	2.5
2018	R&D Spending (Billions) by Software and Computer Services Firms in the Top 2,500 Globally per Worker	3	$15.0	$42.2	$469.7	0.1	0.2	2.7
	Total Scores	**15**				**1.8**	**3.9**	**9.3**

Table 10: Development metrics and scores, adjusted by number of workers

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2017–18	AI Venture Capital and Private Equity Funding per Worker	5	$17.2	$11.2	$102.4	0.7	0.4	3.9
2017–18	Number of Venture Capital and Private Equity Funding Deals per 1 Million Workers	2	0.5	2.6	7.7	0.1	0.5	1.4
2000–19	Number of Acquisitions of AI Firms per 1 Million Workers	2	0.0	0.6	3.2	0.0	0.3	1.7
2017	Number of AI Start-ups per 1 Million Workers	4	0.5	2.9	8.4	0.2	1.0	2.9
2019	Number of AI Firms That Have Received More Than $1 Million in Funding per 1 Million Workers	4	0.3	3.1	10.5	0.1	0.9	3.0
1960–2018	Number of Highly Cited AI Patents per 1 Million Workers	3	0.9	12.0	170.0	0.0	0.2	2.8
1960–2018	Number of Patent Cooperation Treaty Applications per 1 Million Workers	5	1.4	4.3	11.3	0.4	1.3	3.3
	Total Scores	**25**				**1.4**	**4.5**	**19.0**

Table 11: Adoption metrics and scores, percent values

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2018	Firms That Are Adopting AI	5	32%	18%	22%	2.2	1.3	1.5
2018	Firms That Are Piloting AI	5	53%	26%	29%	2.5	1.2	1.3
	Total Scores	**10**				**4.7**	**2.4**	**2.9**

Table 12: Data metrics and scores, adjusted by number of individuals or workers

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2018	Number of Fixed Broadband Subscriptions per 100 People	4	28.0	34.5	33.9	1.2	1.4	1.4
2018	Population Using Mobile Payments	3	45.2%	10.2%	20.2%	1.8	0.4	0.8
2018	Internet of Things Data (TB) per 100 Workers	3	19.3	21.5	41.9	0.7	0.8	1.5
2018	Productivity Data (TB, Millions) per 100 Workers	4	86.9	233.9	585.9	0.4	1.0	2.6
2019	Electronic Health Records (Rank)	2	3	2	1	0.3	0.7	1.0
2019	Mapping (Rank)	2	3	2	1	0.3	0.7	1.0
2019	Genetic (Rank)	2	2	3	1	0.7	0.3	1.0
2019	Regulatory Barriers (Rank)	5	1	3	2	2.5	0.8	1.7
	Total Scores	**25**				**7.9**	**6.2**	**11.0**

Table 13: Hardware metrics and scores, adjusted by number of workers

			Metrics			Scores		
Year	Metric	Weight	CN	EU	US	CN	EU	US
2019	Number of Firms in Top 15 for Semiconductor Sales per 1 Billion Workers	2	1.3	8.0	36.5	0.1	0.4	1.6
2017	Number of Firms in Top 10 for Semiconductor R&D Spending per 1 Billion Workers	2	0.0	0.0	30.4	0.0	0.0	2.0
2019	Number of Firms Designing AI Chips per 10 Million Workers	2	0.3	0.5	3.3	0.2	0.2	1.6
2019	Number of Supercomputers Ranked in Top 500 per 10 Million Workers	2	2.8	3.7	7.1	0.4	0.5	1.0
2019	Aggregate System Performance of Supercomputers (TFLOPs/s) per 10,000 Workers	2	5.9	10.5	36.4	0.2	0.4	1.4
	Total Scores	**10**				**0.8**	**1.5**	**7.6**

IS THE AI RACE A ZERO-SUM GAME?

Many believe countries do not compete when it comes to innovation. In this view, there are only winners, no losers. But in fact, there are both winners and losers in the global AI race. Nations wherein firms fail to develop successful AI products or services are at risk of losing global market share. As Andrew Moore, former dean of computer science at Carnegie Mellon University and current head of Google Cloud AI stated, this part of the race will determine “who will be the Googles, Amazons, and Apples in 2030.”[14] Nations that lag in AI adoption will see diminished global market share in a host of industries, from finance to manufacturing to mining. And nations that underinvest in AI R&D, particularly for military applications, will put their national security at risk.[15] Consequently, nations that fall behind in the AI race can suffer economic harm and weakened national security, thereby diminishing their geopolitical influence.[16]

In some areas, however, the race to develop or adopt AI is not a zero-sum game. Developments of AI science, particularly at universities, can and do spread throughout the world, thereby helping the entire AI ecosystem. And many AI advancements, particularly those focused on health, the environment, and education, can benefit all countries. For example, the development of AI systems that can identify diseases faster and more accurately than clinicians, or produce new medical treatments, offers potentially global benefits. One such development has come in 2019, when Chinese and American researchers created an AI system that accurately diagnoses common childhood conditions. The system diagnoses asthma with more than 90 percent accuracy and gastrointestinal disease with 87 percent accuracy, and to develop it, the researchers trained the system on the electronic health records (EHRs) of 600,000 Chinese patients.[17] In addition, because much AI research is open, researchers worldwide quickly learn from advancements made by others abroad.[18]

Moreover, there are already numerous examples of AI systems created in one nation that are being implemented in others to help the local populations. For example, Google is using one of its AI tools in rural India to diagnose blindness-causing diabetic retinopathy.[19]

METHODOLOGY

There are no standard industrial classifications for firms developing AI technologies, so compiling indicators to compare AI development among nations is challenging. Nonetheless, there are a number of metrics that show the current state of AI development. This report examines six categories of metrics—talent, research, enterprise development, adoption, data, and hardware—to measure AI progress in the economies of China, the European Union, and the United States. We chose these three economies because they are the largest and consistently outperform their peers in the six categories on absolute metrics.

We chose the categories for several reasons. First, nations with the requisite AI talent will be able to better develop and implement AI systems, attract businesses, and ensure their universities have enough talented AI professors to teach the next generation of AI researchers. Second, research will help nations expand AI innovation and solve problems related to domestic priorities and industries. Third, the number of AI companies and start-ups, combined with related investment capital, lays the groundwork for a strong AI industry that will continue to innovate. Fourth, adoption of AI systems will not only allow organizations to learn how to solve problems related to implementation, but generate demand for AI services, thereby likely helping domestic AI developers. Fifth, more and higher-quality data will create new opportunities to use machine learning in AI applications. Finally, leading in hardware will reduce nations' dependency on other nations—something that, given the current trade dispute between China and the United States, may play an important role going forward.

Within each category, we measured a nation's progress using multiple indicators. For example, for the research category, we used the number of AI papers, the quality of the AI papers, and R&D metrics to rank China, the European Union, and the United States. For several of the indicators, complete data was not available for the European Union. For these indicators, we estimate an EU figure using available data. We detail these estimates in the appendix. We show each indicator both in absolute terms and controlling for the size of the economy. For example, AI researchers are shown both as an absolute total and as a share of the economy's total workforce.

We calculated a score for every indicator for each region. To do so, we first calculated a proportional score. For example, on the indicator for the number of supercomputers ranking in the top 500, China has 219 computers, the European Union has 92, and the United States has 116. Thus, China gets a proportional score of 0.5, the EU 0.2, and the United States 0.3. Each indicator is worth between 2 and 5 points. So, if the indicator for supercomputers is worth 2 points, China receives a score of 1 point, the European Union 0.4, and the United States 0.5.

We assigned different weights to different indicators based on our assessment of their relative importance in determining national AI development success. As a result, not all categories are worth the same number of points, although all indicators together are worth a total of 100 points. Appendix 1 lists the categories, indicators, and corresponding weights. For several indicators, we had to use a combination of quantitative and qualitative analysis. In these cases, we ranked the regions first, second, and third, and give their scores as the inverse of their ranking. For example, if China ranked first, it received three points.

To calculate category scores, we summed each region's score for the indicators in the category. To calculate overall scores, we summed the category scores.

We used this method to calculate two sets of scores: one based on the absolute value of the metrics, and one adjusting each metric by the number of workers in the economy.

METRICS

The following sections compare China, the European Union, and the United States on talent, research, enterprise development, adoption, data, and hardware using absolute and size-controlling metrics. After presenting the metrics for each category, this report provides a brief analysis of the state of the AI race in each category.

TALENT

Researchers are key to AI development.[20] As David Wipf, a lead researcher at Microsoft Research in Beijing has said, "The future [of AI] is going to be a battle for data and for talent."[21] Lack of talent not only limits firms' ability to deploy and adopt AI, it increases costs, thereby reducing competitiveness. Given the increased demand for AI talent in a wide range of industries, including transportation, finance, and manufacturing, the current shortage is likely to only grow in the near to moderate term. [22]

Governments in China, the European Union, and the United States have announced or begun initiatives to improve and expand their AI talent. For example, in 2018, China's Ministry of Education announced a plan to promote AI education. In response, several leading Chinese universities have created new AI departments and majors.[23] The U.K. government has announced that it will pay up to £115 million ($140 million) for 1,000 students to earn AI doctorate degrees at 16 of its universities.[24] President Trump issued an executive order that focuses on measures to expand fellowships, training programs, and funding for early-career university faculty conducting AI R&D.[25]

This section analyzes the number of AI researchers, the number of top AI researchers, and the locations of AI researchers' graduate degrees to assess the talent and ability to develop talent in China, the European Union, and the United States. We allotted this category 15 of the 100 available points. On an absolute basis, the most recent data available showed the United States leading in AI talent (6.7 points) followed by the European Union (6.2) and China (2.1). Controlling for the size of their labor force, the United States (8.4 points) also led the European Union (5.8) and China (0.9).

Number of AI Researchers: This section defines an AI researcher as someone who has published a journal article or had a patent on an AI-related topic between 2007 and 2017.[26] The European Union had an estimated 43,064 researchers, ahead of the United States (28,536) and China (18,232).[27] Indeed, the combined number of AI researchers from Germany (9,441), the United Kingdom (7,998), France (6,395), Spain (4,942), and Italy (4,740) was more than that of U.S. researchers.[28] On a per-worker basis, the United States (173 researchers per 1 million workers) led the European Union (173) and China (23).[29]

Table 14: Number of AI researchers, 2017[30]

Metric	China	European Union	United States
Number of AI Researchers	18,232	43,064	28,536
Number of AI Researchers per 1 Million Workers	23.2	172.9	173.1

Number of Top AI Researchers (H-Index): It is not just the number of researchers that matters, but their quality. One measure of quality is the h-index, which measures the productivity and influence of researchers. This indicator examines the number of AI researchers ranking in the top 10 percent internationally according to their h-index.[31] Through 2017, the European Union led with an estimated 5,787 researchers, ahead of the United States (5,158) and China (977). The United Kingdom (1,177), Germany (1,119), France (1,056), Italy (987), and Spain (772) combined for 5,111 such individuals.[32] While the data for the other 23 EU nations was unavailable, it is clear there was enough top AI talent in the remaining countries to eclipse the less-than-100-person gap between the United States and European Union. When controlling for workforce sizes, the United States (31 researchers per million workers) led the European Union (23) and China (1).[33]

Table 15: Number of top AI researchers (h-index), 2017[34]

Metric	China	European Union	United States
Number of Top AI Researchers (H-Index)	977	5,787	5,158
Number of Top AI Researchers (H-Index) per 1 Million Workers	1.2	23.2	31.3

Number of Top AI Researchers (Academic Conferences): A second measure of quality is the number of authors publishing at leading AI academic conferences around the world, which AI start-up Element AI tracked for 21 AI conferences in 2018. In this metric, the United States (10,295 researchers) led the European Union (4,840) and China (2,525).[35] On a per-worker basis, the United States (62 researchers per one million workers) led the European Union (19) and China (3).[36]

Table 16: Number of top AI researchers (academic conferences), 2018[37]

Metric	China	European Union	United States
Number of Top AI Researchers (Academic Conferences)	2,525	4,840	10,295
Number of Top AI Researchers (Academic Conferences) per 1 Million Workers	3.2	19.4	62.4

EDUCATING TOP AI RESEARCHERS (ACADEMIC CONFERENCES):

Developing AI talent is also important. This indicator examines where the researchers publishing at the 21 leading academic conferences in 2018 earned their Ph.D. More of the researchers earned their Ph.D. in the United States (44 percent) than the European Union (estimated 21 percent) and China (11 percent) combined.[38] This provides the United States an advantage in AI talent in large part because 79 percent of students receiving a Ph.D. in the United States in mathematics or computer science plan to stay in the United States.[39] We could not compute an exact per-worker stat for this indicator, but the size of the labor forces indicate that the United States would lead on a per-worker basis, followed by the European Union, and China.[40]

Table 17: Educating AI researchers, 2018[41]

Metric	China	European Union	United States
AI Conference Researchers Receiving Their Ph.D. in Either China, the European Union, or the United States	11%	21%	44%

INTERPRETATION: THE EU IS NOT TAKING ADVANTAGE OF ITS AI TALENT AND ITS POSITION IS NOT SAFE

The European Union is a close second in AI talent, but it may continue to fall behind in commercially leveraging AI because it has less AI talent in businesses than the United States, the United States is attracting significant amounts of foreign talent (including European talent), and China is implementing robust plans to increase its AI talent.

The EU Has Less AI Talent Working in Globally Leading Firms

The data reveals that while the European Union has lots of AI talent, its top businesses have less talent than U.S. firms, which, combined with a lack of venture capital and private equity funding, could hurt its ability to develop globally leading AI firms. For example, of the 20 companies with the most AI talent, according to AI paper and patent records, in 2017, half were based in the United States.[42] These ten U.S. companies combined for 1,623 AI workers. In comparison, the European Union had six such companies, totaling 522 AI workers. The only Chinese company ranking in the top 20 was Huawei, with 73 workers. Similarly, of the 20 companies with the most top AI researchers, according to their H-index, in 2017, the European Union accounted for 85 individuals, compared with 232 for the United States. China accounted for seven researchers.[43]

The United States Is Attracting the Most AI Talent

Another concern for the European Union, as well as China, is U.S. industry is attracting significantly more AI talent from other nations than the European and Chinese industries. Between 1998 and 2017, for example, 1,283 foreign AI academic researchers came to the United States from abroad for U.S. industry positions. Europe and China attracted 834 and 58 such researchers, respectively.[44] Moreover, data collected by Elsevier demonstrates that U.S. industry (318 AI researchers) gained more foreign academic researchers than researchers it lost to foreign academic institutes than European industry (166) between 1998 and 2017.[45]

China Is Working Extensively to Develop AI Talent

Compared with China, the EU has many advantages in AI talent. For example, in 2017, the United Kingdom (1,177), Germany (1,119), France (1,056), and Italy (987) each had a greater number of AI researchers ranking in the top 10 percent internationally according to their h-index than China (977).[46] However, China's lack of top AI talent may be due to its relatively recent interest in AI—only 25 percent of Chinese AI researchers have more than ten years of experience compared with nearly 50 percent of U.S. AI researchers.[47] In addition, there are several reasons why China may be able to reduce both the talent gap and the talent gap may have diminishing importance.

