China's "Great Leap Forward" in Science and Engineering

Richard B. Freeman[a] and Wei Huang[b]

March 2015

Abstract

In the past two decades China leaped from bit player in global science and engineering (S&E) to become the world's largest source of S&E graduates and the second largest spender on R&D and second largest producer of scientific papers. As a latecomer to modern science and engineering, China trailed the US and other advanced countries in the quality of its universities and research but was improving both through the mid-2010s. This paper presents evidence that China's leap benefited greatly from the country's positive response to global opportunities to educate many of its best and brightest overseas and from the deep educational and research links it developed with the US. The findings suggest that global mobility of people and ideas allowed China to reach the scientific and technological frontier much faster and more efficiently.

Keywords: China, Education, Science and Engineering

[a] Harvard University and NBER, 1050 Massachusetts Avenue, Cambridge, MA 02138, USA.

[b] Harvard University and NBER, 1050 Massachusetts Avenue, Cambridge, MA 02138, USA.

E-mail addresses: freeman@nber.org (R. Freeman), weihuang@fas.harvard.edu (W. Huang).

The Cultural Revolution (1966-1976) devastated science and engineering education and research in China. It led to the closing of China's national entrance exam that had for hundreds of years been the pathway for students to enter colleges and universities. Universities admitted no new undergraduate students from 1966 through 1969 and admitted no new graduate students through 1977. In 1970 China had only 47,000 undergraduate students and essentially no graduate students (Li, 2010, Table 8.1). Recovering from the Cultural Revolution in the 1970s and 1980s enrollments in four-year programs increased to 2.1 million in 1990 (Li, Table 8.2) while enrollments in all programs, including more vocationally oriented less than bachelor's programs, reached 3.8 million (Table 1). Still, China's share of world enrollments of 5.6% fell short its one-fifth (31%) of the world's 1990 population.[1] With few S&E graduates, China had fewer research scientists and engineers than did some countries with a tenth of China's population while China-based researchers contributed fewer papers to international science journals than China-born researchers outside the country.[2]

The great leap forward in science and engineering that gives this essay its title was concentrated in the two decades of the 1990s and 2000s. In this short span of time China leaped from bit player in global science and engineering to become the world's largest source of S&E graduates, second largest spender on R&D and second largest producer of scientific papers, in both cases behind the US. The number of patents in China increased so rapidly as to make China the number one country in patents (WIPO, 2014).[3] The number of China addresses on USPTO

[1] World Bank (2012), and http://en.wikipedia.org/wiki/World_population for the world. http://en.wikipedia.org/wiki/Demographics_of_China for China

[2] Some scholars argue that the parts of Chinese science that fit with the goals of the government fared reasonably well during the Maoist period (Wei and Brock 2013) but there is no gainsaying that the drops in admission to undergraduate and graduate S&E programs, banishment of professors and other researchers o the rural parts of the country, absence of scientific papers wrecked the bulk of China's research community.

[3] Incentives linking pay to number of patents have produced a patent system with many short single claim patents that are not readily comparable to patents in the US, EU, and Japan. That China is number one in WIPO patent data does not mean that it is top of the world in patenting. The number of China addresses on US, EU, and Japanese patents has risen but place China far from the top countries in patenting.

patents increased enough to move China from a negligible producer of US patents to 7th among non-US countries with US patents. As a latecomer to modern science and engineering, China trailed the US and other advanced countries in the quality of its universities and research but was improving both through the mid-2010s.

This paper analyzes China's great leap forward in science and engineering. It presents evidence that China's leap benefited greatly from the country's positive response to global opportunities to educate many of its best and brightest overseas and from the deep educational and research links it developed with the US. China first permitted students to self-finance overseas study and for scientific specialists to undertake cross-country research, then awarded fellowships for research students and researchers to study or work overseas while encouraging Chinese universities to hire faculty from abroad and to undertake international research collaborations, and sought multinational transfers of knowledge.[4] Global mobility of people and ideas allowed China to reach the scientific and technological frontier much faster than if it had gone down a more parochial path.

The paper has three parts. Section one examines the increase in domestic university enrollments and in students studying overseas that turned China into the number one source country for scientists and engineers worldwide. Section two documents the growth of R&D spending, production of scientific papers, and international research collaborations that improved the quality of Chinese science. Section three makes the case that the close links that developed between China and the US in education and research constitute a "special relationship" that augurs well for research in both countries and in the world.

1. China Becomes a Higher Education Powerhouse

1.1. Increase of Domestic Higher Education

Table 1 places China's leap forward in university enrollments in the context of the longer run

[4] The role of multinational transfer of knowledge is important in China's application of modern technology to the economy but raises diverse issues that go beyond the scope of our analysis: industrial secrecy, use of patents, Chinese purchase of advanced country high tech companies, and the like.

increase in the share of tertiary enrollments in developing countries from the 1970s to the 2010s. Convinced that development of human capital and adaption of modern technology was critical to economic growth many developing countries invested in higher education in the last 2-3 decades of he 20th century, producing a continuous rise in the developing country share of global tertiary enrollments.[5] China's leap forward -- an eight-fold increase in enrollments that moved it from 6% of world enrollments in tertiary education to 17% – was exceptional even in the context of the worldwide expansion of higher education.[6] The only comparable expansion was in much smaller Korea, which invested so much in education and research from the 1980s onward to become the number one country in the proportion of young persons attending college and university and in the proportion of GDP spent on R&D.[7] The other hugely populous country, India, expanded higher education more slowly but still enrolled 21 million students in 2010. In 2010 one in three college students in the world was from China or India.

[Insert Table 1 Here]

Behind the huge increase in enrollments in developing countries were national investments in new colleges and universities, expansion of existing institutions, and the upgrading lower level institutions into baccalaureate granting colleges or universities (International Association of Universities). In the Chinese case Li (2010) reports that the number of higher education institutions in China more than doubled from the mid 1970s to the mid 1980s – which allowed the country to raise the proportion of students admitted to college after taking the national entrance exam from single digits to 48% in 1999.[8] Looking at developing countries, many of whom barely had any universities, the increase in the number of universities around the world was more strongly associated with changes in enrollments than any other single factor.

