

China's rise as a major contributor to science and technology

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In the past three decades, China has become a major contributor to science and technology. China now employs an increasingly large labor force of scientists and engineers at relatively high earnings and produces more science and engineering degrees than the United States at all levels, particularly bachelor's. China's research and development expenditure has been rising. Research output in China has been sharply increasing since 2002, making China the second largest producer of scientific papers after the United States. The quality of research by Chinese scientists has also been improving steadily. However, China's rise in science also faces serious difficulties, partly attributable to its rigid, top-down administrative system, with allegations of scientific misconduct trending upward.

Chinese science | science education | international competitiveness

Historically, the world center of science has shifted several times, from Renaissance Italy to England to France and to Germany, before crossing the Atlantic Ocean to the United States in the early twentieth century, where it has remained for the past nine decades (1). Comprising only about 5% of the world's population, the United States currently accounts for 35–75% of the world's total scientific activities, depending on what measures one uses (1). Will America's dominance in science last? Two recent reports by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, have raised concerns that the United States may soon lose its scientific leadership role and suffer negative economic consequences (2, 3).

Those who worry that America might lose its place at the center of world science are concerned not only about the possible decline of science in the United States but also about the rise of possible rivals, particularly China. In the past three decades, China has become a major player in world science. This is surprising, given China's relative unimportance to science as it evolved in the West over the past several centuries. Even as recently as 1997–2001, China still produced only 1% of the 1% top-cited publications (4). However, a combination of economic and social changes in China over the past four decades has strengthened China's science and technology role.

China has experienced rapid, sustained economic growth since its economic reform began in 1978. Net of inflation, the annualized growth rate was 7.7% between 1978 and 2010 (5) (Fig. S1). This economic growth has been accompanied by a massive expansion in higher education. In 1982, only 0.8% of Chinese ages 25–29 y had attained postsecondary education. This figure rose to 3.3% in 1990, 6.7% in 2000, and 20.6% in 2010 (6–9) (Table S1). These same two factors—economic growth and educational expansion—were central to the rise of science in the United States in the twentieth century, and thus one might expect them to bring about a parallel change in China (1–3).

In this article, we present the latest data on various aspects of science in China since the 1980s. These include science and engineering (S/E) labor force size, S/E degrees, government policies and investments, and scientific output and impact. For ease of interpretation, we compare China to the United States,

and in a few instances to other countries. The data we have analyzed all indicate that China has become a major contributor to science and technology. We close the article with an interpretation of the data and a discussion of the widespread perception of scientific corruption and fraud in China.

S/E Labor Force

Drawing on population census data, we first report our estimates of the size of the S/E labor force in China from 1982 through 2010 and compare the figures to those in the United States. These estimates were based on Chinese and US census data, supplemented by recent data from the American Community Survey (ACS) (10). We define “scientist” as someone with at least a college education and working in an S/E occupation (1). Our definition includes physical scientists, life scientists, mathematical scientists, and engineers but excludes social scientists (Table S2). Fig. 1 shows an upward trend in the size of the S/E labor force for both countries (Fig. S2 in log scale). In 1982, the Chinese S/E labor force was 1.2 million, about 80% the size of the American S/E labor force (at 1.5 million in 1980). By 2010, China had 3.2 million scientists and engineers, compared with 4.3 million in the United States. The overall growth was similar in the two countries. Given China's much larger population size, however, scientists and engineers constitute a much smaller share of the labor force there, at 0.4% in 2010 than in the United States at 3.1% in 2010 (Table S3).

The bulk of China's growth occurred between 2000 and 2010 (Fig. S3). As we will discuss later, this is attributable to a large expansion of higher education that began in 1999. Engineers make up a much larger share of the total S/E labor force in China than in the United States. In 2010, there were 2.4 million engineers in China, compared with 1.4 million in the United States. Net of engineers, China's scientific labor force of about 160,000 remained much smaller than the ~690,000 scientists in the United States (Table S3). Historically, women occupied a larger share of the S/E

Significance

New data reveal that in the past three decades, China has become a major contributor to science and technology. Four factors favor China's continuing rise in science: a large population and human capital base, a labor market favoring academic meritocracy, a large diaspora of Chinese-origin scientists, and a centralized government willing to invest in science. These factors may serve as an example to other nations aspiring to advance their standing in science. However, China's science also faces potential difficulties due to political interference and scientific fraud.