U.S. industry has attracted significantly more AI talent from other nations than the EU and Chinese industries.

First, China is investing in AI education. In 2017, the State Council, the chief administrative body in China, released a plan calling for the creation of an AI academic discipline.[48] In 2018, the Ministry of Education launched multiple initiatives to boost education, and the combined initiatives include plans to develop 50 AI research centers, world-class online courses, and a 5-year plan to train more than 500 instructors and 5,000 students.[49] Three of China's top universities—Tsinghua University, USTC, and Shanghai Jiao Tong University—have already significantly increased the number of students enrolled in AI and machine learning courses since 2016. For example, between 2016 and 2018, USTC increased its AI and machine learning course enrollment from 1,745 to 3,286 students.[50] Second, Chinese researchers can and do quickly replicate advanced algorithms developed by other nations because AI researchers frequently detail the architecture of their AI model, and how they implemented and trained it, on openly available prepublications websites.[51] Anecdotal evidence also suggests Chinese researchers translate English AI publications significantly more often and faster than Western nations translate papers in Chinese, thereby creating an information asymmetry.[52] Third, AI researcher and venture capitalist Kai-Fu Lee has argued that China's lack of top end talent is not a significant barrier to it leading in AI, stating "[T]he current age of implementation [AI application commercialization] appears well-suited to China's strengths in research: large quantities of highly-skilled, though not necessarily best-of-best, AI researchers and practitioners."[53] Lee believes breakthroughs such as deep learning occur once every several decades, and AI has entered an age in which data will be the decisive factor that determines the ability of AI systems.[54]

RESEARCH

Countries need organizations to perform research in order to sustain innovation. In the past decade, algorithmic innovations, along with greater computing power, have increased the functionality of AI systems and drastically reduced the time it takes to train them.[55] But AI is far from a mature technology; more research and more advances are needed.

This section analyzes the number and quality of AI scholarly papers and business R&D funding to assess China, the European Union, and the United States. Ideally, the study would also include government R&D funding. However, nations have different classifications of what constitutes AI R&D, and some do not report AI R&D figures or distinguish between private and public money in their announcements.

Nonetheless, China, the European Union, and United States are each conducting AI research initiatives. For example, China's New Generation AI Development Plan calls for China to have made significant breakthroughs in AI theory by 2025, and the government has created research centers, including the Artificial Intelligence Research Center, which has more than 100 employees, to reach that goal.[56] In addition, the Chinese Ministry of Industry and Information Technology plans to allocate $950 million annually to fund strategic AI projects.[57] The European Commission has committed to invest €1.5 billion ($1.7 billion) on AI research between 2018 and 2020, and proposed to invest at least €7 billion ($8 billion) from 2021 to 2027 through Horizon Europe and the Digital Europe Program in AI.[58] The U.S. federal government spent $1.1 billion on unclassified R&D for AI-related technologies in 2015.[59] Additionally, in September 2018, the Defense Advanced Research Projects Agency, part of the U.S. Department of Defense (DOD), announced a $2 billion campaign over 5 years to develop the next generation of AI technologies.[60]

We allotted the research category 15 of 100 available points. On an absolute basis, the United States led in AI research (7.6 points), followed by the European Union (3.8 points) and China (3.6 points). Controlling for the size of the workforces, the United States ranked first (9.3 points), followed by the European Union (3.9) and China (1.8).

Number of AI Papers: One indicator of research is the number of AI papers a nation produces each year. In 2017, China published 15,199 AI papers, the European Union 14,776, and the United States 10,287.[61] Historically, however, the EU has produced the most AI papers. From 1998 to 2017, for example, EU researchers authored nearly 164,000 AI papers, compared with 135,000 and 107,000 by Chinese and U.S. authors, respectively.[62] On a per-worker basis, the United States published 63 AI papers per one million workers in 2017, ahead of the European Union (59) and China (19).[63]

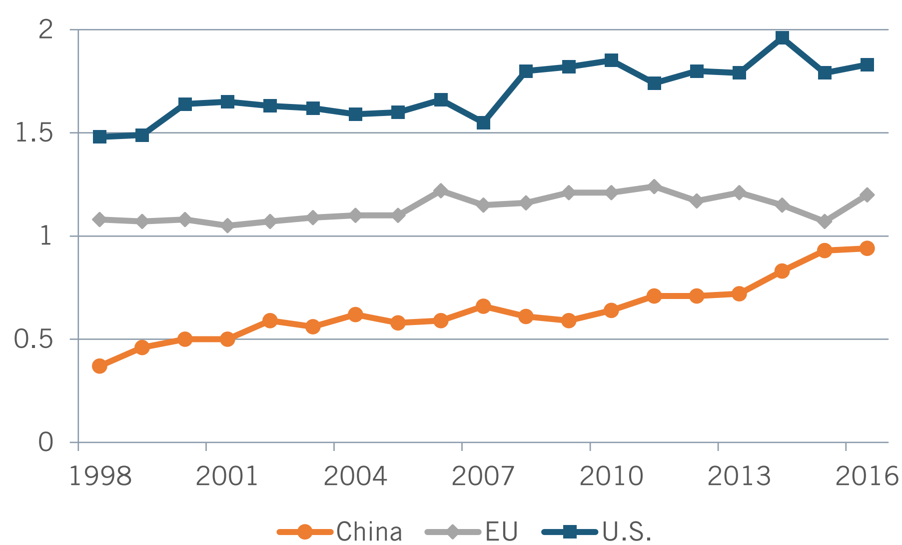
Table 18: Number of AI papers, 2017[64]

Metric	China	European Union	United States
Number of AI Papers	15,199	14,776	10,287
Number of AI Papers per 1 Million Workers	19.2	59.2	62.6

Paper Quality: As the Allen Institute for Artificial Intelligence has written, "[N]ot all papers are created equal."[65] Indeed, the United States produces the highest-quality research.[66] In 2016, the United States had a rebased field-weighted citation impact (FWCI) of 1.83, which means researchers cited U.S. authors 83 percent more than the global average.[67] In comparison, the EU and China had FWCIs of 1.20 and 0.94, respectively, which shows Chinese authors were cited less often than the average AI author globally.[68] China has, however, increased its FWCI every year since 2012, when it was 0.71.[69]

In 2016, researchers cited U.S. authors 83 percent more than the global average.

Figure 1: Field-weighted citation impact, 1998–2016[70]



Top 100 Software and Computer Service Firms for R&D Spending: Another way to measure a region's research capabilities is to examine how much it spends on R&D. It is difficult to know how much firms are spending specifically on AI R&D, but examining the overall R&D expenditures of software and computer services firms, many of which are developing AI services, provides a proxy for AI R&D spending. This indicator examines the

top 100 software and computer service firms for R&D spending in 2018. The United States (62 firms) led the European Union (13), and China (12).[71] Per 10 million workers, the United States also led the EU and China.

Table 19: Top-100 software and computer services firms for R&D spending, 2018[72]

Metric	China	European Union	United States
Number of Firms in the Top 100 Software and Computer Services Firms for R&D Spending	12	13	62
Number of Firms in the Top 100 Software and Computer Services Firms for R&D Spending per 10 Million Workers	0.2	0.5	3.8

Total R&D Spending of Software and Computer Services Firms Ranking in Top 2,500 Globally: There were 268 software and computer services firms in the global top 2,500 firms for R&D spending in 2018. This indicator measures how much the 268 firms spent on R&D by region.[73] The United States (€69 billion, $77 billion) led China (€10 billion, $12 billion) and the European Union (€9 billion, $11 billion).[74] On a per-worker basis, the United States ($470 per worker) led the European Union ($42) and China ($15).[75]

Table 20: R&D spending by software and computer services firms ranking in global top 2,500, 2018[76]

Metric	China	European Union	United States
R&D Spending (Billions) by Software and Computer Services Firms in the Top 2,500 Globally	$11.8	$10.5	$77.4
R&D Spending (Billions) by Software and Computer Services Firms Ranking in the Top 2,500 Globally per Worker	$15.0	$42.2	$469.7

INTERPRETATION: THE UNITED STATES IS LEADING IN AI RESEARCH, BUT CHINA IS CATCHING UP

An analysis of the data shows the United States leading in AI research, both because of its immense spending on R&D and its elite research organizations. Nonetheless, China is catching up to the United States and European Union not only because it produces more research, but because it has begun producing higher-quality research.

The United States Has Elite Research Organizations

The United States leads in research in part because it has elite organizations. For example, the top-five software and computer services firms for R&D are U.S. firms. Another way to assess the quality of research a nation produces is to examine the impact of its organizations publishing the most AI papers. The United States leads in this measure as well. U.S.-based organizations that published the most AI papers between 2013 and 2017 were Carnegie Mellon University, the Massachusetts Institute of Technology, Microsoft, IBM, and Stanford University. Collectively, these five-organizations had an FWCI of 4.0, which was significantly higher than the FWCI of the top-five EU (1.9) and Chinese (1.4) organizations.[77]

The EU's Second-Place Position Is Not Secure

While the EU's top organizations are producing higher-quality research on average than the best Chinese organizations, the EU is nonetheless experiencing relative stagnation in paper output and quality. Since 1998, the European Union's FWCI has grown only 11 percent, compared with 24 percent for the United States and 154 percent for China.[78] Maintaining the same rapid increase in FWCI as it experienced between 2012 and 2016, China may have surpassed the EU in FWCI by 2018 (data was only available through 2016).[79] In addition, five nations—the United Kingdom, Germany, France, Spain, and Italy—primarily drive AI research in the EU, but their annual AI publication output has actually contracted since 2014.[80]

China's Research Quality Is Rising

The EU's stagnation is coupled by a rising China. While the FWCIs for the United States and European Union in 2009 were almost identical to their FWCIs in 2016 (1.82 and 1.83 for the United States, and 1.21 and 1.20 for the EU), China's FWCI grew from 0.59 to 0.94 in the same period.[81] Consequently, China's FWCI is rapidly approaching, or has surpassed, the global average of 1.00.[82]

China also does not need to match the FWCI of the United States to produce more substantial research because it produces such a large amount of it. For example, a recent analysis of AI papers by the Allen Institute for Artificial Intelligence (AI2) found that the U.S. share of the 10 percent most cited AI papers shrank from 47 percent in 1982 to 29 percent in 2018. China's share, however, has grown to 26.5 percent, from roughly 0 percent in 1982.[83] AI2's research suggests China will surpass the United States in producing papers ranked in the top 10 and 1 percent of all AI research papers by 2020 and 2025, respectively.[84] While China's number of citations may be inflated by self-citation, which is when an article cites another article in the same journal, the quality of Chinese research has increased both absolutely and relative to the United States and the European Union.[85]

DEVELOPMENT

To experience the full benefits of AI, nations must have healthy AI ecosystems that lead to the development of innovative AI technologies and firms. For example, nations must have sufficient venture capital and private equity funding to connect inventors with the money, expertise, and contacts necessary to develop and sell their products or services.[86] In addition, the number of firms indicates the health of a nation's ecosystem. Finally, patents indicate the ability of a firm or nation to innovate. This section analyzes AI venture capital and private equity funding, the acquisitions of AI firms, the number of AI firms, and patent data to compare China, the European Union, and the United States.

The governments of China, the European Union, and the United States have each focused on developing AI firms, including by providing funding to AI start-ups. For example, China partially funds private equity firms such as Canyon Bridge, and the Guangzhou Municipal Government provided a $301 million grant to CloudWalk, which develops facial recognition software, in 2017.[87] The EU Commission is using the European Fund for Strategic Investments to address market failures and stimulate private investment in AI. It created VentureEU, a venture capital fund, to provide up to €410 million ($459 million) to start-ups, including AI start-ups.[88] Lastly, In-Q-Tel, a U.S. government taxpayer-funded venture capital firm, has invested in at least 10 AI firms, including Forge.ai, which creates technology to transform unstructured information into machine-ready data, and Mythic, which creates computer chips for AI applications.[89]

We allotted the development section 25 of the 100 available points. On an absolute basis, the most recent data available showed the United States (14.9 points) leading the European Union (5.3 points) and China (4.8 points). Controlling for the size of their economies, the United States (19 points) led the European Union (4.5) and China (1.4).

TOTAL VENTURE CAPITAL AND PRIVATE EQUITY FUNDING (2017–2018): Tracking private funding is one way to measure the ability of nations to develop AI firms. This indicator measures venture capital and private equity funding for AI firms between 2017 and 2018. The United States (estimated $16.9 billion) led, followed by China (estimated $13.5 billion) and the European Union (estimated $2.8 billion).[90] On a per-worker basis, the United States led significantly over China and the European Union.[91]

Our overall findings align with research done by multiple groups, including the Organization for Economic and Cooperative Development (OECD), which also found the United States received the most funding over the last three years.[92] In addition, data from PitchBook, a private-capital market-data provider, confirmed that the United States, followed by China and the European Union, led in private equity and venture capital funding.[93]

Table 21: AI venture capital and private equity funding (2017–2018) [94]

Metric	China	European Union	United States
AI Venture Capital and Private Equity Funding (Billions)	$13.5	$2.8	$16.9
AI Venture Capital and Private Equity Funding per Worker (Billions)	$17.2	$11.2	$102.4

NUMBER OF VENTURE CAPITAL AND PRIVATE EQUITY FUNDING DEALS (2017–2018): AI Venture capital and private equity funding can be concentrated in a few a large deals, which is why it is not only important to measure the level of venture capital and private equity funding in dollar amounts, but to also track the overall number of venture capital and private equity funding deals. Between 2017 and 2018, U.S. AI firms received the most investments (1,270 deals) ahead of the European Union (660) and China (390).[95] Per one million workers, the United States (8 deals) led the European Union (3) and China (0.5).