Table 2 shows that the huge expansion of enrollments produced a commensurately large increase in students obtaining bachelor's, master's and PhDs in China in the 1990s and 2000s. From 1990 to 2010 the number of bachelor's graduates increased tenfold from 307,865 to 3,038,473. The difference between the 3 million graduates and Table 1's 30 million enrollments might suggest that China suffered from high university drop out during its enrollment spurt. With

---

[5] The increase in enrollments in developing countries (16 million to 137 million) is 81% of the total increase.

[6] The absolute increase was from 3.8 million in 1990 to 30 million in 2010

[7] Freeman (2015)

[8] Li, 2010 table 8.1 and 8.2 and p 273

4-5 years normally spent to earn a bachelor's degree, 30 million enrollments could be expected to produce ~ 6-7 million graduates.[9] But the divergence reflects something very different: the fact that nearly half of enrolled students take 2-3 year degree programs with greater occupational training and less academic content than traditional baccalaureates.

[Insert Table 2 Here]

The data for postbaccalaureate degrees in Table 2 show that the number of students receiving master's and doctorate degrees increased more rapidly than those receiving bachelor's degrees. Master's degrees increased nearly fifteen-fold from 1990 to 2010. Doctorate degrees increased nearly twenty-fold. Comparing S&E PhDs in China and the US, in 1990 China graduated just 5%-7% as many S&E PhDs as the US[10] whereas in 2010 it graduated about the same numbers of S&E PhDs to the US.[11] Because many Chinese citizens earn PhDs in advanced countries, moreover, China's contribution to the worlds' supply of new S&E specialists was even greater.

All of these developments reflected both the policies of the Chinese government to expand higher education and the desire of young Chinese students to invest in additional years of schooling, in part due to the high returns to education in China's new market economy.

---

[9] Estimated as about 1/4th to 1/5th of the 30 million.

[10] See http://www.nsf.gov/statistics/doctorates/pdf/sed2000.pdf table 5, p 36 for 1990 US PhDs by field. Subtracting humanities, education, and professional from the total gives 23,228. National Science Board National Science Foundation, Division of Science Resources Statistics Science and Engineering Indicators 2004 Arlington, VA (NSB 04-01) [May 2004] footnote 12 estimates that 1,069 S&E doctoral degrees were granted to Chinese students within Chinese universities in 1990. (http://www.nsf.gov/statistics/seind04/c2/c2s4.htm. The 7% figure divides the number in Table 2 by the US's 23,228. The 5% uses the smaller NSF estimate for China.

[11] China-US comparisons vary with how one treats Hong Kong and social/behavioral sciences. With Hong Kong counted as part of China, China produces more S&E PhDs than the US excluding social/behavioral sciences but fewer inclusive of social/ behavioral science. See http://www.nsf.gov/statistics/seind14/content/chapter-2/at02-39.pdf Appendix table 2-39 (National Science Board, 2014, http://www.nsf.gov/statistics/seind14/content/chapter-2/at02-39.pdf) reports 32,649 US S&E PhDs inclusive of the social/behavioral sciences and 24,559 excluding them; and 31,410 China PhDs inclusive of social/behavioral sciences and 29,039 excluding them. This exceeds the 27,066 in Table 2, which covers mainland universities and appears to exclude social sciences. All told, these data show that China graduates from 10% to 18% more natural science and engineering PhDs than the US while it graduates 3.8% fewer in all S&E.

There are three caveats to China's leap forward in world higher education. First, the huge number of enrollments and degrees results from China's large population more than from exceptionally high rates of college-going relative to the population. With a population roughly four times that of the US, China would have as many students/graduates as the US with a students/graduates to population ratio about one-fourth that of the US.[12] Given China's large rural population and relatively low quality education for persons with rural hukou, the country would have to invest substantially in elementary and secondary school to raise the proportion of young persons in tertiary education much beyond 2010 levels.

The second caveat is that the quality of China's college and university system lags behind that of higher educational systems in the US and other advanced countries. Table 3 demonstrates this with statistics on the global rank of universities in China from Shanghai Jiao Tong University's Academic Ranking of World Universities in 2003 (first year of its report) and 2014 compared to the rank of universities in the US, UK, Germany, and Japan In 2003 just 10 Chinese universities were in the top 500 universities in the world.[13] None were in the top 100 or 200. The leading university was Peking in 251-300 grouping. The next decade's improvement still left China's universities far behind the world's best. In 2014, thirty-two Chinese universities were in

[12] Taking a broader age group, the OECD estimates that the 2010 ratio of persons who attained at least a tertiary education to persons aged 25-34 was 8% in China compared to 42% in the US, 38% for the OECD average, and world high of 65% for Korea (OECD, 2012, Chart A1.1). The China figures are for persons 25-34. As the OECD does not make clear the relevant age group it has chosen, the above comparison is based on the assumption that the relevant group is the number of persons at a single age between 25 and 34, assuming a flat distribution of persons within the age category. The figures reported in the Scorecard (2012) for China are a decimal point off. At the PhD level, the ratio of graduates to persons in the relevant age group was about 0.25% for China (STI Performance of China, Annex p 4) compared to 1.6% for the US and 1.5% for the OECD (OECD, 2011, figure 2.1.1).

[13] The Shanghai ARWU uses five objective indicators to rank world universities: the number of alumni and staff winning Nobel Prizes and Fields Medals, number of highly cited researchers selected by Thomson Reuters, number of articles published in journals of *Nature* and *Science*, number of articles indexed in Science or Social Sciences Citation Index, and per capita performance of a university. On the basis of these statistics Shanghai, it ranks the top 100 universities and groups the rest into categories with fifty each. Other well-known rating systems give roughly comparable ratings, with however some idiosyncracy: the London Times ranking, for example, places British universities higher in its rankings than does the Shanghai rating.

the top 500, six were in the top 200, three in the 101-150 grouping, but none had reached the top 100.[14]

[Insert Table 3 Here]

The improved rating of China's universities did not occur by happenstance. The government spent considerable sums on a diverse set of number-designated funding programs to improve the quality of the university system and create a few world-class academic centers: the 211 project to support the top 100 universities; the 985 project to transform the 40 top universities to world-class status; the 863 program to fund research and development of technology; and the 973 project to fund basic research.[15] Aware of the quality gap between top universities in China and in more advanced economies, moreover, Chinese students and researchers have sought to compensate for their country's lagging quality by going abroad to learn from the best in foreign countries.