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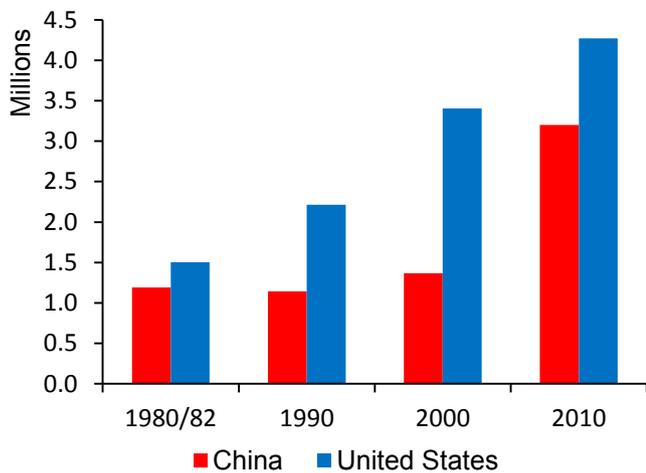


Fig. 1. Labor force in S/E, 1980/1982–2010. In the 1980/82 category, 1980 represents the United States, and 1982 represents China.

labor force in China than in the United States. However, due to a steady increase in US women's representation in S/E over the period (1, 11), the proportion of women among scientists and engineers in the two countries had converged by 2010 (around 25%), although women constituted a higher proportion among engineers in China (25%) than in the United States (13%) (Table S3).

Earnings returns to higher education have increased in the general American labor force (12, 13). Some economists have attributed this trend to the growing importance of technology in the US economy (12, 14). Past research has documented, however, that the earnings of American scientists have stagnated and lost ground in comparison with those of other high-status professionals such as doctors and lawyers (1, 13, 14). Because expected earnings affect youths' career choices, the relatively unfavorable labor market outcomes of American scientists may discourage talented youths from pursuing scientific careers (1). Is this also the case in China?

To answer this question, we compare the earnings of scientists to those of four other high-status professionals—social scientists, medical doctors, lawyers, and engineers—in both China and the United States. The data analyzed came from the 2005 minicensus survey in China (15) and the 2006–2008 ACS. We present summary results from a regression analysis adjusting for standard human capital and labor supply factors (Table S4). Fig. 2 shows the estimated earnings ratios of selected other professionals compared with scientists. Except for engineers, Chinese scientists have an earnings advantage relative to these professionals, whereas American scientists face a disadvantage. Engineers in both countries enjoy about a 25% premium over scientists. In China, scientists earn 25% more than social scientists, 13% more than medical doctors, and 5% more than lawyers, whereas American scientists earn 7% less than social scientists, 50% less than medical doctors, and 34% less than lawyers. These results indicate that the financial incentives for working in science are stronger in China than in the United States. When talented youth face alternative career options, everything else being equal, more Chinese would be attracted to science than Americans.

S/E Degrees

Chinese culture recognizes merit through education, regardless of one's social origin (16–18). In modern China, the demand for higher education has always far exceeded the supply, which has been limited by inadequate physical facilities and teaching faculty. After much political debate, the government decided in 1998

to expand China's higher education system (18). Not only did the number of higher education institutions more than double from 1,022 in 1998 to 2,263 in 2008, but all previously existing institutions were also restructured, upgraded, and enlarged to accommodate this policy (19) (Table S5).

As a result, China is now the world's distant leader in bachelor's degrees in S/E, with 1.1 million in 2010, more than four times the US figure. This large disparity reflects not only China's dramatic expansion in higher education since 1999 but also a much higher percentage of students majoring in S/E in China, around 44% in 2010, compared with 16% in the United States (20, 21) (Table S6). In Fig. 3A, we present the divergent trends in the production of S/E degrees at the bachelor's level in the two countries (Fig. S4A in log scale). The figure shows an increasingly larger gap between China and the United States from 1998 to the present. Of course, China's population is much larger, around 1.3 billion, than that of the United States, which is around 300 million. Adjusting for population size differences, the two countries now have similar proportions of graduates with S/E bachelor's degrees. The main focus here is on trends, which point to China's rapid increase.

China's massive production of scientists and engineers is not limited to the bachelor's level. Its growth in S/E doctoral degrees has been comparably dramatic. In Fig. 3B, we present the trends in S/E doctoral degrees awarded between 1993 and 2010 for both China and the United States (Fig. S4B in log scale). In 1993, China's number of degrees was only 10% that for the United States, but by 2010 China exceeded the United States by 18%.