Table 22: Number of venture capital and private equity funding deals, 2017–2018[96]

Metric	China	European Union	United States
Number of Venture Capital and Private Equity Funding Deals	390	660	1,270
Number of Venture Capital and Private Equity Funding Deals per 1 Million Workers	0.5	2.6	7.7

ACQUISITIONS (2000–2019): Firms can bolster their ability to develop AI products and services through acquisitions. This indicator tracks the number of acquisitions of firms in the AI category group on CrunchBase by region from January 2000 through May 2019. U.S. firms (526 acquisitions of AI firms) were ahead of both EU (139) and Chinese firms (9).[97] Per one million workers, U.S. companies had made three acquisitions while both EU (0.6) and Chinese (0.01) companies had made fewer than one acquisition each.[98]

Table 23: Number of acquisitions of AI firms (January 2000–May 2019)[99]

Metric	China	European Union	United States
Number of Acquisitions of AI Firms	9	139	526
Number of Acquisitions of AI Firms per 1 Million Workers	<0.1	0.6	3.2

NUMBER OF AI START-UPS (2017): Similar to other technology-based start-ups, AI start-ups can be an important driver of a nation's economic growth and competitiveness.[100] Roland Berger, a global consultancy, and Asgard, a Berlin-based investment firm, categorized AI start-ups as firms that produce a primary product or service that utilizes AI, excluding hardware. The firms' research found that the United States was home to 1,393 AI start-ups in 2017, ahead of the European Union (726 start-ups) and China (383 start-ups).[101] Per one million workers, the United States led (8), followed by the European (3) and China (0.5).[102]

Table 24: Number of AI start-ups, 2017[103]

Metric	China	European Union	United States
Number of AI Start-ups	383	726	1,393
Number of AI Start-ups per 1 Million Workers	0.5	2.9	8.4

NUMBER OF AI COMPANIES (2019): It is not just the number of AI start-ups that matters, but also the number of well-funded AI firms, including start-ups. This indicator tracks the number of firms in the AI category group on CrunchBase that have received at least $1 million in combined funding, whether that funding be venture capital, private equity, debt financing, grants, etc. The United States (1,727 firms) has more such firms than the European Union (762) and China (224) combined.[104] Per one million workers, the United States leads (10), followed by the European (3) and China (0.3).[105]

Table 25: Number of AI companies, 2019[106]

Metric	China	European Union	United States
Number of AI Companies	224	762	1,727
Number of AI Companies per 1 Million Workers	0.3	3.1	10.5

NUMBER OF HIGHLY CITED AI PATENT FAMILIES (1960–2018):
One measure of innovation is patents. However, using patents to measure innovation is difficult, in part because national standards for granting patents differ. Many patents issued by the Chinese Patent Office are of relatively poor quality, and therefore patent counts from China cannot be compared easily against patents issued by the U.S. Patent and Trademark Office (USPTO) or from European patent offices.[107] Indeed, just 4 percent of AI patents first filed in China were also filed in another jurisdiction, compared with 32 percent of patents first filed at the USPTO—which is an indicator of the significantly higher quality of U.S. patents.[108]

As a result, this report primarily focuses on Patent Cooperation Treaty (PCT) patent applications and highly cited patent families, which are patents filed for the same invention in numerous jurisdictions.[109] Between 1960 and 2018, patent applicants filed 28,031 highly cited patent families at the USPTO, which was significantly more than the number of highly cited patent families filed at EU (2,985) and Chinese (691) offices.[110] While this metric reveals where applicants filed patents, and not their location, most applicants typically first file in the nation in which they reside.[111] Per one million workers, the United States led (170 patent families) the European Union (12) and China (4).[112]

Table 26: Number of highly cited AI patents, 1960–2018[113]

Metric	China	European Union	United States
Number of Highly Cited AI Patents	691	2,985	28,031
Number of Highly Cited AI Patents per 1 Million Workers	0.9	12.0	170.0

NUMBER OF PCT AI PATENT APPLICATIONS (1960–2018): Another measure of patents is patents filed under the international Patent Cooperation Treaty (PCT). In this indicator, the World Intellectual Property Organization (WIPO) tracked the number of AI patents first filed between 1960 and 2018 as PCT patents. The United States (1,863 filings) led China (1,085) and the European Union (1,074).[114] Per one million workers, the United States (11 PCT applications) led the European Union (4) and China (1).[115] According to WIPO, not all patents included the address of the applicant. Consequently, these figures are likely deflated.

Table 27: Number of PCT patent applications, 1960–2018[116]

Metric	China	European Union	United States
Number of PCT Patent Applications	1,085	1,074	1,863
Number of PCT Patent Applications per 1 Million Workers	1.4	4.3	11.3

INTERPRETATION: THE UNITED STATES IS LEADING, AND CHINA MAY SOON SURPASS THE EU

The United States led in every AI-development indicator, suggesting it is better positioned than China and the European Union to continue to develop leading global firms in AI. Patent and acquisition data also reveals that the United States already has a significant lead in developing world-class AI firms. However, China, partially due to its robust venture capital and private equity ecosystem, is catching up to the EU and the United States. On the contrary, the EU, despite currently ranking slightly higher than China in AI development, likely lacks the funding to seriously challenge U.S. supremacy.

The United States Is Already Leading in Developing World-Class AI Firms

U.S. firms perform strongly in patents and dominant AI acquisitions. For example, Microsoft and IBM have applied for more patents than any other entity in 8 of 15 subcategories of machine learning, including supervised learning and reinforcement learning. The Chinese Academy of Sciences has applied for the most patents in deep learning, however, and Siemens (Germany) has applied for the most patents in neural networks. [117] Nonetheless, a U.S. firm leads in patent applications in 12 of 20 fields, including agriculture (John Deere), security (IBM), and personal devices, computing, and human-computer interaction (Microsoft).[118] In addition, between 2012 and 2016, IBM led in AI patent applications (3,677) globally, with Google parent company Alphabet (2,185) and Microsoft (1,952) ranking in the top five.[119]

Table 28: All-time leaders in AI patent families by application field[120]

Field	Firm	Location
Agriculture	Deere	U.S.
Arts and Humanities	Sony	Japan
Banking and Finance	IBM	U.S.
Business	IBM	U.S.
Cartography	Alphabet	U.S.
Computing in Government	Microsoft	U.S.
Document Management and Publishing	IBM	U.S.
Education	IBM	U.S.
Energy Management	State Grid Corporation of China	China
Entertainment	Sony	Japan
Industry and Manufacturing	IBM	U.S.
Law, Social, and Behavioral Sciences	State Grid Corporation of China	China
Medical and Life Sciences	Siemens	EU
Military	Samsung	Korea
Networks	Microsoft	U.S.
Personal Devices, Computing, and Human Computer Interaction	Microsoft	U.S.
Physical Sciences and Engineering	Siemens	EU
Security	IBM	U.S.
Telecommunications	Microsoft	U.S.
Transportation	Toyota	Japan

In addition, all ten of the companies that lead in AI company acquisitions are based in the United States. The leading companies include Alphabet (19), Apple (16), Microsoft (10), Amazon (7), and Facebook (7).[121]

Table 29: Number of AI acquisitions by top acquirers, January 2000–May 2019[122]

Acquiring Company	Number of Acquisitions	Acquiring Company	Number of Acquisitions
Alphabet	19	Intel	7
Apple	16	Salesforce	7
Microsoft	10	Cisco	6
Amazon	7	Oracle	6
Facebook	7	Yahoo	6

These acquisitions have bolstered U.S. firms, with multiple of the acquired companies having provided significant research and commercial offerings since their purchase. For example, Alphabet acquired DeepMind, one the world's leading AI organizations, for $500 million in 2014.[123] Since its acquisition, DeepMind has developed an AI system that can analyze eye scans to make diagnoses (e.g., hemorrhages), increased the value of wind energy from Google turbines by 20 percent using AI, and released an interactive dataset of more than 100,000 panoramic images to advance the development of AI systems that can navigate using visual cues instead of maps.[124] Similarly, Apple acquired Siri for $200 million in 2010, and Amazon acquired Evi Technologies for $26 million in 2013.[125] Amazon used its acquisition's technology to develop its virtual assistant, Alexa, and has since sold more than 100 million devices that incorporate it.[126]

World-leading firms, coupled with ample funding for start-ups, means the United States is well positioned for multiple models of AI adoption. In the first model, firms mostly adopt general-purpose, standardized AI services.[127] Similar to China, the United States has large technology firms, including Google and Amazon, that are providing these services. In the second model of adoption, AI start-ups focused on creating products and services to solve specific problems, such as drone delivery, disrupt traditional businesses using AI.[128] The United States is well positioned in this AI-uptake scenario as well because of its breadth and depth of well-funded AI start-ups.

China is Catching Up

While the United States may be in the lead in AI development, it is not clear it will maintain its lead. Multiple analyses of funding data for AI start-ups, including this one, have found at least one year where Chinese AI start-ups received more funding than U.S. start-ups. For example, Chinese AI start-ups received an estimated $8.1 billion in investment in 2017, compared with an estimated $6.2 billion for U.S. start-ups.[129] In addition, research by Tencent, a Chinese technology company, found the average time for an AI start-up to receive investment was 14.8 months in the United States, compared with 9.7 months in China.[130]

China has also begun to close its large gap to the United States in terms of the number of investments in AI start-ups, reducing the difference from 476 investments in 2016 to 371 in 2018.[131] The smaller gap is both due to significant growth in the number of investments in Chinese start-ups and relatively stagnant growth in the number of deals involving U.S. AI start-ups. U.S. AI start-ups did receive a record amount of investment in 2018, however, receiving an estimated $10.7 billion in investment, while Chinese AI start-ups received an estimated $5.4 billion in funding.[132] Data on financing in 2019 should help clarify whether the United States will be able to maintain its lead, or China will be able to match, or surpass, the United States in funding consistently.

EU Firms Lack Large Funding Deals

While private equity and venture capital funding for EU AI start-ups nearly tripled between 2016 and 2018, the European Union is firmly behind the United States and China.[133] For example, the United States received more funding in any year between 2016 and 2018 than the European Union received in the three years combined.[134] Similarly, Chinese AI start-ups received billions of more dollars in private equity and venture capital funding than the EU in both 2017 and 2018. Unless EU start-ups begin to garner significantly more funding, the European Union is at risk of falling further behind the United States and China.

It is difficult for the European Union to compete against the United States and China in AI funding in part because its investments, while noteworthy in number, are typically smaller. For example, a vast majority (70 percent) of EU's 2018 private equity and venture capital funding AI was through seed or angel rounds (rounds in which investors help new and small companies gain traction).[135] Indeed, roughly 45 percent of investments made in U.S. or Chinese AI start-ups in 2018 were part of seed or angel rounds. Due to the high risk of firms seeking such seed or angel funding not succeeding, the rounds typically involve transactions that total between $10,000 and $2 million. In contrast, Series C funding rounds, which are for more-established companies, are usually at least $10 million, and are often much larger. For example, the average Series C deal for a U.S. AI company in 2018 was nearly $61 million.[136] The EU lacks such transactions, however—only 1 percent of deals going to EU AI start-ups in 2018 were part of a Series C round, compared with 5 percent and 6 percent in the United States and China.[137] In addition, EU funding deals are almost always smaller on average, no matter the funding stage. For example, between 2016 and 2018, the average size of Chinese deals was larger than EU deals at the seed/angel, Series A, Series B, and Series C stages.[138] Similarly, the median U.S. deal has been larger than the median EU deal the past three years. These figures match anecdotal accounts that characterize Europe's start-up market as traditionally fraught with barriers, even though it is improving. For example, Irina Haivas, a principal at Atomico, a global technology investment firm, noted that in Europe there are barriers "to tech transfer and IP, access to funding to scale capital-intensive, research-based businesses, and to some degree, a perception barrier around the feasibility of 'commercially-driven,' non-academic careers."[139]

ADOPTION

Technological innovation is key to raising standards of living, and AI is likely to be a primary driver of technological innovation in the emerging innovation wave.[140] Indeed, AI adoption is estimated to create $13 trillion of gross domestic product (GDP) growth by 2030.[141] Firms increasingly need to adopt AI in order to remain competitive in the global economy because it allows them to automate and optimize many facets of their business, derive faster and more accurate insights from data, and develop new products and services. As a result, countries where businesses are late adopters will lag in the global economy.[142] In addition to the economic gains, AI stands to enable important societal gains, such as reducing automobile accidents and injuries and enabling better treatment of diseases.[143]

The governments of China, the European Union, and the United States have each publicly recognized the importance of AI adoption. For example, China's Ministry of Industry and Information Technology released the "Three-Year Action Plan for Promoting the Development of a New Generation of Artificial Intelligence Industry (2018–2020)" in 2017, which called for the integration of AI in the manufacturing industry.[144] In addition, the EU's coordinated plan on AI calls for the creation of "common European data spaces" in sectors such as manufacturing and energy to support the development and adoption of AI.[145] Lastly, U.S. President Trump issued an executive order in 2019 that called for the creation of technical standards to enable the adoption of AI.[146]

To assess the level of AI adoption in China, the European Union, and the United States, we analyzed surveys regarding AI adoption. We allotted this section 10 of 100 available points. On an absolute basis, China led (7.7

points) over the European Union (1.3) and United States (1). In terms of the percentage of firms adopting or piloting AI, China led (4.7 points), followed by the United States (2.9 points) and the European Union (2.5 points).

Percentage of Firms That Are Adopting AI: The first way to measure AI adoption is to track the percentage of firms that are successfully adopting AI into their business processes. In 2018, China (32 percent of firms) led in this indicator, followed by the United States (22 percent) and European Union (estimated 18 percent).[147]

Table 30: Percentage of firms adopting AI, 2018[148]

Metric	China	European Union	United States
Firms Adopting AI	32%	18%	22%

Percentage of Firms Piloting AI: A second way to measure AI is to track the percentage of firms that are piloting AI. This metric tracks firms that were piloting AI initiatives as of September and October 2018.[149] In this metric, China also led (53 percent of firms), followed by the United States (29 percent) and the European Union (estimated 26 percent).[150]

Table 31: Percentage of firms piloting AI, 2018[151]

Metric	China	European Union	United States
Firms Piloting AI	53%	26%	29%

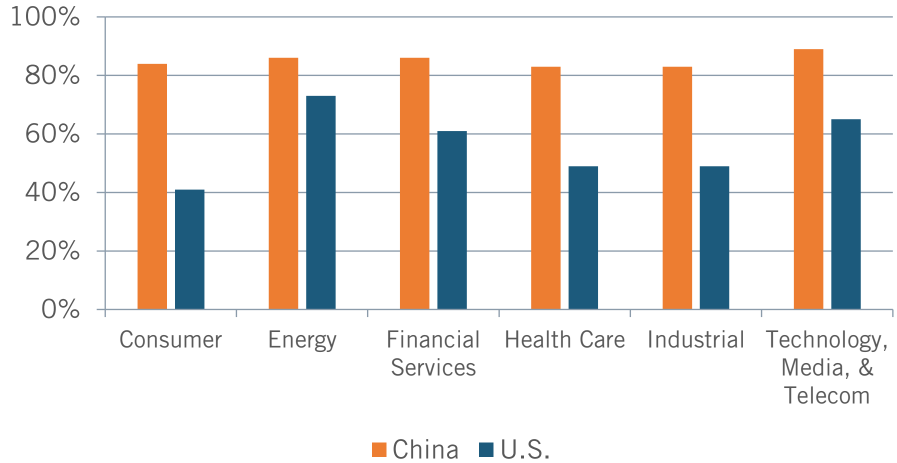
INTERPRETATION: THE CHINESE PEOPLE'S VIEWS OF AI MAY BE SPURRING ADOPTION

While different surveys have found varying rates of adoption, they indicate similar trends: China is adopting AI at a faster rate than the United States and the European Union.[152] China may be ahead in AI adoption in part because its people and businesses recognize the value of AI at higher rates.