1.2. Going Out: More International Students and Visiting Researchers

The globalization of higher education was characterized by an exceptionally rapid growth in the number of international students. Between 1975 through 1990 the number of international students doubled from 0.6 million to 1.2 million. The number then increased 3.8 fold to 4.5 million in 2012. China was a latecomer in sending students overseas. In 1978 China's Ministry of Education asked the central government to send more students aboard, but the numbers were minuscule – barely 2,000 students in the five years 1978-1982, of whom 16% were graduate students and 9% undergraduate students, with the vast majority being visiting researchers. The government selected students for overseas study on the basis of its goals rather than the career plans of students.[16] Few Chinese had the funds to self-finance study abroad and those that did needed administrative department approval of their studies.

---

[14] For an assessment of China's higher education system see OECD (2009).

[15] See Li (2010) section 8.4.

[16] The State Board of Education's "The temporal policies about the students studying abroad and going back" emphasized the main channel of the students to go abroad is to be sent by the government.

The flow of Chinese international students increased in the 1980s, with the US the favored destination. The Chinese government maintained the policy of allowing international students and researchers to study outside the country even after the 1989 Tiananmen incident, which led many overseas students to seek permanent immigrant status in the US.[17] This loss of talent would almost surely have caused many countries to stop the flow of students overseas but China went in the other direction.[18] In 1993 the Communist Party Central Committee endorsed overseas education with the slogan "Support going, Encourage Back, Go and Back Free"[19] The number of Chinese studying overseas increased moderately through 2000, then accelerated as the State Board of Education simplified procedures for self-financed students to study abroad.[20] In 2005 the Ministry of Education announced that it would "select the highest talent student in China and send them abroad to the best universities/institutes and follow the best advisers". In 2007 it joined with the Ministry of Finance to set up the "national high-level university researchers program" to subsidize more students and visiting researchers.

Figure 1 shows the ensuing increase in the number of Chinese international students from the late 1990s through 2014, with a break after 2001 due to the US State Department rejecting more visa applicants than in the past and making it difficult for international students to travel outside the USA – all in response to the 9/11 terrorist destruction of the World Trade Center. The

[17] The US, in particular, offered Chinese students an opportunity to remain in the country, first through administrative decree and then in 2002 with the Chinese Student Protection Act that targeted permanent residence for Chinese students in the United States. An estimated 54,000 persons gained green cards and presumptively citizenship thereafter.

[18] We can only speculate on the possible reasons the government continued its international student policies. One likely reason the government was so favorable to top Chinese students studying overseas was recognition that necessary for them to reach their potential as scholars, consistent with China's historic cultural respect for scholarship. Another likely reason was the need for up-to-date scientific and technological expertise available only from overseas experts. And government also likely to be influenced by the desire of top officials and wealthy business persons to give their children best education world has to offer.

[19] Central Committee of Communist Part "The decisions about constructing the socialism market economy system"

[20] It canceled the qualification check procedure and the "training fees" charges for going abroad, and set up a "Chinese Government Award for Outstanding Self-Financed Student Abroad"

increased flow of Chinese students to Australia in the early 2000s suggests that some Chinese students went to Australia instead of the US. In 2005/06 the number of Chinese students going to the US increased massively as the State Department reformed the student visa program (National Academy of Sciences 2005). This change in policy may have reduced the number of Chinese students going to Australia shown in Figure 1.

[Insert Figure 1 Here]

With so many students overseas, the Central Committee's tenth Five Year Plan (2000) declared that the government would expand policies to attract and hire overseas Chinese talent and to encourage international students to come back. In 2003 the Personell Department declared that it wanted the talent coming back "to innovate and register new companies that served the nation". Li (2010, section 8.7,) describes a host of programs that offered high salaries and opportunities for returning researchers: Changjiang Scholarship Fellowships, various Province level fellowships; Distinguished young scholar awards, and the joint Research Fund for Overseas Chinese Young Scholars to do part of their work at a Chinese institute. In addition, China sought to attract foreign-born talent to lead research activities in China in particular thorough the Thousand Talents Program.[21]

Table 4 documents the concentration of Chinese students overseas in the US. Indicative of the preference of Chinese students for the US, the US share of Chinese overseas students far exceed the share of the US share of international students from outside China. Between 2007 and 2012, the Chinese international students going to the US increased from an already high 44% to 59%. With more Chinese enrolling in US colleges and universities, China's proportion of US international students zoomed from 12% (2007) to 29% (2012), exceeding China's share of all international students. In 2013 the 236,000 students from China to the US was over twice the number from the second largest supplier, India (Institute of International Education 2014).

[Insert Table 4 Here]

---

[21] Mara Hvistendahl, Science, Oct 2014

Furthering the link between China and the US, a larger proportion of Chinese earning PhDs in the US remain in the US than graduates from any other country. Finn's (2014) analysis of the social security numbers of foreign-born students shows that 86% of Chinese PhD graduates of 2006 worked in the US five years later, the highest rate of staying from a sizable country. His data show further that the rate at which Chinese PhDs stay in the US drops by about 2 percentage points a year so that on the order of 75% would remain in the US ten years after gaining their PhD.[22] NSF data on the post-graduate plans of foreign-born PhD graduates tells a similar story. In 2000-2003 92.5% of new S&E doctorate graduates from China planned to stay in the US – a figure above those for all countries, including India, where relatively many PhDs planned to remain in the US. From 2000-2003 to 2008-2011, however, the proportion of Chinese planning to stay fell to 85.6% (NSB, 2014, appendix table 3-22).

Does China benefit or lose from having so many international students working in the US or in other foreign countries upon completion of their studies?

The early "brain drain" literature worried that developing countries suffered from the immigration of highly educated workers, but more recent analyses stress the value of information flows from persons working overseas back to their country of birth that can speed up economic development.[23] Whether the benefits from having researchers overseas dominate the initial brain drain concerns about the reduced supply of researchers in the home country is not known. Given the huge increase in the supply of S&E PhDs in China, it is at least plausible that the value of information flows exceeds the loss of supply due to international students remaining in the US and other advanced countries.