China's rapid increase in the quantity of S/E degrees inevitably invites questions about their quality. Are the scientists and engineers being graduated *en masse* by newly created or restructured Chinese educational institutions as good as US-trained professionals (22)? Unfortunately, we have no appropriate data with which to address this question. There is evidence, however, shown below, that performance by Chinese scientists has improved over the period during which degree production increased so dramatically. Thus, we concur with a prediction made by Freeman, an economist, in 2009 that over time the "quality [of Chinese education] will undoubtedly improve" (23).

The quality of China's science education, at least at the bachelor's level, can also be seen in the increasingly large number of Chinese graduate students in American S/E programs; a threefold increase from 15,000 in 1987 to 43,000 in 2010 (20, 24–26) (Tables S7 and S8). The number of S/E doctoral degrees awarded by US universities to Chinese citizens peaked at 4,300 in

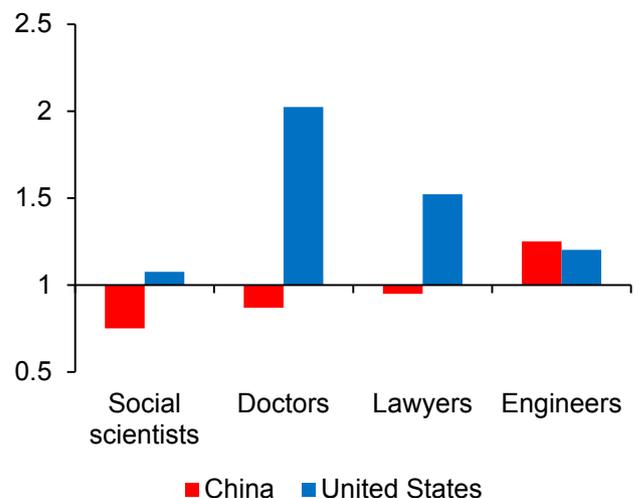


Fig. 2. Earning ratios compared with scientists, mid-2000s.

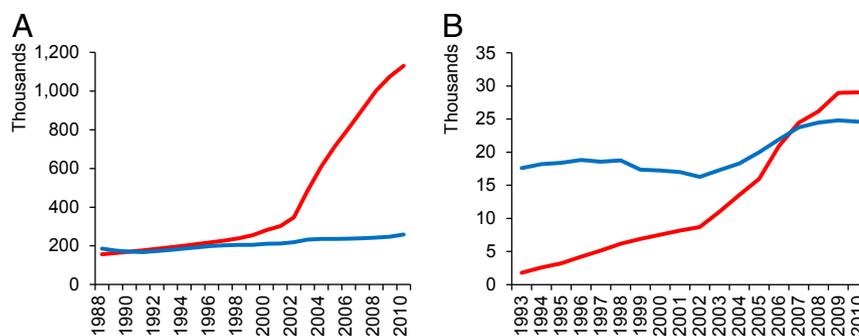


Fig. 3. (A) The number of bachelor's degrees awarded from 1988 to 2010. (B) The number of doctoral degrees awarded from 1993 to 2010. The red line is for China and the blue line is for the United States.

2007, making China the largest foreign supplier of US doctoral recipients (27) (Table S9).

Government Policies and Investments

A country's economy and science affect each other in mutually dependent, dynamic, and positively reinforcing ways (1–3). On the one hand, much of today's economic growth is driven by technological advances (2, 3, 12, 14, 28). Keenly aware of this, China's government policymakers have pushed technological development as the basis for upgrading China's industry (29) and making China more competitive in the global market (30). On the other hand, a country's economic prowess provides the foundation for its scientific strength (1, 4, 31). One important property of science as a social institution is that its product, scientific knowledge, is a public good, which anyone can use without loss of value.

For these two reasons—economic role and public good—most policymakers believe that governments should spend public funds to support science. Indeed, virtually all governments in the world invest in science as a national strategy. Thus, it is not surprising that the Chinese government, having access to centralized resources, has repeatedly formulated state policies to promote Chinese science.

The Chinese government's proscience policy after the Cultural Revolution began in 1977, with Deng Xiaoping's announcement that the State Science and Technology Commission would be restored and College Entrance Examinations resumed. A government document released in 1982 further declared, "Economic development should rely on science and technology; Science and technology should be oriented to serving economic development" (32). In 1986, the National Natural Science Foundation of China was established, modeled after the National Science Foundation of the United States. This was followed by the 863 Program, or State High-Tech Development Plan, intended to stimulate the development of advanced technologies. For institutions of higher education, the government launched Project 211 in 1995 to upgrade the research capabilities of roughly 100 universities, costing approximately US\$2.2 billion in the first phase from 1996 to 2000 (33). Project 211 was followed in 1998 by an even more ambitious program, Project 985, dedicated to building world-class, elite universities in China. The government provided generous funding and increased this over time for those select universities supported by Project 985. Peking University and Tsinghua University, for example, each received about US\$300 million in the first phase, in 1999–2001, with the funding level more than doubled in 10 y (34).