Chinese Individuals Believe in the Value of AI

Unlike the United States and the European Union, China's adoption scores are relatively uniform no matter the business sector. For example, the percentage of U.S. firms active in AI, meaning they are adopting or piloting AI, varies as much as 32 percentage points between different sectors. Yet, China's share of active AI firms varies only as much as 6 percentage points between the highest- and lowest-adopting sectors.[153]

Figure 2: Percentage of firms that have adopted AI or are piloting AI in China and the United States by industry, 2018[154]



There are several possible explanations for this phenomenon. The first is that the importance of AI has permeated Chinese culture. Indeed, in the public sector, Chinese mayors and other local officials began rushing to invest in AI start-ups and adopt AI following the release of the State Council's "New Generation of Artificial Intelligence Development Plan" in 2017.[155] By embracing AI, Chinese governments not only provide capital to AI firms, but also create use cases that demonstrate the benefits of AI, thereby encouraging private firms to adopt AI.[156] Moreover, a higher share of Chinese individuals (76 percent) believe AI will have an impact on the entire economy than individuals in the United States (58 percent), France (52 percent), Germany (57 percent), Spain (55 percent), and the United Kingdom (51 percent).[157] The second potential explanation is that, compared with its Western counterparts, China's techno-utilitarian culture is more willing to adopt AI if it provides a broader social good, even if some individuals believe there are ethical questions concerning AI.[158]

Indeed, Chinese individuals have many extremely positive views of AI while also believing in several negative implications. For example, more Chinese people (53 percent) believe that their job will no longer exist in the next ten years because of AI than people in the United States (26 percent), France (27 percent), Germany (27 percent), Spain (38 percent), and the United Kingdom (30 percent). This view, however, is counterbalanced by 91 percent of Chinese individuals believing AI will create new jobs, compared with 48 percent of U.S. individuals. Individuals in France (42 percent), Germany (37 percent), Spain (44 percent), and the United Kingdom (40 percent) were even less likely to believe AI will create new jobs in the next 10 years. Chinese individuals also believe in higher rates that AI will create more inequality between the privileged and underprivileged, and the educated and uneducated.[159]

U.S. Businesses Are Lagging in Conveying the Importance of AI to Their Employees

Chinese firms are doing a better job than U.S. firms of conveying the importance of AI to their employees. For example, 43 percent of U.S. individuals say their employers present the development of AI and the digital transformation of the organization as being strategically important, compared with 85 percent of Chinese individuals.[160] Regarding the development of AI and digital transformation, Chinese individuals are also more likely to expect their manager to make statements about the subject, hire new individuals because of it, increase the number of training courses for the topic, and launch new projects because of it.[161] Thus, it is unsurprising that the same survey found 54 percent of U.S. individuals responded that their workplace had no plan to deploy AI tools, versus 22 percent of Chinese individuals.[162]

Many EU Individuals Are Skeptical of AI

While U.S. firms may not be properly conveying the importance of AI to their employees, many EU individuals are outright skeptical of AI. As such, while the European Union is only slightly behind the United States in adoption, it is significantly behind China. Similarly, individuals in the European Union typically have more negative feelings toward AI in the workplace than workers in the United States, and significantly more negative feelings than employees in China. For example, a higher share of individuals in the United Kingdom (55 percent), Germany (61 percent), France (65 percent), and Spain (53 percent) cite at least one negative feeling when thinking about the consequences of AI regarding their work, compared with 51 percent and 24 percent of individuals in the United States and China, respectively.[163] Individuals in the European Union may lack enthusiasm for AI because they have had fewer positive experiences with it—77 percent and 91 percent of individuals in the United States and China reported AI tools having had positive implications for their effectiveness. Lower shares of French (62 percent), German (65 percent), Spanish (72 percent), and British (74 percent) people report similar feelings.[164]

Other surveys have found that Europe has shown less urgency to adopt AI. For example, a survey of executives found that 40 percent of European respondents thought AI "is still nascent and unproven," compared with just 27 percent and 30 percent of North American and Asian-Pacific firms, respectively.[165] These trends represent correlations, not causes, and suggest a link between the adoption of AI and nations' views of AI.

DATA

AI systems often rely on vast quantities of data for training. Large datasets help AI systems develop highly accurate models to perform tasks ranging from navigating without a map to identifying faces to answering Google search queries.[166] Moreover, machine learning techniques allow AI systems to recognize subtle patterns in large datasets that are difficult or impossible for humans to perceive. This is one reason why many AI systems perform certain tasks better than human experts, such as identifying the signs of lung cancer in commutated tomography scans.[167]

Policymakers in China, the European Union, and the United States have recognized the importance of data. In 2015, to support the use of big data, China listed open data as one of ten national projects.[168] The EU's coordinated plan on AI states, "AI needs vast amounts of data to be developed … The larger a data set, the better AI can learn and discover even subtle relations in the data."[169] In the United States, President Trump's American AI Initiative directs the government to "enhance access to high-quality and fully traceable federal data," and directs the U.S. Office of Management and Budget to identify and address data quality limitations.[170]

There is no straightforward metric for measuring the relative amount and value of data available for AI in a particular place. However, individuals produce a significant amount of data when they engage in various online and offline activities, such as using search engines, posting on social media, and making purchases. These activities produce data that can have enormous value for machine learning models. Therefore, one way to estimate the potential value of data in a country or region is to consider the percentage of the population that engages in digital activities.

This section measures the amount and availability of data in China, the European Union, and the United States concerning Internet activity, the Internet of Things (IoT), productivity (i.e., big data analytics), mobile payments, EHRs, genetics, and high-resolution maps. We also accounted for how regulations in a region may create barriers to data collection, access, and use. For some of these indicators, we have data to make direct comparisons. In others, we could not find directly comparable data. Consequently, we used a combination of quantitative and qualitative analysis to rank the regions first, second, and third.

In some cases, the most important measure is the percentage of the population participating in these activities. For example, using mobile-device locations to analyze traffic patterns in a certain location likely depends on having a critical mass both for accuracy and completeness of the model. In other cases, the total number of users is likely more important. For example, for drug development, it is likely more important to have the largest number of patients using EHRs than to have the largest percentage of patients. In some cases, this gives China a natural advantage given its larger population; however, it also suggests the European Union and United States should look to build population-level datasets that go beyond their borders.

We allotted this category 25 of 100 possible points. On an absolute basis, the most recent data available showed China leading (11.6 points), the United States (8.1 points) and the European Union (5.4 points). Controlling for workforce sizes, the United States led (11 points) China (7.9) and the European Union (6.2).

Fixed Broadband Subscriptions: Internet users generate data each time they browse the web, and AI systems can analyze this data to improve the effectiveness of advertisements. This indicator tracks the number of broadband subscriptions. As of 2018, China (394 million fixed broadband subscriptions) led the European Union (176 million) and the United States (110).[171] Per 100 people, the European Union (35 fixed broadband subscriptions) ranked ahead of the United States (34) and China (28).[172]

Table 32: Fixed broadband subscriptions, 2018[173]

Metric	China	European Union	United States
Number of Fixed Broadband Subscriptions (Millions)	394.2	175.7	109.8
Number of Fixed Broadband Subscriptions per 100 People	28.0	34.5	33.9

Mobile Payments (2018): Consumers also generate data technology firms can analyze each time they use a mobile device to purchase a product. We define ”mobile payments” as using a mobile device to scan, tap, swipe, or check in order to make a point-of-sale transaction, which does not include purchases such as those of digital goods on mobile devices.[174] Over 525 million Chinese individuals were estimated to have made a mobile payment in 2018, compared with 55 million in the United States and an estimated 44 million people in the European Union.[175] An estimated 45 percent of the Chinese population used mobile payments in 2018, compared with 20 percent for the United States, 13 percent for the United Kingdom, and 8 percent for Germany.[176]

Table 33: Number of individuals using mobile payments, 2018[177]

Metric	China	European Union	United States
Number of Individuals Using Mobile Payments (Millions)	525.1	44.7	55.0
Population Using Mobile Payments	45.2%	10.2%	20.2%

Note: Data for the EU was only available for Germany and the United Kingdom.

IoT Data (2018): IoT devices can generate large amounts of data organizations can use to train machine-learning systems. These systems can then automate a wide range of tasks, from monitoring the health of railway tracks to dynamically controlling traffic lights that ease congestion to tracking pollution.[178] This indicator tracks the estimated amount of IoT data each region produced in 2018 in terabytes (TB). China (152 million TB) led the United States (69 million TB) and the European Union (53 million TB).[179] Per 100 workers, the United States (42 TB) led the European Union (21 TB) China (19 TB).[180]

Table 34: Amount of new IoT data generated, 2018[181]

Metric	China	European Union	United States
New IoT Data Generated (TB, Millions)	152	53	69
New IoT Data Generated (TB) per 100 Workers	19.3	21.5	41.9

Productivity Data (2018): Organizations are constantly generating data they can use as inputs to train their AI systems. For example, an airline can analyze its customer-, agency-, airplane-, and itinerary-map data to better control its flight costs.[182] This indicator tracks the estimated amount of productivity data, which is a combination of big data and meta data, each region produced in 2018. The United States (966 million TB) led China (684 million TB) and the European Union (583 million TB). Per 100 workers, the United States led (586 TB) the European Union (234 TB) and China (87 TB).[183]

Table 35: Amount of new productivity data generated, 2018[184]

Metric	China	European Union	United States
New Productivity Data Generated (TB, Millions)	684	583	966
New Productivity Data Generated (TB, Millions) per 100 Workers	86.9	233.9	585.9

Electronic Health Records: Researchers have used EHRs to develop AI systems that can perform a wide range of functions, from predicting whether patients will likely be hospitalized to helping track the spread of diseases.[185] Comprehensive data for China, all European Union member states, and the United States concerning EHR adoption was not available. However, a combination of quantitative and qualitative information suggests the United States has the greatest access to EHRs, ahead of the European Union and China. Consequently, the United States also leads in access per capita, followed by the European Union and China.

The adoption of EHR systems is relatively high in all the examined regions, but the availability to access EHRs across borders and between providers is not. For example, a 2015 survey found that the 84 percent of U.S. primary care physicians used EHR systems, compared with 99 percent of Swedish physicians, 98 percent of Dutch physicians, 98 percent of U.K. physicians, 84 percent of German physicians, and 75 percent of French physicians.[186] In China, a 2012 survey found that 48 percent of hospitals had basic forms of EHR systems.[187] Since 2012, the number of Chinese hospitals using electronic records may have grown to more than 90 percent.[188] In 2017, more than 96 percent of U.S. hospitals used certified EHR systems.[189]

Yet, in 2015, only 30 percent of U.S. hospitals could find, send, and receive EHRs to and from other providers.[190] Qualitative evidence suggests interoperability is even lower in China and the European Union. In China, hospitals frequently use EHR systems that are not interoperable, forcing patients to bring printed health records when seeing doctors in different hospitals.[191] In the European Union, the ability to access and share medical data across borders varies greatly, limiting the ability to train AI systems on cross-border data.[192] Indeed, many European citizens have no access to EHRs.[193]

Genetic Data: Another type of data that is useful to improving human health is genetic data. AI can analyze DNA sequences to find mutations linked to illnesses such as cancer and heart disease.[194] This indicator tracks the availability of genetic data from individuals in China, the European Union, and the United States. The United States, followed by China and the European Union, leads in absolute terms. Consequently, the United States definitively leads on a per capita basis. While it is difficult to compare China and the EU, China's rising genetic testing industry and bans in the EU suggest China is ahead of the EU on a per capita basis.

As of 2017, more than 15 million U.S. consumers had purchased genetic testing kits, compared with 300,000 consumers in China.[195] And as of 2019, three U.S. firms—Ancestry.com, 23andMe, and Gene by Gene—had sold roughly 25 million testing kits.[196] Similar data for Chinese firms was not available, but it is known that 23Mofang, the largest of the more than 100 Chinese genetic testing companies, has more than 200,000 users.[197] In addition, several U.S. firms such as Gene by Gene, Veritas Genetics, and Full Genomes Corporation are sequencing entire human genomes, unlike many direct-to-consumer genetic testing companies that often analyze only 1 percent of the total genome.[198] These facts suggest U.S. firms have greater access to genetic data. In contrast, direct-to-consumer genetic testing bans in Germany and France, nations that account for roughly 30 percent of the EU's population, suggests the United States and China are ahead of the European Union.[199]

High-Resolution Mapping Data: High-resolution mapping data is important to the development of numerous AI systems, including autonomous vehicles. This indicator tracks the availability of 3D elevation data—a 3D computer graphics representation of a terrain's surface—at the 1-meter level. The United States leads in this indicator, followed by the European Union and China. Consequently, the United States, followed by the European Union and China, leads when controlling for the size of each labor force.

As of April 2019, there is 1-meter or better resolution data currently available or in progress for 45 percent of the United States.[200] In contrast, only 6 EU member states, representing approximately 15 percent of the geographic territory of the EU, provide public access to complete high-resolution 3D elevation data. The rest either provide partial coverage, low-resolution coverage, or do not make the data available to the public.[201] In China, the PRC Surveying and Mapping Law requires all entities performing mapping to have a license, which only 14 Chinese entities had obtained as of January 2018. Indeed, Chinese entities view the license as a "gold key" because it is difficult to obtain. The license requirement has the effect of only allowing 14 entities to produce autonomous driving maps.[202]

Regulatory Barriers: Data protection regulations may affect the amount of data available to organizations to train and use AI systems. Some data protection regulations, such as requirements for reporting data breaches, have little effect on the availability of data. Others, such as requirements to minimize data collection or retain data for limited periods of time, can have a significant impact on data availability. The EU's General Data Protection Regulation (GDPR), which came into effect on May 25, 2018, has put constraints on the collection and use of data.[203]

We assessed how regulations in China, the European Union, and the United States affect the collection and use of data in each region. We believe the EU's regulatory environment creates the most restrictions on the collection and use of data, followed by the United States and China. Consequently, China received three points, the United States received two points, and the European Union received one point for this indicator. Notably, our overall data rankings do not change when we remove regulatory barriers as an indicator.