2. China Becomes a Research Giant

2.1. China's Emerging in S&E Research

China massively increased its R&D expenditures and demand for researchers in the 1990s

[22] Consistent with this, Finn's data for the graduates of 2001 (Finn, 2014,figures 2 and 3) show modest declines in stay rates for cohorts of foreign-born PhDs of all nationalities.

[23] Docquier and Rapoport (2012) provides a valuable overview of how this literature has changed.

and 2000s. In 1990 China spent negligible amounts on research and development. Two decades later, China's research spending surpassed that of all of the major R&D spending countries save for the US (Figure 2). While China spent less than the EU on R&D, the ratio of RD/GDP in China jumped from 0.76 in 1999 to 1.84 in 2011, nearly the same ratio as the EU. Extrapolating the trends in R&D spending of China, the EU, and the US in 2014, the OECD expected that China would surpass the EU in total R&D in 2014-2015 and to surpass the US in 2019.[24]

[Insert Figure 2 Here]

The increased supply of doctorate and other scientists and engineers, expansion of higher education, and increase in R&D spending set the stage for a huge increase in the key measurable outputs from scientific research, academic papers and citations to those papers.[25]

Panel A of Table 5 shows the quantity of scientific papers in the US, Japan, Germany, UK and China in 1990, 2000, and 2012. China jumped from being a minor producer of papers to become a major producer between 1990 and 2012. Its share of world papers tripled from 3.3% in 2000 to 13.7% in 2012. The contrast of China's rising position in the production of papers with Japan's declining position is striking. In 2000 China had one-third as many papers as Japan. In 2010 China had twice as many papers as Japan.

[Insert Table 5 Here]

What about the quality of Chinese science? The most widely used metric for measuring the quality of scientific output is the citations that a paper garners. Because citations are influenced by the social norms of citations in different fields and by the network links among scientists as well as by the “innate quality” of the science itself, citations are an imperfect measure of the

---

[24] Data can be found here:
http://www.oecd.org/newsroom/china-headed-to-overtake-eu-us-in-science-technology-spending.htm

[25] In China as in other countries, the vast majority of papers have UNIV or COLL in their addresses while few have addresses of firms. Tabulating addresses in China we found that 70.1% are universities, (which defines as the names include “UNIV” or “COLL”; while 23.3% are institutes (which defines as the names include “INST” or “ACAD”, usually for Chinese Academy of Sciences, or of Social Sciences. Therefore, in China, over 93% of the papers are in Universities or institutes (the above two has little overlap)

scientific contribution of a paper (Adler et al. 2009). Because scientists in a given area are more likely to cite papers written by persons in the same locale, papers with a country address from a major science producing country such as the US will generally receive more citations than papers from countries with smaller scientific communities even if the papers are comparable in their scientific content.[26] These problems notwithstanding, citations remain the most widely used indicator of the scientific contribution of a paper. A paper cited by more scientists has greater value than one of comparable quality cited by fewer scientists.

To examine the position of China in citations, panel B of Table 5 records the share of the top 1% cited papers with addresses for China and other leading producers of scientific papers. The Table also reports the ratio of China's share of the top 1% of cited papers divided by its share of all papers. This ratio exceeds 1 when a country has a higher share of the top 1% papers than of all papers and falls short of 1 in the opposite situation. It is a rough indicator of the average quality of papers. By these metrics, China lags behind the lead countries in the quality of its scientific output. In 2002 China had a negligible absolute share and modest relative share of the top 1% of papers. However, both statistics increase through 2012 with China moving ahead of Japan in its share of top 1% papers. Still, China fell far short of reach the position in top cited papers of the US and EU. It is easier to leap forward in the quantity than in the quality of research activity.

2.2. More International Collaborations

Science has increasingly moved from individual researchers to teams of researchers, as evidenced by a continuous upward trend in the number of authors per paper (Wuchty, Jones and Uzzi, 2007; Adams, Black, Clemmons, and Stephan, 2005). Scientific research has also increasingly become international, with the proportion of papers with coauthors from different countries trending upwards even more rapidly (National Science Board, 2014; Adams, 2013).

While the number of authors per paper increased in China as in other countries, Table 6 shows that China diverged from the trend in increased internationalization of papers. The ratio of

[26] NSB, Science and Engineering Indicator 2014, table 5-26

articles with two or more international addresses relative to all country articles in the columns "Share of Country S&E Articles Internationally Co-authored" increased worldwide save for China. China's growth of articles was fueled by papers written by within-country collaborations,[27] presumably because the massive growth of researchers in China made it relatively easy for Chinese scientists to find co-authors in their own country.[28]

[Insert Table 6 Here]

Turning to the countries with which Chinese researchers collaborated, the columns "Country's Share of China's international collaborations" record the ratio of papers with at least one address from China and at least one from the specified country relative to the total number of Chinese international collaborations. What is striking is the large and increasing share for the US, China's biggest collaborator by far. In 2012 the US accounted for 47.5% of China's international collaborations.

The columns labeled "China's share of Country's International Collaborations" show that the growth of Chinese papers was so large that China's share of international papers increased by nearly four fold from 4.1% in 1997 to 16% in 2012. China became the US's number one international collaborator, surpassing the UK, Canada, and Germany in numbers of co-addressed papers.

2.3. It Matters: Associations with Scientific Quality

To see how international collaborations affect the quality of China's scientific papers, we have regressed the impact factor of the journal which published a paper[29] and citations to a paper five years after it was published to various measures of international collaborations. Table

---

[27] The higher share of internationally co-authored papers for individual countries than for the world in Table 6 is because the tabulations count an international paper with co-authors from two countries as a single paper at the world level but as two international papers at the country level, with one for each country.

[28] The same pattern is observed in Korea, which has also zoomed forward in researchers, research spending, and papers written (Freeman, 2015).

[29] The impact factor of the journal of publication has problems as a measure of quality as noted by European Association of Science Editors (2007).