Knowing that capital investment alone would not make Chinese science strong, the Chinese government has also tried to attract talent from abroad by targeting overseas Chinese-born scientists, especially those working in the United States. Two programs were designed to encourage them to return to China.

The Changjiang Scholars Program, which began in 1998, first offered the scientists incentives that were mostly on a short-term visiting basis. Then, in 2008, the government launched the Thousand Talent Program called "The Recruitment Program of Global Experts" with the explicit goal of raiding first-tier foreign research institutions for senior-level scientists. Recruitment packages typically include a high salary, research funds and space, and a standard tax-free relocation allowance in the amount of US\$160,449 (35). Aided in part by a global financial crisis, the program attracted numerous overseas Chinese scientists back to China. Even as the number of students studying abroad continued to increase, the ratio of returnees to exits rose from 30.56% in 2007 to 38.54% in 2008, and again to 47.23% in 2009 (36). By April 2012, the program had attracted 2,263 scientists to work in China (37).

Some of the returning scientists were so prominent that the US science community was taken by surprise. Three of these were the biological scientists Yi Rao, Yigong Shi, and Xiaodong Wang. Rao left his named chair professor position at Northwestern University at age 45 to return to Peking University in 2007 (38). Shi quit his named chair position at Princeton University at age 42 to return to Tsinghua University in 2008 (39). This was followed in 2009 by the return of Xiaodong Wang, the first Chinese American scientist who grew up in China after the Communist Revolution to be elected to the National Academy of Sciences, to head the National Institute of Biological Sciences, Beijing (40, 41). American media reacted to these losses with concern. In the *New York Times*, LaFraniere declared that "the return of Dr. Shi and some other high-profile scientists is a sign that China is succeeding more quickly than many experts expected at narrowing the gap that separates it from technologically advanced nations" (39).

The Organisation for Economic Co-operation and Development has been tracking research and development (R&D) gross expenditures in different countries. According to their estimates, the ratio of China's R&D expenditure to that of the United States increased sharply, from 5% in 1991 to 44% in 2010 (42). China's steady growth in R&D expenditure, at 20% per year (43), has resulted from both the increase in gross domestic product (GDP) and the increase in the share of GDP spent on R&D. In Fig. 4, we present the most recent data on the share of GDP spent on R&D, separately for China and the United States. Whereas the trend has stagnated in the United States, it has moved steadily upward in China, more than doubling from 0.7% in 1991 to 1.8% in 2010, albeit still at a much lower level than in the United States' 2.8% in 2010 (Table S10).

Scientific Output and Impact

Have the Chinese government's efforts to upgrade science worked? One concrete way of determining this is to assess changes in China's output of scientific articles and their impact. For lack of

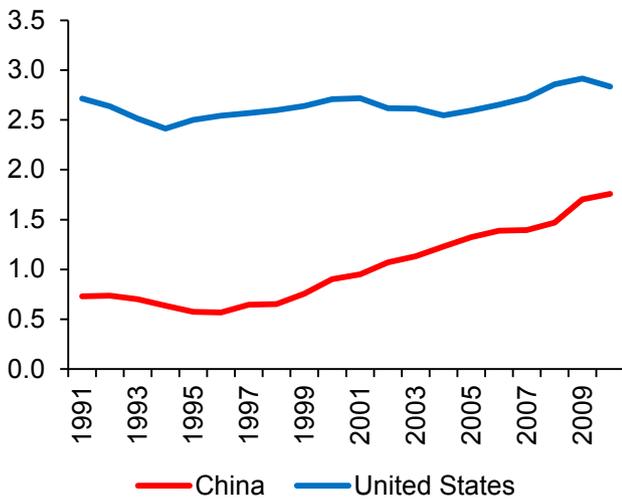


Fig. 4. Gross expenditures for R&D as share of GDP, 1991–2010.

better data, we rely on Thomson Reuters' InCites and Essential Science Indicators (ESI) databases for S/E publications produced in China, the United States, the United Kingdom, the European Union (EU-15), Germany, Japan, and India, and their citation counts (Table S11). Because Thomson Reuters does not track Chinese-language publications, and the Chinese scientific community began a major shift to publishing in English language journals in the 1990s, the Thomson Reuters data overestimate the increase of scientific output for China. With this limitation in mind, we constructed trend series for (i) the total number of articles between 1990 and 2011, shown in Fig. 5A (Fig. S5A in log scale; Fig. S6A for GDP-adjusted); (ii) average times cited per article per year for articles published between 1990 and 2011, shown in Fig. 5B (Fig. S5B in log scale;

Fig. S6B for GDP-adjusted); and (iii) number of top 1% highly cited articles between 2001 and 2011, shown in Fig. 5C.