We arrived at this ranking for several reasons. First, the GDPR has created an artificial scarcity of data by making it more difficult for organizations to collect and share data. The law regulates how organizations use or process the data of anyone living in the EU, and generally prohibits organizations from using data for any purposes other than those for which they first collected it. Indeed, Article 5 requires data be "collected for specified, explicit and legitimate purposes," and "adequate, relevant and limited to what is necessary."[204] These two restrictions—purpose specification and data minimization—significantly limit organizations innovating with data by restricting them from both collecting new data before they understand its potential value and reusing existing data for novel purposes. It is not always feasible for companies to know what data is most valuable or will yield the most important insights. Indeed, organizations often create new value by combining datasets, which makes it difficult to predict the future value of datasets at the outset.[205] By imposing stringent restrictions on the collection and use of data, the GDPR makes it more challenging for businesses to use the data consumers are creating.

Second, the United States has multiple federal data privacy laws, including sector-specific and state privacy laws.[206] For example, the Health Insurance Portability and Accountability Act (HIPAA) and the Family Educational Rights and Privacy Act (FERPA) impose multiple restrictions on the use of medical and educational records, respectively. In California alone, there are more than 25 privacy and data security laws, including the recently passed California Consumer Privacy Act of 2018, which will create substantial restrictions on how organizations may collect and use data when it comes into effect on January 1, 2020.[207] However, U.S. data privacy laws have not restricted organizations from collecting and using data as much as those in the EU.

Finally, China established a national standard on personal information protection in 2018. On paper, the standard is onerous.[208] Indeed, it requires organizations to only collect the minimum amount of data required, use it only for its original purposes, and retain it for the shortest amount of time necessary.[209] However, this standard is not legally enforced, and its drafters intended the standard to be more permissive and business friendly than the GDPR.[210] Nonetheless, China uses such national standards to develop laws, and Chinese legislators are in the process of drafting a law to protect national data privacy.[211] In addition, Chinese regulators have already begun to increase enforcement activities using existing laws, such as announcing a review of 1,000 mobile apps and threatening to revoke the business licenses of those that mishandle user data.[212]

Still, anecdotal evidence suggests Chinese companies face fewer restrictions on collecting and using consumer data than their U.S. and European counterparts.[213] Consequently, we ranked China's regulations as the least restrictive. Moreover, Chinese companies have formed a number of partnerships with local government to collect data in public spaces, which laws in the United States and EU would often restrict.[214]

INTERPRETATION: CHINA COULD HAVE A BIGGER DATA ADVANTAGE IN THE FUTURE

China leads in both data collected and likely the amount of data available to large Internet firms, which are also the firms best leveraging AI. This fact, combined with multiple data deficiencies that changes in Chinese policies could alleviate, means China could have an even bigger advantage in the future.

Chinese Internet Firms Likely Have Greater Access to a Wider Variety of Data

Large Chinese Internet firms likely have a data advantage compared with their Western counterparts for at least two reasons. First, services in the West are relatively divided between firms. For example, Amazon users are able to buy groceries but not book a hotel. Chinese technology companies, on the other hand, have created all-in-one super apps. For example, Kai-Fu Lee has written that WeChat, an app owned by Chinese technology company Tencent, allows users to "hail a taxi, order a meal, book a hotel, manage a phone bill, and buy a flight to the United States, all without ever leaving the app."[215] In the United States, these services, and thus the data, are divided between such firms as Uber, Postmates, Expedia, Verizon, and Venmo.[216]

Second, Chinese technology companies have embedded themselves in traditionally off-line activities. For example, Didi, the Chinese equivalent of Uber, has bought gas stations and auto repair shops. In addition, Meituan Dianping, whose origins are similar to that of Yelp, not only provides users with a platform to compare businesses, but also handles food delivery.[217] Chinese Internet companies are therefore afforded the opportunity to collect a greater variety and depth of data than their American counterparts.[218] It should be noted, however, that the broader global reach of some U.S. technology giants provides them with their own data advantage. For example, Facebook has more than 2 billion users, while WeChat has only 1.1 billion users. Should Chinese firms achieve more success internationally, such as with the social media video app TikTok, the U.S. advantage will diminish.[219]

China Is Not Close to Its Data Potential

China is also not fully taking advantage of the data it generates. For example, U.S. companies have been collecting structured data, such as loan repayment rates, for decades in industries such as insurance and finance.[220] But Chinese companies have been slower to adopt enterprise data storage, making it more difficult to extract insights and value from such data.[221] China is also behind its Western counterparts in creating standards that help organizations share data across platforms.[222] Government agencies have neglected fundamental standards on data collection, causing significant amounts of data to be unreadable by computers, thereby lowering the quality and usability of data for analysis.[223] China is behind its counterparts in making government data available to the public, despite listing open data as a national project in 2015, and local governments making some progress.[224] Finally, while other countries are benefiting from the increase of global cross-border data sharing, China's Internet ecosystem remains closed, limiting the amount of data it shares and receives from foreign nations.[225] This "closedness" reduces the diversity of data Chinese companies collect.

HARDWARE

AI systems rely on semiconductor devices, such as integrated circuits, that can perform large numbers of operations per second. Indeed, graphics processing units (GPUs), which are circuits that perform mathematical operations in parallel, have catalyzed recent AI developments.[226] In addition, technologies such as supercomputers, which combine processing units such as GPUs and central processing units, can expand the capabilities of AI systems through massive computational power. For example, researchers have combined supercomputers and machine learning techniques to model climate change as well as the merging of blackholes.[227]

The aforementioned hardware is important to a nation's AI competitiveness for several reasons. First, nations with a weak semiconductor industry can be vulnerable to the actions of other countries. For example, in 2018, the United States banned American companies from providing parts and software to ZTE, a large Chinese telecommunications equipment manufacturer. Due to ZTE's reliance on semiconductor devices from U.S. firms, the company nearly folded. While the United States ultimately lifted the ban, the situation highlighted China's dependence on Western technology.[228] More recently, the United States has blocked U.S. firms from selling chips to five specific supercomputing entities, and the U.S. Commerce Department has black listed Huawei, which prevents firms from selling U.S. technology to Huawei without a license.[229] Second, many experts believe AI chips designed specifically for AI applications, such as autonomous vehicles or facial recognition, will outperform such proven technologies as GPUs.[230] As a result, non-semiconductor firms, such as Apple, Alphabet, and Amazon, are designing their own AI chips to meet their specific needs, which could increase the performance of their AI systems and thereby provide them with a competitive advantage.[231] Third, high-performance computing has fueled breakthrough discoveries in several sectors, and access to the best performing supercomputers provides nations an advantage in developing leading-edge weapons systems and applications faster than other nations. [232]

This section analyzes China, the European Union, and the United States in terms of semiconductor sales, semiconductor R&D spending, the number of firms designing AI chips, the number of supercomputers ranked in the top 500 by performance, and the aggregate system performance of the supercomputers. We allotted this category 10 of the 100 available points. On an absolute basis, the most recent data available showed the United States leading in hardware (6 points), followed by China (2.5) and the European Union (1.5). Controlling for workforce sizes, the United States (7.6 points) led the European Union (1.5) and China (0.8).

Semiconductor Sales: This indicator measures the number of semiconductor firms in the top 15 globally for sales during the first quarter of 2019. The United States (6 firms) led the European Union (2) and China (1).[233]

Table 36: Number of firms in top 15 for semiconductor sales, 2019[234]

Metric	China	European Union	United States
Number of Firms in Top 15 for Semiconductor Sales	1	2	6

Semiconductor Research and Development Spending: It is not just semiconductor sales that matter, but the R&D spending by semiconductor firms, which is typically a major factor affecting who develops the best chips.[235] This indicator examines the number of semiconductor firms ranked in the top 10 for R&D spending in 2017. The United States led (5 firms) the European Union (0) and China (0), with the 5 U.S. companies spending a combined $24 billion on R&D.[236]

Table 37: Number of firms in top 10 for semiconductor R&D, 2017[237]

Metric	China	European Union	United States
Number of Semiconductor Firms in Top 10 for R&D Spending	0	0	5

Number of Firms Designing AI Chips (2019): Because some firms have found that developing customized AI chips has improved the performance of their AI systems, it is also important to track the number of firms designing AI chips. We analyzed multiple data sources, including CrunchBase, to track the number of firms developing chips for AI use cases.[238] The United States (55 firms) leads China (26 firms) and the European Union (12 firms).[239] Per 10 million workers, the United States leads (3) the European Union (0.5) and China (0.3).[240]

Table 38: Number of firms designing AI chips, 2019[241]

Metric	China	European Union	United States
Number of Firms Designing AI Chips	26	12	55
Number of Firms Designing AI Chips per 10 Million Workers	0.3	0.5	3.3

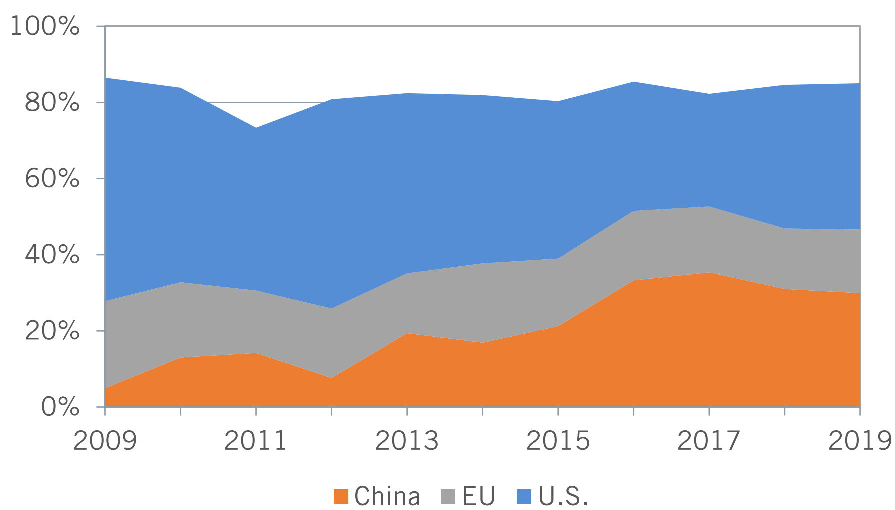
Number of Supercomputers (2019): This indicator examines the number of supercomputers in the top 500 in terms of performance, which is how many floating-point calculations the computer can perform per second.[242] China has more supercomputers ranked in the top 500 (219) than the United States (116) and European Union (92) combined. Per 10 million workers, the United States (7 supercomputers) is ahead of both the European Union (4) and China (3).[243]

Table 39: Number of supercomputers ranked in top 500, 2019[244]

Metric	China	European Union	United States
Number of Supercomputers Ranked in Top 500	219	116	92
Number of Supercomputers Ranked in Top 500 per 10 Million Workers	2.8	3.7	7.1

Supercomputers (Aggregate Systems Performance, 2019): Another way to evaluate nations is to measure the aggregate systems performance of their supercomputers ranked in the top 500. The United States has the highest share of the aggregate systems performance of the world's top 500 supercomputers (38 percent), ahead of China (30 percent) and the European Union (17 percent).[245] Per 10,000 workers, the United States (36 TFLOPs/s) leads the European Union (10) and China (6).[246]

Figure 3: Aggregate performance for supercomputers ranked in the top 500, 2009–2019[247]



INTERPRETATION: THE UNITED STATES STILL HOLDS A SUBSTANTIAL LEAD, BUT CHINA IS CATCHING UP WHILE THE EUROPEAN UNION IS FALLING BEHIND

An analysis of the data shows the United States still has a strong lead in hardware, but China is challenging the United States in supercomputers, China is rising in AI semiconductors, and the European Union is lagging behind its peers.

The United States Is in a Supercomputer Race With China

The U.S. position in the development of the world's fastest supercomputers demonstrates both its strengths and the rising capabilities of China. For example, 6 of the 10 fastest supercomputers reside in the United States. Moreover, the world's two fastest supercomputers, Summit and Sierra, are at U.S. Department of Energy (DOE) sites. In addition, Intel, a U.S. firm, developed 96 percent of the processors in the top-500 supercomputers. And of the 133 supercomputers that use accelerators or coprocessors, which enhance the performance of computers, 98 percent come from U.S. firms Nvidia or Intel.[248]

Yet, in some ways, China has caught up to the United States as a global leader in supercomputers. In June 2010, 282 of the 500 best-performing supercomputers in the world resided in the United States. In 2018, however, the United States had an all-time low of 109 supercomputers rank in the top 500.[249] In addition, both the United States and China are developing exascale computers, which can a perform quintillion calculations per second.[250]

China Is Rising in AI Chips

While China is competing with the United States in supercomputers, it has begun to show signs it may be able to close at least some of the gap with the United States in semiconductors, at least for AI chips.[251] In the past two years, several Chinese AI chip start-ups have received at least $100 million of funding. And some experts have argued China is better positioned to compete in the AI chip market than in the overall semiconductor market.[252] For example, Horizon Robotics, which develops AI chips for robots, received $600 million in a 2018 Series B funding round led by SK Hynix, a world-leading South Korean semiconductor firm. Similarly, Bitmain, which originally developed chips for bitcoin mining, has developed an AI chip and received nearly $765 million in funding between 2017 and 2018. Finally, Cambricon Technologies, which developed the world's first commercial deep learning processor for phones in 2016, received $100 million from the Chinese government-backed State Development & Investment Corporation in 2018.[253]

In addition, several leading Chinese technology firms, including Baidu, Tencent, Alibaba, and Huawei, are developing AI-optimized integrated circuits, which large U.S. technology firms are also doing. Huawei—which in particular has demonstrated some design prowess—and Apple were the first firms to create a smartphone processor that uses 7 nanometer (nm) process technology, which refers to the size of the transistors in a processor. Smaller transistors more efficiently use power than larger ones and increase the potential number of transistors in a processor, thereby making it potentially more powerful.[254]

These developments do not guarantee China will match or even substantially close the gap to the United States. After all, China's advances are relatively recent and have not translated into consistent market share in AI chips. For example, 0.1 percent of Bitmain's revenue for the first half of 2018 came from non-crypto-related business.[255] In comparison, many Western semiconductor firms have been designing processors and culminating engineering talent for decades. Indeed, several Chinese leaders have remarked that China's best chance to compete in AI chips is to develop specialized AI chips in the hope they become more important to AI than GPUs, where Nvidia dominates.[256] U.S. firms are also developing specialized AI chips, such as Google's Tensor Processing Unit and Luminous Computing's optical microchip—which uses different colors of light to move data.[257] Nonetheless, China's development of well-funded AI chip start-ups and advancements in chip design indicate it may be able to close at least some of the gap to the United States.