7 records the estimated regression coefficients and standard errors linking impact factors and citations to dummy variable measures for whether the first author and/or last author of a paper had a Chinese name (=1) or had a non-Chinese name (=0). To identify Chinese-named authors we use William Kerr's name-ethnicity matching program (Kerr 2008, Kerr and Lincoln 2010), which assigns an ethnic identity to authors based on the distribution of names by ethnicity.[30] The identification hinges on the fact that last names such as Zhang are likely to be Chinese, names like Johnson likely to be Anglo-American, names like Singh likely to be Indian, and so on.

[Insert Table 7 Here]

The sample for these regressions is the papers that appeared in the Pub Med database for life and medical sciences. We use this sample rather than the Web of Science sample of all papers because it allows us to use the Torvik and Smalheiser (2009) algorithm for differentiating same-named people that is important in some comparisons. Since we are interested in the relationship between China and US, all the papers used contain an address in US or China. As the life and medical sciences publish the most papers of any scientific fields, our analysis treats a large sample. To compare likes with likes we include an array of co-variates as listed at the bottom of the Table: the number of authors, number of addresses, and number of references – all of which are positively associated with impact factors and citations; dummy variables for language of paper (most are in English), for the country addresses, for the year of the paper; and for the field of the journal of publication.

The columns "Non-China-based papers with Chinese-named authors" record the estimated relation between having first or last Chinese names on the impact factor of the journal in which a paper appeared and 5-year forward citations for papers *with all addresses in the US*, and thus relate to the research contribution of Chinese researchers usually working in advanced countries. The surname ethnicities are divided into four categories: Anglo-Saxon, Chinese, Other Asian and

[30] The Program divides ethnicity into nine categories: Chinese (CHN), Anglo-Saxon/English (ENG), European (EUR), Indian/Hindi/South Asian (HIN), Hispanic/Filipino (HIS), Japanese (JAP), Korean (KOR), Russian (RUS) and Vietnamese (VNM).

Other Non-Anglo-Saxon. The reference group is Anglo-Saxon authors and the coefficients on Other Asian and Other Non-Anglo-Saxon are not reported. The coefficients for Chinese-named authors are positive for both the impact factor and citation regressions, indicating that the papers with first or last author having Chinese surnames gain greater attention and are more likely to be published in high-impact journals than papers by other papers. One likely reason for this is positive selectivity of Chinese researchers working in the US and other overseas destinations. Chinese international students and visiting researchers to the US and elsewhere are often the best and brightest from China while the non-Chinese researchers to which the regression compares them include persons with a wider range of research skills. Note, however, that the coefficients on Chinese named last authors are positive but have a smaller magnitude, especially for impact factor. Since last authors are often the senior authors who have the connections or reputation to best place a paper in more prestigious journals, the smaller effect on impact factors may come from the older generation of Chinese researchers having weak connections in placing papers.

The columns "Overseas Experience of Chinese Authors on China-based papers" distinguish Chinese authors working in China by whether or not they had published a prior paper based on overseas research, which we define as a paper with no address in China. This definition assures us that the researcher worked outside of China on the earlier paper. It is a conservative estimate of outside China research and publication experience, since a China located author could have worked outside China with someone in China, and thus have outside China research experience that we would not capture. This measurement error should downward bias our estimated coefficients on the overseas experience variable. Even so, the regressions show that past overseas publication experience in the US (defined as a paper with all addresses in the US) or elsewhere (other papers with no China addresses) in by China-based authors are associated with higher impact factors and citations. We report the coefficients on the English language dummy to show the huge value of publishing in an English language journal, which invariably have higher impact factors than other journals, and are associated with more citations.

One likely reason for the estimated positive coefficients on the overseas experience variables is that the Chinese researchers learned valuable skills from international experience, ranging from better research techniques to gaining insight into the latest scientific ideas, which often depend on tacit knowledge from the leading researchers who developed them. Another likely reason is that working overseas created connections that increase the likelihood that international journals accept someone's papers and of generating citations from overseas researchers. It is also possible that the positive effect of overseas experience may reflect positive selection of researchers who published papers while working overseas.

Finally, the columns “Overseas Collaboration on China-addressed papers” examines the relation between papers based on collaborations of China-based scientists with scientists in the US or in other countries and the impact factors and forward citations to their papers. The sample for these calculations is limited to papers in Pub Med with at least one address in China. Since papers written in China have on average lower impact factors and citations than those written in the US and other major research producing locations, we expect that collaborations between researchers in China and researchers in advanced countries raises the impact factor and citations of collaborative papers relative to papers written solely in China. The estimated coefficients confirm this expectation. The regressions also show that collaborating with US-based scientists has larger positive effects on impact factors and citations than does collaborating with scientists in other countries. This result fits with the fact that US-based papers average higher impact factors and citations than papers from most other countries. The estimates in the last line “China-US & other collaboration” shows that papers with US and other country collaborations have the largest impact factors and citations. The scientific input that goes into multi-country papers is often greater than that of smaller collaborations, in part due to use of special equipment such as huge telescopes or special research facilities like the CERN Hadron collider or to large clinical trials. A paper with authors from many counties is also likely to gain greater attention by tapping into networks of researchers in more countries.

3. Conclusion

China's leap forward in science and engineering in the 1990s and 2000s is one of the defining events in modern intellectual history and as important to the future of the world as China's extraordinary economic growth. With hundreds of thousands of Chinese researchers contributing to the advance of scientific knowledge, and millions of Chinese engineers and scientists working to apply modern scientific technology to the production of goods and services, the frontier of useful knowledge will almost surely advance more rapidly than if China had remained a scientific backwater.

Our analysis has shown that this achievement was achieved not only by China's decision to rebuild itself from the disaster of the Cultural Revolution and Mao's “great leap forward” in the 1960s but also by China's accessing the global higher education and research system, and in particular through a “special relation” in education and research with the United States, the world's leading scientific power (Freeman and Huang, 2014). The special relation took the form of international student flows, where the US is the main destination of China's overseas students, and China is the single largest source of international students in the US; the high rate at which Chinese PhDs from US universities remain in the US and together with immigrant scientists and engineers, constitute a sizable share of researchers with US addresses; to each country being the major partner of the other in international collaborations on scientific papers; and to the higher impact factor of journals of publication and numbers of citations of papers with Chinese addresses from US and other foreign collaborations. There is much more that can be done in exploring the special relation between China and the US and China's education and research link to other countries, as well. Analysis of the extent to which collaborations develop between faculty advisers and their PhD students and/or among students in the same university or laboratory; the extent to which persons of Chinese ethnicity in the US (or other foreign addresses) disproportionately collaborate with researchers in China, and whether any such pattern holds for persons of other ethnicity (which we would expect to be the case); and the contribution of Chinese government support for international students and research visits on scientific outcomes are natural follow-ups of the findings in this paper. More broadly, all of our results regarding the relation between the US and China could be fruitfully expanded to include other countries.