Fig. 5A shows that China is by far the fastest-growing country in terms of article productivity between 1990 and 2011. Growing at an annual rate of 15.4%, China's total number of S/E articles increased 20 times, from 6,104 in 1990 to 122,672 in 2011. In comparison with other countries, China overtook the United Kingdom in 2004, and Japan and Germany in 2005, and has since remained second only to the United States. By 2011, China's article output was two-thirds that of the United States, and more than half of the total production by all EU-15 countries combined.

China's ascendancy in total scientific output has also been accompanied by a substantial improvement in quality. To measure quality, we use data from Thomson Reuters' Web of Knowledge on the number of citations per article up to 2011. Papers produced in China generated on average 8.4 citations in 1990–1994, but this number increased to 10.7 in 2000–2004, despite a shorter exposure of more recent papers. To adjust for unequal exposure for citation over time, we use US data as the benchmark against which we compare China and other countries in Fig. 5B. Relative to the United States, China has steadily improved in average citation counts over the past two decades, with the China:US ratio rising from 26% in 1990 to 55% in 2010. Although the figure also shows that even for the latest period, citations of Chinese papers remained far below those produced in the United States, the United Kingdom, and Germany, China has significantly narrowed its gap with other countries in producing the top 1% highly cited articles (shown in Fig. 5C), surpassing Japan in 2005 and reaching parity with Germany and the United Kingdom around 2009. The China:US ratio in number of highly cited articles climbed sharply from 6% in 2001 to 31% in 2011. Patent applications from China have also increased sharply since 2000 (44) (Fig. S7).

Despite China's rapid increases in both total productivity (Fig. 5A) and high-quality productivity (Fig. 5C), China's current productivity levels are not out of expectation given the large and

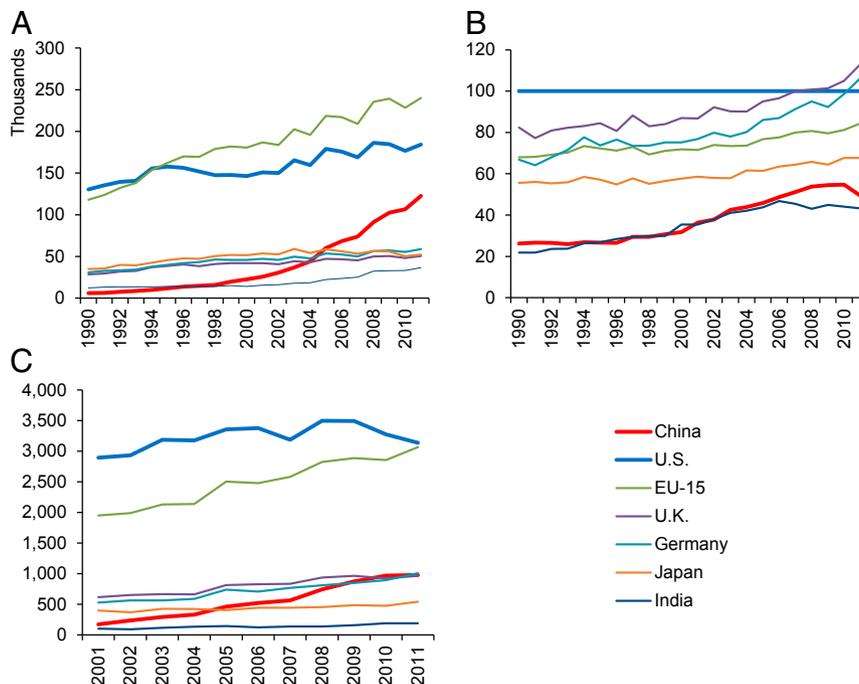


Fig. 5. (A) Total number of articles in S/E, 1990–2011. (B) Average times cited per article compared with the United States (%), 1990–2011. (C) Number of highly cited articles in S/E, 2001–2011.

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