The EU Is Falling Behind

While China is rising, the European Union is falling. European industry still has market share in areas such as sensors, but it has abandoned the production of advanced digital semiconductors.[258] Moreover, there are signs the EU will remain a laggard in developing advanced chips for AI, which are costly and have a long development cycle. First, no EU semiconductor firm ranks in the top 10 for R&D spend.[259] Second, several of the most innovative chip designs are coming from large yet traditionally digital U.S. and Chinese firms, such as Alphabet, Facebook, and Baidu. But EU digital start-ups have struggled to gain scale due to the continent's fragmented markets and competition regulations.[260] As a result, there are fewer European equivalents to Alphabet and Baidu that have the money and motivation to design AI chips. Third, non-EU firms are acquiring promising European semiconductor design firms. Indeed, Softbank, a Japanese conglomerate, purchased ARM, a U.K. semiconductor company, for $32 billion in 2016. Similarly, Canyon Bridge, a Chinese-government-backed private equity firm, purchased Imagination Technologies, a semiconductor designer also based in the United Kingdom, for £550 million ($616 million) in 2017.[261]

POLICY RECOMMENDATIONS

China, the European Union, and the United States can each do more to win the global AI race. This section discusses recommendations for each.

CHINA

China has made significant progress in AI, but still lags behind, especially on a per capita basis. China however, produces more AI research papers and has an advantage in data. While China is on a path toward challenging the United States for global AI leadership, several of its policies limit its immense potential in AI.[262] For example, policies such as "civil-military" integration make it harder for its firms to succeed in the global market because such policies foster distrust in other societies. A lack of trust will hinder Chinese firms' ability to acquire significant global market share outside of nations that are taking part in China's subsidized Digital Silk Road initiatives.

Talent

China has a large talent base—due to its massive population—but still has a shortage of AI talent, lacks elite talent, and frequently loses workers who leave to pursue education abroad. Consequently, China should focus on increasing its ability to develop and retain homegrown talent.

- The Chinese government should encourage Chinese firms to develop research institutes in foreign nations with significant AI talent. Chinese firms such as Baidu have already established such research centers, which can attract talent that is willing to work for a Chinese firm but would rather not live in China.[263]
- The Chinese government should encourage the development of joint programs that allow students to major in both AI and another field to foster creativity.[264]
- The Ministry of Education has approved 35 universities to offer an AI undergraduate major. It should rapidly expand this number.[265]
- China should increase the goal of its International AI Training Program, in which AI experts train teachers and students, to train more than 750 teachers and 7,500 students over five years.[266]
- The government should follow the lead of the United Kingdom, which has announced it will pay up to £115 million ($140 million) for 1,000 students to earn AI doctorate degrees at 16 of its universities, and fund at least 1,000 AI students to get their Ph.D. in AI-related degrees.[267]

Research

China has experienced a significant growth in AI research papers and patents in recent years. However, both are of lesser quality on average compared with papers and patents by the United States and EU member states.

- China should alter its incentive structures for researchers to increase the number of individuals performing quality research. Part of China's growth in the number of AI papers and patents results from performance-evaluation systems that reward high quantity, instead of high impact.[268]

- China should expand funding for basic AI research, such as by expanding the Artificial Intelligence Research Center, which China created in 2018.[269] China should also fund new national AI labs. In 2017, the National Development and Reform Commission approved funding for a national AI engineering lab led by Baidu.[270]

- China should explicitly encourage university-industry AI research collaborations by increasing funding for university-industry R&D projects and emphasizing the number of R&D contracts with industry in the performance measures for universities.[271]

- China should encourage organizations to form partnerships with foreign entities to perform research and develop AI platforms. Several entities have already engaged in such partnerships, including the Chinese Academy of Sciences, which is working with the French Institute for Research in Computer Science and Automation on AI projects.[272]

Data

China's large population gives it a significant data advantage over other nations. However, China limits the size of this advantage through a weak open data culture and a lack of standardized data formats.

- China's State Council issued a regulation in 2018 directing data produced through government funded scientific research be open to the public.[273] China should implement a policy to make government data open by default and require it to be in a machine-readable format.

- China should task its regulatory bodies to establish standardized data formats to make it easier to transfer data from one system to another.[274]

- China should reduce or remove its restrictions on cross-border data flows, in part because such restrictions both limit international AI partnerships and encourage reciprocal limits on exports of data to China.[275]

Hardware

Several Chinese AI chip start-ups have recently received hundreds of millions of dollars in funding and firms such as Huawei have developed impressive chip designs.[276] Nonetheless, the complexity of developing chips, China's shortage of talent, and the lack of multiple Chinese semiconductor firms being in the top 15 globally for sales indicate China still needs to make significant progress in order to match the United States in semiconductors. China should also stop unfair trade practices such as forced technology transfers and intellectual property theft, which have led to increased scrutiny of its firms by the Committee on Foreign Investment in the United States (CFIUS) and put its ability to use Western semiconductors and designs in peril. Computing power used to be a commodity China could easily procure.[277]

- The Ministry of Education should work with universities to develop AI engineering courses and degree programs that focus on teaching the design of AI chips. According to the Ministry of Industry and Information Technology, China needs at least 400,000 more employees to meet its goals for the semiconductor industry by 2030.[278]

EU

The European Union has the talent to compete with China and the United States in AI. However, EU researchers frequently leave for U.S. firms, and the EU has a smaller AI venture capital ecosystem compared with China and the United States.

Talent

Although the EU has lots of AI talent, it often fails to retain that talent, and EU executives list a lack of in-house expertise as an impediment to adopting AI.[279] Thus, the EU should focus on both initiatives that incentivize talent to stay within the EU, and the development of a workforce that can contribute to an algorithmic economy.

- The European Commission should support policies that encourage AI researchers and entrepreneurs to move to the EU. EU policymakers can follow the lead of Lithuania, whose national AI strategy created “start-up visas” that made it easier for innovators from abroad to settle and work in the country.[280]

- The Commission should establish a program that awards €1 million ($1.1 million) per year for 5 years to the top 100 or so individual academic researchers doing work in advanced information and communications technology (ICT) areas, including AI, that industry values. This funding will help the best academic talent not only stay and develop in Europe, but also stay in academia rather than being lured to industry.[281]

- The Commission should provide matching grants to member states to establish teacher-certification programs in computer science.[282]

- The EU should build on public-private partnerships for computer science education and digital skills development. Many leading companies making or using digital technologies would likely be active participants in such programs.[283]

- The Commission should fund a pilot program to establish more maker spaces in European high schools in order to boost digital manufacturing and engineering skills.[284]

Research

The EU is strong in both the quality and output of its AI research. However, China surpassed the EU in AI publications in 2017, and is significantly reducing the gap between itself and the EU in research quality. Compared with the United States, the European Union also struggles to translate research into business applications. Consequently, the EU should focus on increasing R&D as well as prioritizing technology transfer. As part of an EU strategy:

- The EU should support the efforts of the Directorate General for Research and Innovation to increase funding for R&D in AI.[285]

- The Commission should reduce its role as a direct funder of large numbers of individual research projects and instead fund many more industry-funded university R&D centers, including for AI, on multiyear contracts.[286]

- The Commission should adopt an ICT R&D funding system that gives EU industry much more say in determining the technology areas the EU funds.[287]

- For individual academic researchers and academic research centers, the Commission should identify areas of importance for ICT research and devote funds to projects in those areas.[288]

- The EU should expand its VentureEU program, which will provide up to $410 million to start-ups, and dedicate funding specifically for AI start-ups.[289]

Data

The EU should leverage public data. For example, public health authorities provide most of the health care in Europe, meaning the EU has an opportunity to amass extensive datasets on patients and outcomes that can fuel the development of AI.

- The EU should establish data trusts for public-sector data in several sectors that are promising for AI research and tools, such as health care, energy, and transport.

- EU policymakers should build and implement a data policy across member states to accelerate data access and interoperability between government authorities, researchers, and companies in critical areas such as health and geospatial data.

- The European Data Portal has a wide variance of participation from EU member states.[290] The EU should foster the further development of open data policies in its member states to increase the number of datasets available to the public.

- EU policymakers should amend the GDPR, which they developed before fully understanding AI. The GDPR imposes severe restrictions on how European businesses use data, a key building block for AI. Absent reform, they will not be able to use AI to its full potential.[291]

Adoption

In terms of the percentage of firms adopting AI, the European Union is behind China and the United States. Thus, the EU should focus on both initiatives that decrease the barriers to public-sector adoption and those that foster private-sector adoption.

- EU member states should develop local AI skills training by developing partnerships with local universities and industry, including through data-science "boot camps."[292]

- EU member states should ensure small and medium-sized enterprises that may not be able to hire AI experts full-time can hire companies that provide these services. Achieving this will require training these companies on AI capabilities and opportunities, as well as on how to successfully manage these types of projects and contracts.

- The EU should encourage the development of more off-the-shelf AI tools that do not require extensive knowledge about AI, and instead require only baseline programming or analytical skills.

- Every EU member state should appoint a chief digital officer to not only champion data innovation domestically, but also serve on an EU-wide advisory panel charged with counseling the European Commission on development of a cohesive vision and strategy for capturing the full benefits of data-driven innovation.[293]

Regulation

The EU should not subject new digitally-based business models to the same regulation as incumbents—which often limits innovation. Instead, the EU should focus on providing equal protection, not equal regulation. As part of an EU strategy:

- European authorities need to recognize that scale in the digital economy is usually pro-consumer and a requirement for success. Some of Europe's most successful commercial companies, such as Airbus—which will be crucial to compete with China and the

United States—could not have been created under current competition rules.[294]

- The Commission should have political-level support to preempt digital economy regulations individual member states adopt, and it should create within the Regulatory Scrutiny Board an Office of Innovation Review whose mission would be to serve as an "innovation advocate" in the regulatory process.[295]

- The Commission should lead a dialogue that explores adopting the innovation principle, rather than the precautionary principle, when it comes to AI and other emerging technologies.[296]

UNITED STATES

The United States is still the global leader in AI. The Obama administration initiated some steps to support AI through the National Artificial Intelligence Research and Development Strategic Plan, which the Trump administration has since expanded on. For example, President Trump launched the American AI Initiative in 2019 through an executive order.[297] The order seeks to improve AI R&D, workforce development, and international engagement.[298]

While the executive order is important in ensuring U.S. leadership, the government can do more. In particular, Congress should reform immigration rules and increase research funding. It is also critical for Congress to avoid overly restrictive policies, including data protection rules, that would discourage the use of AI.

Talent

The United States benefits immensely from its ability to attract, educate, and retain foreign and domestic talent. Therefore, the United States should focus on policies that both encourage foreign talent to continue to immigrate to the United States and increase its domestic talent base.[299]

- Congress should enable more foreign AI talent to work in the United States by raising the cap on both employment-based green cards and per-country limits to ensure U.S. firms can hire as much AI talent as they need. In particular, Congress should pass the Fairness for High-Skilled Immigrants Act that removes country caps on issuing green cards for employment-based immigrant visas.[300]

- The National Science Foundation (NSF) should provide grants to colleges and universities to increase their enrollment in computer science courses. Evidence suggests the supply of courses—not student demand—constrains the size of course enrollment in AI courses at universities.[301]

- Congress should follow the lead of the United Kingdom, which has announced it will pay up to £115 million ($140 million) for 1,000 students to earn AI doctorate degrees at 16 of its universities, and create a competitive AI fellowship program through NSF to fund 1,000 students to earn AI-related doctorate degrees at U.S. universities.[302]

- Congress should fund and authorize a program at NSF to provide competitive awards for up to 1,000 academic AI researchers, conditional on their remaining in academia for 5 years. These awards would incentivize more AI researchers to stay in academia and help U.S. universities meet the demand for AI skills.[303]

Research

Compared with China and the European Union, the U.S. strength in research is not its volume of output, but its quality. Thus, the federal government should increase funding for computer science research, which private firms have fewer incentives to perform, as well as encourage private firms to increase R&D spending.

- Congress should pass the Artificial Intelligence Initiative Act, which would allocate $2.2 billion to developing AI over the next five years, including an extra $1.5 billion to DOE to expand its AI research efforts, and $100 million a year to the NSF to create five new centers that promote AI research and education.[304]

- Congress should pass the Growing Artificial Intelligence Through Research Act (H.R. 2202), which directs the president to establish a National Artificial Intelligence Initiative to coordinate federal AI R&D activities to accelerate the development of the technology.[305]

- NSF should expand funding for the National Robotics Initiative and broaden its mission to support not just research that augments rather than replaces workers, but that uses AI to replace human workers and boost productivity.[306]

- A significant portion of U.S. AI talent is in private firms or universities and not in the federal government. Thus, to maximize the benefits of federal research dollars, federal agencies and military branches should establish research partnerships with firms and universities. Federal actors can follow the lead of the Air Force, which is collaborating with MIT to develop AI technologies for the "public good."[307]

- Congress should increase the R&D tax credit to keep pace with competing countries. A healthy AI ecosystem requires both government and business funding of AI research. Companies will do more AI research in the United States with a more generous R&D tax credit. However, as of 2018, the United States ranked

32nd among OECD nations in terms of R&D tax-credit generosity, behind China and such European countries as France, Germany, and the United Kingdom. As such, Congress should increase the Alternative Simplified Credit from 14 percent to 20 percent.[308] In addition, Congress should support the R&D Tax Credit Expansion Act, which would double the refundable credit for small businesses from $250,000 to $500,000, and increase the business eligibility cap from $5 million to $10 million in gross receipts.[309]

- China produces an important volume of research on AI, but a significant portion of it is not translated into English. In contrast, English-language research is quickly translated to Chinese. NSF should fund an AI research hub that curates and translates non-English AI research to make it accessible to U.S. researchers.

- Congress should direct federal research agencies to coordinate their funding for joint areas of interest in AI, such as cybersecurity and safety, as well as collaborate with allied nations' research agencies on joint initiatives in these areas.

Data

Compared with China and the European Union, the United States' smaller population is a modest disadvantage in generating the data necessary to develop AI systems. Thus, the United States should focus on ways to maximize the value of the data it generates, especially by creating a regulatory environment that facilitates data sharing and reuse.

- Federal agencies should develop partnerships with other countries to facilitate access to large, standardized datasets for U.S. companies and researchers in fields such as health care, to expand the available data pools. China's size provides it an advantage in generating data, but the United States can mitigate China's advantage by partnering with allies such as those in the European Union on sharing data to build AI systems with clear societal benefits.