Ideally, the China -US collaboration in education of scientists and engineers and in research will spur the development and spread of knowledge in ways that benefit not only the Chinese and American people but people around the world and that strengthens the cooperative relations between the two countries. Globalization of knowledge may not be the “one ring that rules them all” that Freeman (2014) hypothesized but it is surely a necessary ring for the world to overcome its problems and to improve lives everywhere. We look forward to China's increasing contribution to the global world of knowledge production. In research perhaps more than anywhere else, the emerging China needs the world and the world needs an emerging China. 崛起的中国需要世界，世界需要一个崛起的中国。

References

Adams, James D. (2013). “Collaborations: The Fourth Age of Research.” *Nature*, 497(7451), 557-560.

Adams, James D., Grant C. Black, J. Roger Clemmons, and Paula E. Stephan (2005). “Scientific Teams and Institutional Collaborations: Evidence From US Universities, 1981–1999.” *Research Policy,* 34(3), 259-285.

Adler, Robert, John Ewing, and Peter Taylor. (2009) "Citation statistics." *Statistical Science* 24.1: 1.

Australia, Department of Immigration and Border Protection

Bound, John, Sarah Turner, and Patrick Walsh (2009). “Internationalization of US Doctorate Education,” (NBER Working Paper 14792 (March). http://www.nber.org/papers/w14792.

Cao, C. (2004). China's scientific elite. Routledge.

Cao Cong and Denis Simon, China's emerging technological edge: Cambridge University Press, 2007

Docquier, F., & Rapoport, H. (2012). Globalization, brain drain, and development. *Journal of Economic Literature*, 681-730.

European Association of Science Editors (2007) “The EASE Statement on Inappropriate Use of Impact Factors”. Available at: http://www.ease.org.uk/sites/default/files/ease_statement_ifs_final.pdf

Finn, M. G. (2014). Stay Rates of Foreign Doctorate Recipients from US Universities, 2011. *National Center for Science and Engineering Statistics of the National Science Foundation*. Available at: http://orise.orau.gov/files/sep/stay-rates-foreign-doctorate-recipients-2011.pdf

Freeman, Richard B. (2014). “One Ring to rule them all? Globalization of knowledge and knowledge creation” Nordic Economic Policy Review: Globalization, labour market institutions and Wage structures, number 1, 2013, pp 11-43 available at NBER Working Paper 19301. http://www.nber.org/papers/w19301

Freeman, Richard B. and Wei Huang, (2014).”Research Collaborations Between Chinese and US Scientists and Engineers: A New Special Relationship?” presented at AEA Meeting, Jan 5, 2014 Philadelphia

Freeman, Richard B. (2015) “Knowledge, Knowledge, My Economy for Knowledge”, for Korea Development Institute

Gomory, Ralph E. and William J. Baumol (2001). *Global Trade and Conflicting National Interests*. Cambridge, MA: MIT Press.

International Mathematical Union (2008). Joint IMU/ICIAM/IMS - Committee on Quantitative Assessment of Research Citation Statistics. Available at: http://www.mathunion.org/fileadmin/IMU/Report/CitationStatistics.pdf

Kerr, William R., and William F. Lincoln (2010). "The Supply Side of Innovation: H-1B Visa Reforms and U.S. Ethnic Invention," *Journal of Labor Economics*, University of Chicago Press, vol. 28(3), pages 473-508, 07.

Kerr, William. R. (2008). Ethnic Scientific Communities and International Technology Diffusion,” *The Review of Economics and Statistics*, *90*(3), 518-537.

Hvistendahl, M. (2014). China tries to kick its salt habit. *Science*, *345*(6202), 1268-1269.

Li, Haizheng. (2010). "Higher education in China: Complement or competition to US universities?." In *American universities in a global market*, pp. 269-304. University of Chicago Press.

National Academy of Science (2005). The National Academies, Committee on Science, Engineering, and Public Policy, Policy Implications of International Graduate Students and Postdoctoral Scholars in the United States, Washington, DC, May.

National Science Board (NSB) (2014). *Science and Engineering Indicators 2014*. Arlington VA: National Science Foundation (NSB 14-01).

OECD, M. (2008). OECD reviews of innovation policy: China. Chapter 6 Human Resource For Science and Technology and Innovation in China. Paris: OECD Publishing.

OECD (2009) Review of Tertiary Education in China

OECD (2011), Education at a Glance 2011: OECD Indicators, OECD Publishing.
http://dx.doi.org/10.1787/eag-2011-en

OECD (2012), Education at a Glance 2012: OECD Indicators, OECD Publishing.
http://dx.doi.org/10.1787/eag-2012-en

OECD (2013) Science and Technology Scoreboard

OECD (2014). Education at A Glance 2014: OECD Indicators. Paris: OECD Publishing. *http://dx.doi.org/10.1787/eag-2014-en*

People's Republic of China, Ministry of Education, Educational Statistics Yearbook of China, various editions.

Science, Technology and Innovation (STI) Performance of China D9: Final Report Annex

http://eeas.europa.eu/delegations/china/documents/eu_china/research_innovation/4_innovation/sti_china_study_annex.pdf

Springut, Micah, Stephen Schlaikjer, and David Chen. (2011). *China's Program for Science and Technology Modernization: Implications for American Competitiveness: Prepared for the US-China Economic and Security Review Commission*. CENTRA Technology

Torvik, Vetle I., and Neil R. Smalheiser (2009). Author name disambiguation in MEDLINE. *ACM Transactions on Knowledge Discovery from Data (TKDD)*,*3*(3): 11.

UNESCO, Institute for Statistics, on line files, 2010

Wei, Chunjuan Nancy, and Darryl E. Brock, eds. (2013). Mr. Science and Chairman Mao's Cultural Revolution: science and technology in modern China. Rowman & Littlefield.