- Federal agencies should develop and pilot data trusts to facilitate data sharing in specific application areas, such as health research, among academia, businesses, and government agencies.[310]

- Policymakers should continue to encourage free trade in data by ensuring trade agreements do not restrict cross-border data flows.

- Congress should pass a data privacy bill that maximizes consumer welfare while minimizing harm to innovation. Such a bill should preempt state laws, improve transparency requirements, strengthen enforcement, and provide U.S. citizens with a clear set of data privacy rights. However, the bill should not reduce the ability of firms to use data or create exorbitant compliance costs, which companies will pass on to consumers, that reduce incentives for firms to improve services through automation.

- Policymakers should ensure any data protection rules adopted are innovation-friendly and do not hamper the adoption of AI by limiting the collection and use of data, restricting automated decision-making, or increasing compliance costs and risks.[311]

Adoption

Similar to Europe, the United States may be lagging in AI adoption in part due to negative perceptions of AI. For example, more U.S. adults (35 percent) disagree with the belief that innovations such as AI will make workers better off in the future than those who agree (31 percent).[312] Consequently, the United States should focus on demonstrating the value of AI to its citizens and businesses while using the federal government's ability to fund, procure, and regulate AI to spur its adoption.

- Congress should pass the AI in Government Act (H.R. 2575), which would establish an AI Center of Excellence within the General Services Administration to improve the federal government's ability to adopt and deploy AI.[313]

- Each federal agency should identify within the next six months at least two high-impact opportunities to use AI, and authorize funds to pilot these AI initiatives.[314]

- Federal agencies should establish domain-specific programs to spur AI adoption. For example, DOD recently established the Joint Artificial Intelligence Center to help teams "swiftly deliver new AI-enabled capabilities and effectively experiment with new operating concepts in support of DoD's military missions and business functions." Other departments, such as the United States Department of Health and Human Service and Transportation Department, should consider developing similar programs and Congress should provide ample additional funding.[315]

- DOD should create a body with both government and industry stakeholders to accelerate the adoption of dual-use AI technologies by the military. This acceleration effort could include publishing performance and safety standards for various key military AI applications so industry could more readily develop those solutions, or creating guidelines for modifying commercial AI applications for military use.[316]

- Federal agencies should work with industry to develop strategies for supporting AI adoption in relevant sectors of the economy, such as education, transportation, financial services, and health care. These strategies should provide guidance on how best to leverage AI to advance agency missions, as well as identify opportunities to encourage AI adoption in relevant industries, such as by proactively providing guidance on policy questions, ensuring procurement supports AI, ensuring regulations do not limit AI usage, and creating incentives for firms to invest in AI. These strategies should be updated regularly as agencies become more familiar with the technology and AI matures, creating new challenges and opportunities to address.[317]

- The Department of Commerce (DOC) should establish organizations designed to advance the development of innovative AI applications in various sectors. For example, Manufacturing USA, which is overseen by federal agencies, including DOC and DOE, is a network of research institutes focused on fostering innovation and collaboration in the manufacturing sector. Among them is the Advanced Robotics for Manufacturing, a public-private partnership in Pittsburgh that focuses on AI and automation. Using this model, agencies should support similar institutes that include industry, academia, and government agency resources to advance AI in other sectors such as city management and precision medicine.[318]

- Congress should appropriate funds for the Economic Development Administration to create a national economic development competition in which states would compete for funds to establish their own state development plans and policies for supporting both AI development—especially through new start-ups—and AI adoption, particularly by small and mid-sized firms.[319]

- Congress and the administration should support the use of AI for defense systems, and explore appropriate ways to increase transparency and accountability for the use of AI for national security, including to address the implications of deep fakes and lethal autonomous weapons.[320]

Hardware

The United States has a significant lead in semiconductors, and its best supercomputers have a higher aggregate performance than China's supercomputers. However, China has surpassed the United States in the number of supercomputers ranked in the top 500. High-performance computing has fueled breakthrough discoveries in sectors such as aerospace, life sciences and manufacturing, and it would be a risk to depend on foreign vendors for access to the leading supercomputers.[321] Consequently, the United States should prioritize regaining an undisputed lead in high-performance computing and the creation of supercomputers designed for AI applications.

- The U.S. DOE has begun to procure supercomputers that are explicitly designed for AI applications, and should prioritize the development of such computers.[322]

- Congress should continue to affirm technology transfer and commercialization as a core mission of the national laboratories, including by increasing the weighting attached to technology transfer and commercialization activities as part of the labs' Performance Evaluation Management Plan process.[323] Increasing the weighting will help amplify the number of collaborations between the labs and the private sector that leverage high-performance computing resources.[324]

- Federal programs involved in supporting technical education programs should emphasize high-performance computing (HPC)-related skills. The United States has had trouble attracting sufficient HPC talent—both the talent needed to develop exascale HPC systems and for industry to apply HPC to industrial needs to the maximum extent possible.[325]

Regulation

The United States should learn from its light-touch regulation of the Internet in the 1990s and 2000s, which was a critical enabler of the U.S. digital economy. This means avoiding the temptation to embrace policies that would limit innovation and discourage AI adoption.[326] Such policies would undermine economic growth, U.S. competitiveness, and social progress.[327]

- Policymakers should pursue an innovation-friendly framework built around the principle of "algorithmic accountability," in which the operators of algorithms are held accountable for explicit and severe harms.[328]

- Regulatory agencies should conduct a review to determine whether any of their rules are limiting AI adoption, and identify opportunities to encourage AI. For example, in 2019, the Food and Drug Administration (FDA) published a draft regulatory framework for medical devices that use machine learning to continuously improve. The FDA has already approved medical devices that use AI, but requires the devices to go through the approval process each time they are changed, which can be cumbersome for machine learning systems that regularly iterate and improve over time. The FDA's proposed framework includes reviewing the performance of manufacturers' algorithms, manufacturers' ability to manage the risk of changes, and an option for manufacturers to submit a plan for how they would make modifications to or retrain their models.[329]

- Congress and the administration should caution regulators against viewing the mere act of collecting or possessing large amounts of data (which is necessary for specific uses of AI) as potentially anticompetitive behavior.[330]

- DOC should avoid overly burdensome export restrictions on AI technology that could substantially reduce commercial opportunities for U.S. technology companies to sell their AI-enabled products and services. If DOC applied strict exports controls, firms from other countries would likely step in to provide products and services to these markets, thereby reducing revenue that could fund additional R&D in U.S. firms.[331]

- CFIUS should continue to scrutinize and limit Chinese foreign acquisition of U.S. firms, including those in AI.

APPENDIX

APPENDIX 1: WEIGHTS

Talent indicators and weights

Indicator	Weight
AI Researchers	5
Top AI Researchers (H-Index)	5
Top AI Researchers (Academic Conferences)	3
Educating Top AI Researchers	2

Research indicators and weights

Indicator	Weight
AI Papers	5
Paper Quality (Field-Weighted Citation Impact)	4
Top 100 Software and Computer Service Firms for R&D Spending	3
R&D Spending by Software and Computer Service Firms in Top 2,500	3

Development indicators and weights

Indicator	Weight
Venture Capital and Private Equity Funding	5
Venture Capital and Private Equity Funding Deals	2
Acquisitions	2
AI Start-Ups	4
AI Firms That Have Received More Than $1 Million in Funding	4
Highly Cited AI Patent Families	3
AI PCT Patents	5

Adoption indicators and weights

Indicator	Weight
Firms Adopting AI	5
Firms Piloting AI	5

Data indicators and weights

Indicator	Weight
Fixed Broadband Subscriptions	4
Individuals Using Mobile Payments	3
IoT Data	3
Productivity Data	4
Electronic Health Records	2
Mapping Data	2
Genetic Data	2
Regulatory Barriers	5

Hardware indicators and weights

Indicator	Weight
Semiconductor Sales	2
Semiconductor R&D Spending	2
Firms Designing AI Chips	2
Number of Supercomputers	2
Aggregate Supercomputer Performance	2

APPENDIX 2: NUMBER OF EU AI RESEARCHERS

SOURCES

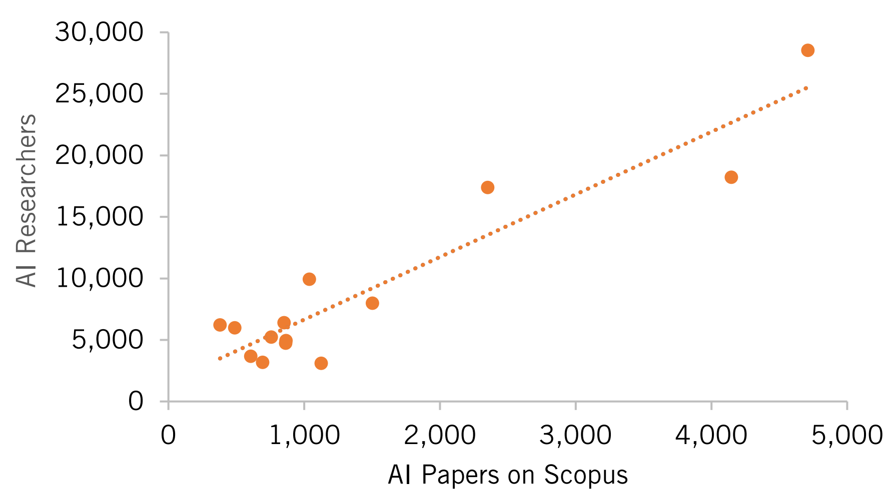
2018 AI Index, Scopus (publications by region; accessed April 5, 2019), https://docs.google.com/spreadsheets/d/1x3STejq1Q4IHM_1bQIbez8R7_GaKKygvC1dod33u3bl/.

China AI Development Report 2018 (China Institute for Science and Technology Policy at Tsinghua University, July 2018), http://www.sppm.tsinghua.edu.cn/eWebEditor/UploadFile/China_AI_development_report_2018.pdf.

The number of AI papers is from the 2018 AI Index Report, which queried Scopus to get the count of papers tagged with the keywords "Artificial Intelligence." This methodology is different from Elsevier's, which used 800 keywords to identify AI papers. For this imputation, we used the AI Index's methodology because it provides AI paper counts for more nations. The number of AI researchers is from the *China AI Development Report 2018,* which categorized AI talent using paper and patent records of individuals.

METHODOLOGY

The total number of AI researchers in the EU was unavailable. We used the EU's 2017 AI paper output (8,157 AI papers), along with the paper outputs and number of researchers for 14 nations, to impute the EU's number of AI researchers (43,064). The chart below displays the imputation ($R^2 = 0.87$).



Note: Number of AI Researchers = 5.09 * (Number of AI Papers on Scopus) + 1562.5

APPENDIX 3: NUMBER OF EU TOP AI RESEARCHERS

SOURCES

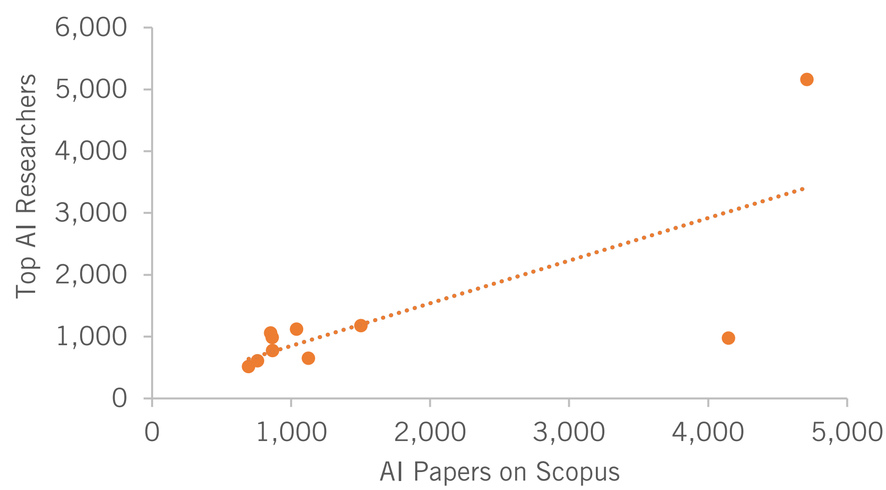
2018 AI Index, Scopus (publications by region; accessed April 5, 2019), https://docs.google.com/spreadsheets/d/1x3STejq1Q4IHM_1bQIbez8R7_GaKKygvC1dod33u3bl/.

China AI Development Report 2018 (China Institute for Science and Technology Policy at Tsinghua University, July 2018), http://www.sppm.tsinghua.edu.cn/eWebEditor/UploadFile/China_AI_development_report_2018.pdf.

The number of AI papers is from the 2018 AI Index Report, which queried Scopus to get the count of papers tagged with the keywords “Artificial Intelligence.” This methodology is different from Elsevier’s, which used 800 keywords to identify AI papers. For this imputation, we used the AI Index’s methodology because it provides AI paper counts for more nations. The number of AI researchers is from the *China AI Development Report 2018,* which categorized AI talent using paper and patent records of individuals.

METHODOLOGY

The total number of top AI researchers in the EU was unavailable. We used the EU’s 2017 AI paper output (8,157 AI papers), along with the paper outputs and number of top researchers for 10 nations, to impute the EU’s number of AI researchers (5,787). The chart below displays the imputation (R^2 = 0.56).



Note: Number of AI Researchers = 0.69 * (Number of AI Papers on Scopus) + 159.8

APPENDIX 4: NUMBER OF RESEACHERS EDUCATED IN THE EU

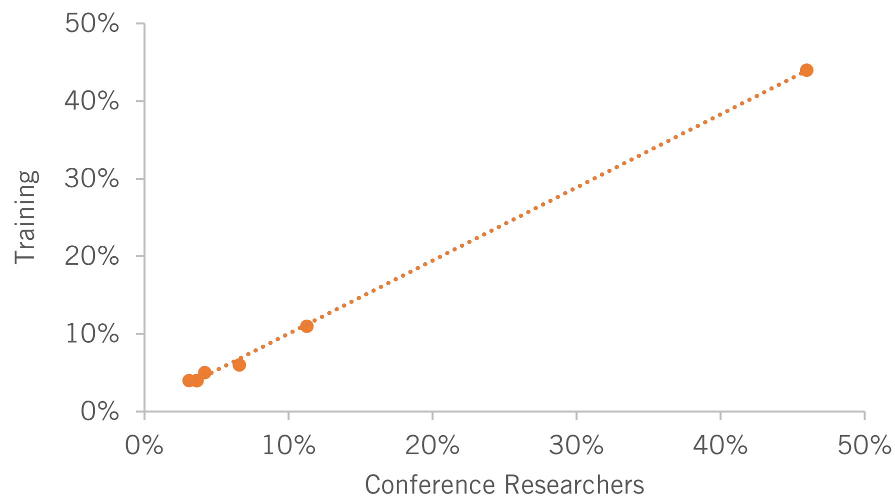
SOURCES

JF Gagne, Grace Kiser, and Yoan Mantha, "Global AI Talent Report 2019" (Element AI, April 2019), https://jfgagne.ai/talent-2019.