WIPO, 2014. World Intellectual Property Indicators. Economics & Statistics Series. Link:
http://www.wipo.int/edocs/pubdocs/en/wipo_pub_941_2014.pdf

World Bank. (2012). "Statistics about the Population Growth in China, 2001–2011, World Bank, July 2012. Retrieved 10 April 2013. Available at: http://www.statista.com/statistics/270129/population-growth-in-china/ "

Wuchty, Stephan, Benjamin F. Jones, and Brian Uzzi (2007). "The Increasing Dominance of Teams in Production of Knowledge," *Science*, *316*(5827) (May 18):, 1036-1039.

Web sites referenced in paper

http://en.wikipedia.org/wiki/World_population

http://en.wikipedia.org/wiki/Demographics_of_China

http://www.oecd.org/newsroom/china-headed-to-overtake-eu-us-in-science-technology-spending.htm

http://www.nsf.gov/statistics/doctorates/pdf/sed2000.pdf

http://www.nsf.gov/statistics/seind04/c2/c2s4.htm.

www.eol.cn

http://www.iie.org/Research-and-Publications/Open-Doors

Table 1: Millions of Enrollments and Shares of Enrollment in Tertiary Education, by Area of the World, 1970-2010

Area	1970	1990	2010
World	29.4	67.6	177.6
Developing	16.0 (54%)	41.0 (61%)	136.5 (76%)
China	<0.1 (0%)	3.8 (6%)	30 (17%)
India	2.5 (9%)	5 (7%)	20.7 (12%)
US	8.5 (29%)	13.7 (20%)	20.4 (11%)
Other Adv	4.9 (17%)	12.9 (19%)	23.7(13%)

Notes: Data source is UNESCO, Institute for Statistics, on line files, 2010 from Tables 15, 20A.

Table 2. Number of Bachelor's, Masters, PhDs graduating in China, by year, Total and S&E

Year	Bachelors		Masters		PhDs	
	Total	S&E	Total	S&E	Total	S&E
2012	3,038,473	1,258,643	434,742	191,048	51,713	27,652
2011	2,796,229	1,163,643	379,705	165,450	50,289	27,584
2010	2,590,535	1,082,271	334,613	145,266	48,987	27,066
2009	2,455,359	1,028,129	322,615	145,380	48,658	26,956
2008	2,256,783	956,214	301,066	138,441	43,759	24,229
2007	1,995,944	861,834	270,375	127,357	41,464	22,530
2006	1,726,674	770,441	219,655	104,282	36,247	19,371
2005	1,465,786	680,301	162,051	80,084	27,677	14,885
2004	1,196,290	576,627	127,331	61,042	23,446	12,572
2003	929,598	454,946	92,241	44,279	18,806	10,278
2002	655,763	324,550	66,203	31,884	14,638	8,060
2001	567,839	283,080	54,700	25,715	12,867	7,647
2000	495,624	262,119	47,565	25,421	11,004	7,019
1999	440,935	237,705	44,189	25,119	10,320	6,450
1998	404,666	222,103	38,051	22,443	8,957	5,711
1997	381,647	214,552	39,114	22,729	7,319	4,803
1996	347,194	199,754	34,026	20,613	5,430	3,564
1995	325,484	186,873	27,123	17,591	4,641	3,091
1994	310,291	178,380	24,181	15,443	3,723	2,481
1993	298,959	142,536	25,167	16,263	2,940	2,054
1992	.	.	23,015	.	2,528	1,769
1991	323,434	156,461	29,193	18,672	2,610	1,727
1990	307,865	148,886	31,505	20,303	2,457	1,626
1989	308,930	153,032	32,890	21,169	2,046	1,890
1988	279,791	137,065	34,732	.	1,538	.
1987	252,973	121,802	20,307	13,629	464	350
1986	227,764	109,101	15,221	9,704	284	228

Notes: Data source is Ministry of Education of People's Republic of China and Educational Statistics Yearbook of China. The Bachelors here are those with Normal Courses and do not account those with Short-cycle courses.

Table 3. Rating of Universities: China, US, UK, Germany, and Japan, 2003-2014

Measure	China	US	UK	Germany	Japan
# in top 500 in 2014	32	146	38	39	19
in 2003	9	157			
# in top 200 in 2014	6	77	20	13	8
in 2003	0	86			
# in top 100 in 2014	0	52	8	4	3
in 2003	0	53	9	5	5
Rank/name of 2014 top university	101-150, Peking, Tsinghua, Shanghai Jiao Tong	1, Harvard	5, Cambridge	49, Heidelberg	21, Tokyo
Rank/name of 2003 top university	201-250, Tsinghua	1, Harvard	5, Cambridge	49, Munich	19, Tokyo

Notes: Data source is Shanghai Jiao Tong University, Academic Ranking of Work Universities.

Table 4. The Growing Mainland China-US Special Relation in International Education

Year	Number Going Abroad (10,000)	Number Going to the US (10,000)	Proportion going to US	Proportion of Mainland Chinese among international students in the US
2005	14.24	6.3	0.44	--
2006	14.71	6.7	0.46	--
2007	16.64	8.1	0.49	11.6
2008	17.94	9.7	0.54	13.0
2009	22.32	12.1	0.54	14.6
2010	28.47	15.8	0.55	18.5
2011	33.97	19.4	0.57	21.8
2012	39.96	23.6	0.59	25.4
2013	41.39	--	--	28.7

Notes: Data source for first three columns is Ministry of Education of the PRC and the data are collected by www.eol.cn. The last column is from open door data (http://www.iie.org/Research-and-Publications/Open-Doors).

Table 5. Quantity and Quality of Papers by Country Addresses, 1990-2012

Panel A: Quantity of Papers

	Number of Papers			Share of World Papers %		
	1990	2000	2012	1990	2000	2012
World	508 795	619 680	852 110	100	100	100
US	191 559	212 781	262 266	32.5	34.3	30.8
China	6 285	20 900	116 633	1.2	3.3	13.7
UK	39 069	59 855	71 156	7.7	9.7	8.4
Germany	32 295	55 648	70 533	6.3	9	8.3
Japan	38 570	61 343	55 316	7.6	9.9	6.5

Panel B. Quality of papers

	Share of top 1%		Relative Share (Share of top 1%/ Share of All papers)	
	2002	2012	2002	2012
US	57	46.4	1.8	1.7
EU	28.2	29.8	0.8	0.9
China	0.3	5.8	0.1	0.4
Japan	5	4	0.6	0.6

Notes: Data source are NSB, Science and Engineering Indicators 2004, Table 5-35 and NSB, Science and Engineering Indicators 2014, Table 5-41 and Table 5-57.