The percentage of AI researchers that published at least once at any of 21 academic conferences and the percentage of conference researchers receiving their Ph.D. in a particular nation are both from the "Global AI Talent Report 2019."

METHODOLOGY

The percentage of AI researchers that published work at least once at any of 21 conferences and graduated from Ph.D. programs in the EU was unknown. We used the percentage of conference researchers that were working in seven nations and the EU (22 percent) and the percentage that received their Ph.D. in the seven nations to impute the percentage of researchers who received their Ph.D. in the EU (21 percent). The chart below displays the imputation (R^2 = 0.99).



Note: Percentage of Ph.D. = 0.94 * (Percentage of Conference Researchers) + 0.01

APPENDIX 5: NUMBER OF EU AI PAPERS

SOURCES

2018 AI Index, Elsevier (annual AI papers; accessed April 5, 2019), https://docs.google.com/spreadsheets/d/1c9R4sZVwj647sv58RtWK96m26_xKqWAhch9DeXRjU8g/.

"Elsevier's Artificial Intelligence Program," Elsevier, 2018, https://public.tableau.com/profile/isabella.cingolani1149#!/vizhome/ElseviersAIprogramme/Dashboard?publish=yes.

The number of 2017 EU AI papers is from the 2018 AI Index Report. Elsevier provided the AI Index annual data for China, Europe, and the United States. Elsevier used the Scopus query tool to get the count of papers tagged with 800 keywords related to AI and used a supervised classifier to eliminate false positive publications. The number of AI papers from 1998 to 2017 is from Elsevier's AI Resource Center and uses the same methodology. It should be noted that the AI Index also reports alternative AI paper counts, which we did not use to estimate an overall EU AI paper count. These figures are smaller because the AI Index team counted the number of papers tagged in Scopus with the keywords "Artificial Intelligence" and not 800 keywords related to AI.

METHODOLOGY

A recent annual AI paper count for the EU using Elsevier's expanded keyword list methodology was unavailable. However, a paper count for Europe (17,211 AI papers), which is defined as the 28 EU member states and 16 nations available for Horizon 2020 funding, was available. To estimate an EU-only AI paper count, we calculated an estimate of the 2017 AI paper count of the non-EU member states eligible for Horizon 2020 funding (2,435 AI papers) and subtracted it from the European AI paper count total (17,211) for an estimated 2017 EU paper count of 14,776 AI papers.

To perform this calculation, we first summed the 1998–2017 AI paper counts for the 16 non-EU member states eligible for Horizon 2020 funding for a total of 26,990 AI papers. We also divided Europe's 2017 AI paper count (17,211) by its AI paper count for 1998–2017 (190,765) to determine Europe's 2017 AI paper count was 9 percent of its total AI paper count between 1998 and 2017. We then multiplied the AI paper count of the non-EU member states in the EU 44 (26,990) by 9 percent to get a total of 2,435 AI papers. We then subtracted Europe's 2017 AI paper count (17,211) by the 2017 estimated AI paper count of the 16 non-EU nations (2,435) to get an estimated 2017 EU paper count of 14,776 AI papers.

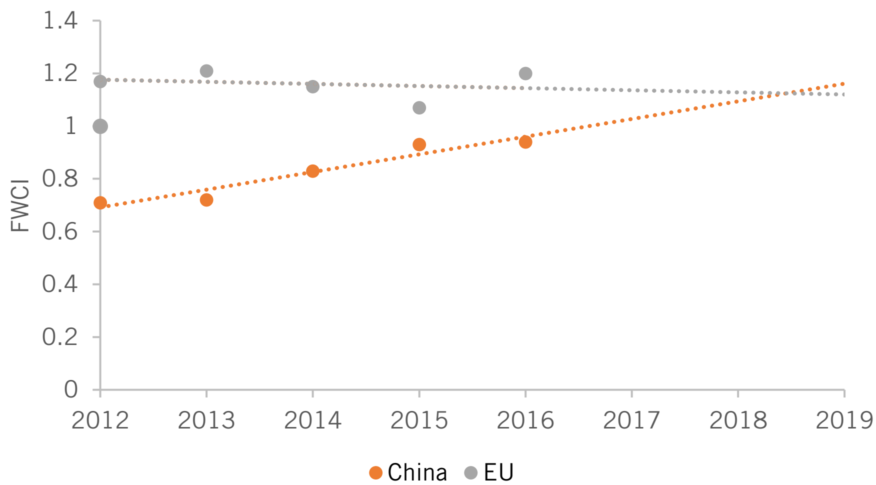
APPENDIX 6: FORECASTED FWCI FOR CHINA AND EU

SOURCES

2018 AI Index, Elsevier (FWCI; accessed April 5, 2019), https://docs.google.com/spreadsheets/d/1c9R4sZVwj647sv58RtWK96m26_xKqWAhch9DeXRjU8g/.

METHODOLOGY

We forecasted the FWCI for China and Europe by fitting a trend line for 2012–2016 and extending it to 2019.



APPENDIX 7 VENTURE CAPITAL AND PRIVATE EQUITY FUNDING

SOURCES

CB Insights, Advanced Search (Industry & Geography, Company Attributes, Financing & Exit; accessed March 14, 2019), https://app.cbinsights.com.

METHODOLOGY

We used CB Insight's advanced search tool to get the number and size of venture capital and private investments made in Chinese, EU, and U.S. AI firms. We filtered our search by firms in the Artificial Intelligence collection and by only including deals CB Insights classified as seed or angel, series A–E, convertible note, growth-equity, private-equity, or other venture capital funding.

However, 20 percent of the deals did not have a known investment size. For each of China, the European Union, and the United States, we used that region's median AI deal size for the year to impute a total. For example, in 2018, U.S. AI firms were part of 616 deals for a known total of $10.3 billion. However, 72 of the deals had no corresponding dollar amount. Consequently, we multiplied 72 by the median U.S. AI deal size in 2018 ($5 million) and added it to the known total of $10.3 billion to get an estimated total of $10.7 billion.

Note: Funding Total = Known Total ($) + (Number of Missing Deals * Median Deal Size)

APPENDIX 8: PERCENTAGE OF FIRMS THAT ARE ADOPTING AI

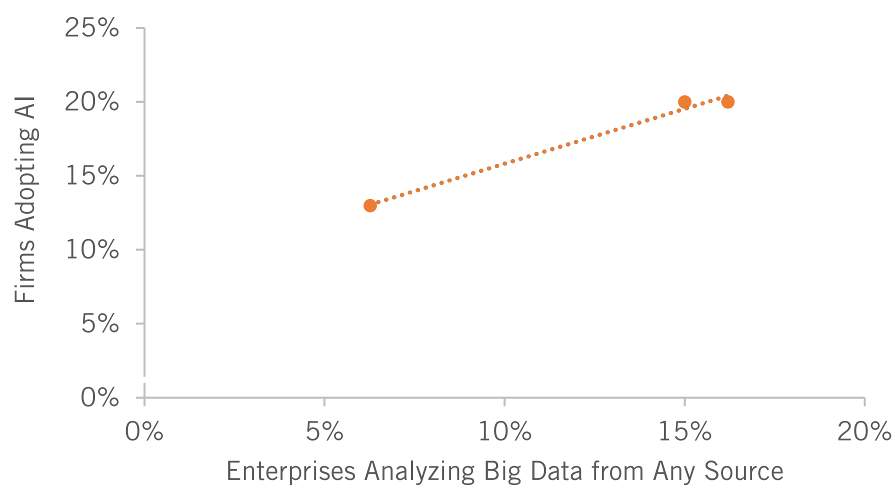
SOURCES

Sylvain Duranton, Jörg Erlebach, and Marc Pauly, "Mind the (AI) Gap" (Boston Consulting Group, December 2018), http://image-src.bcg.com/Images/Mind_the%28AI%29Gap-Focus_tcm108-208965.pdf.

European Commission, Digital Single Market (digital scoreboard, visualizations, digital agenda scoreboard key indicators, eBusiness, enterprises analyzing big data from any data source), https://digital-agenda-data.eu/charts/analyse-one-indicator-and-compare-countries.

METHODOLOGY

The percentage of EU firms that are adopting AI is unknown. Boston Consulting Group (BCG) surveyed managers from seven nations—Austria, China, France, Germany, Japan, Switzerland, and France—to find the proportion of companies that were moving to adopt AI in some existing processes. We used the percentage of firms that are using big data in France (16 percent), Germany (15 percent), Austria (6 percent), and the EU as a whole (12 percent) and the percentage of companies that are adopting AI in France (20 percent), Germany (20 percent), and Austria (13 percent) to impute the percentage of EU firms that are active players in AI (18 percent). The chart below displays the imputation (R^2 = 0.99),



Note: Percentage of Firms Adopting AI = 0.74 * (Percentage of Enterprises Analyzing Big Data from Any Data Source) + 0.08

APPENDIX 9: NUMBER OF FIRMS DESIGNING AI CHIPS

SOURCES

CrunchBase (companies, operating status, headquarters location, categories, accessed May 2019), https://www.crunchbase.com/search-home.

Shan Tang, "AI Chip (ICs and IPs)," accessed June 4, 2019, https://github.com/basicmi/AI-Chip.

Paul Triolo and Jimmy Goodrich, "From Riding a Wave to Full Steam Ahead" (New America, 2018), https://www.newamerica.org/cybersecurity-initiative/digichina/blog/riding-wave-full-steam-ahead.

Paul Triolo and Graham Webster, "China's Efforts to Build the Semiconductors at AI's Core," New America, December 7, 2018, https://www.newamerica.org/cybersecurity-initiative/digichina/blog/chinas-efforts-to-build-the-semiconductors-at-ais-core/.

METHODOLOGY

We used CrunchBase's "Companies" search tool to search for companies that were categorized under the terms "Semiconductor," "GPU," "ASIC," "FGPA," and for companies that had the aforementioned terms in their description. We also searched for firms that were categorized both as AI and Hardware firms. We verified companies that were designing AI chips by visiting their websites and searching for articles. The large majority of firms showed no evidence of designing chips, and were therefore not included in the list of AI chips firms. Thus, if a firm designed semiconductor products but did not design chips for AI uses, we did not include it.

We also used Shan Tang's GitHub post "AI Chip (ICs and IPs)," which lists firms designing AI chips and provides links to references confirming the firms are designing such chips, to add firms to our list that were not found in our CrunchBase searches.

APPENDIX 10: EU IOT DATA

SOURCES

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David Reinsel et. al, “The EMEA Datasphere: Rapid Growth and Migration to the Edge” (white paper, International Data Corporation, 2019), https://www.seagate.com/files/www-content/our-story/trends/files/data-age-emea-idc.pdf.

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International Telecommunication Union (Country ICT Data (Until 2017), mobile-cellular subscriptions; accessed July 11, 2019), https://data.worldbank.org/indicator/IT.NET.BBND.P2.

METHODOLOGY

We estimated the amount of data IoT generated in China, the European Union, and the United States using data from International Data Corporation (IDC)’s global datasphere. IDC details the amount of new data generated in China (7.6 ZB), Europe, the Middle East, and Africa (EMEA) (9.5 ZB), and the United States (6.9 ZB) for 2018. For each region, IDC lists the data type by share for 2015. For example, IDC lists that 1 percent of the new data generated in the United States in 2015 was IoT data. To estimate the amount of IoT data for each region, we multiplied their 2018 overall data generation by the percentage of their new data generation in 2015 coming from IoT. We then converted the data from zettabytes to terabytes.

As EMEA consists of Europe, the Middle East, and Africa, we needed to estimate the amount of EMEA data coming from the European Union. To do so, we used total mobile-cellular subscriptions as a proxy. We divided the number of mobile-cellular subscriptions in the EU in 2017 (628,264,128) by the number of mobile-cellular subscriptions in all EMEA countries (2,231,317,886) to get 28 percent. We then multiplied the estimated 2018 EMEA new IoT data generation (190,000,000 TB) by 28 percent to get the EU’s estimated IoT data generation figure (53,497,615 TB).

APPENDIX 11: EU PRODUCTIVITY DATA

SOURCES

David Reinsel et al., "The China Datasphere: Primed to Be the Largest Datasphere by 2025" (White Paper, International Data Corporation, 2019), https://www.seagate.com/our-story/data-age-2025/.

David Reinsel et al, "The EMEA Datasphere: Rapid Growth and Migration to the Edge" (white paper, International Data Corporation, 2019), https://www.seagate.com/files/www-content/our-story/trends/files/data-age-emea-idc.pdf.

John F. Gantz, David Reinsel, and John Rydning, "The U.S. Datasphere: Consumers Flocking to Cloud" (white paper, International Data Corporation, 2019), https://www.seagate.com/files/www-content/our-story/trends/files/data-age-us-idc.pdf.

World Bank, World Bank Open Data (GDP (current US$; accessed June 26, 2019), https://data.worldbank.org/indicator/ny.gdp.mktp.cd.

METHODOLOGY

We estimated the amount of productivity data generated in China, the European Union, and the United States using data from IDC's global datasphere. IDC detailed the amount of new data generated in China (7.6 ZB), EMEA (9.5 ZB), and the United States (6.9 ZB) for 2018. For each region, IDC listed the data type by share for 2015. For example, IDC listed that 14 percent of the new data generated in the United States in 2015 was productivity data. To estimate the amount of productivity data for each region, we multiplied their 2018 overall data generation by the percentage of their new data generation in 2015 coming from productivity. We then converted the data from zettabytes to terabytes.

As EMEA consists of Europe, the Middle East, and Africa, we needed to estimate the amount of EMEA data coming from the European Union. To do so, we used GDP as a proxy. We divided the EU's GDP in 2017 by the GDP of all EMEA nations to get 68 percent. We then multiplied the estimated 2018 EMEA new productivity data generation (190,000,000 TB) by 68 percent to get the EU's estimated IoT data generation figure (582,762,991 TB).

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src.bcg.com/Images/Mind_the%28AI%29Gap-Focus_tcm108-208965.pdf.

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40. The source only presents percentages, and the number of conference researchers who have published at 1 of the 21 conferences could include researchers who do not have a Ph.D. Thus, we don't know the absolute figure for the number of researchers receiving their Ph.D. in each region. As a result, we cannot compute per-worker stats. JF Gagne, Grace Kiser, and Yoan Mantha, "Global AI Talent Report 2019" (Element AI, April 2019), https://jfgagne.ai/talent-2019.

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