Table 6. Share of Articles internationally co-authored and Country Shares of Collaborations

	Share of Articles internationally co-authored (%)		Country's Share of China's International Collaboration (%)		China's Share of Country's International Collaboration (%)	
	1997	2012	1997	2012	1997	2012
World	15.7	24.9	--	--	4.1	16.1
China	25.7	26.7	--	--	--	--
US	19.3	34.7	35.1	47.5	3.2	16.2
Japan	16.4	30.0	8.2	8.8	3.4	18.1
Germany	35.5	55.5	11.0	8.1	2.3	7.0
UK	31.0	55.1	11.1	9.5	2.4	8.2

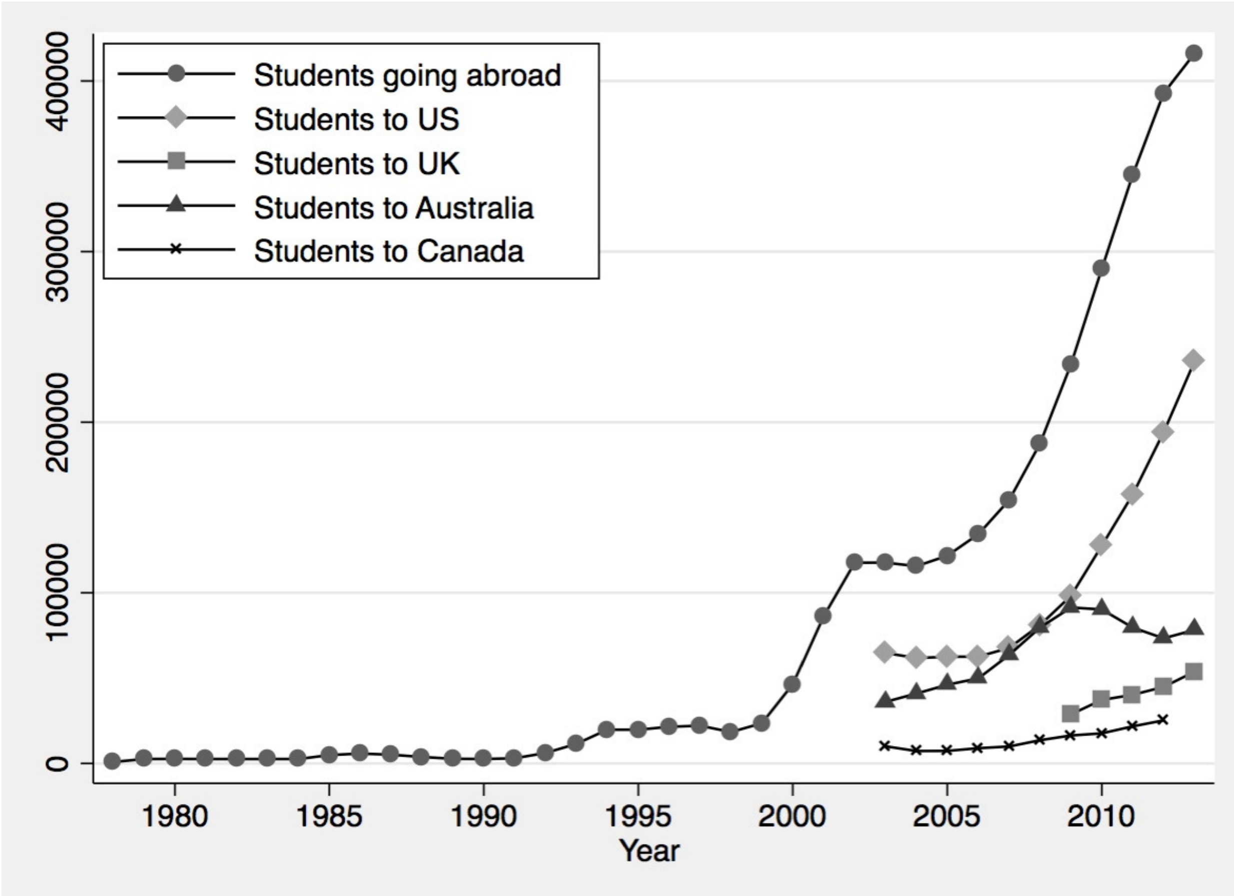
Notes: Data are tabulated from Science and Engineering Indicators 2014, table 5-41 and 5-56.

Table 7. Impact Factors and Five year citation rates for Papers Written by Chinese Authors With International Connections, Based on PubMed data

Sample	Non-China-based papers		China-based papers with all Chinese Authors		China-addressed papers	
VARIABLES	Impact Factor	Five-year citations	Impact Factor	Five-year citations	Impact Factor	Five-year citations
Surname ethnicity of first and last author (Reference group is Anglo-Saxon)						
First author	0.276***	2.216***				
Chinese	(0.00730)	(0.0602)				
Last author	0.191***	2.189***				
Chinese	(0.00950)	(0.0783)				
Oversea experience (The reference group is authors with no oversea experience)						
USA experience			0.689***	1.852***		
			(0.0698)	(0.371)		
Other oversea			0.671***	1.770***		
experience			(0.0591)	(0.288)		
English journal			0.602***	0.743***		
			(0.0297)	(0.221)		
Collaboration or Country where the paper is produced (Reference group is China only)						
China-only US					0.598***	1.967***
collaboration					(0.0251)	(0.177)
China-only other					0.263***	0.799***
collaboration					(0.0282)	(0.199)
China-US & other					0.717***	4.312***
collaboration					(0.0447)	(0.315)
Observations	5,884,586	5,884,586	51,802	51,802	118,837	118,837
R-squared	0.388	0.168	0.405	0.265	0.421	0.208

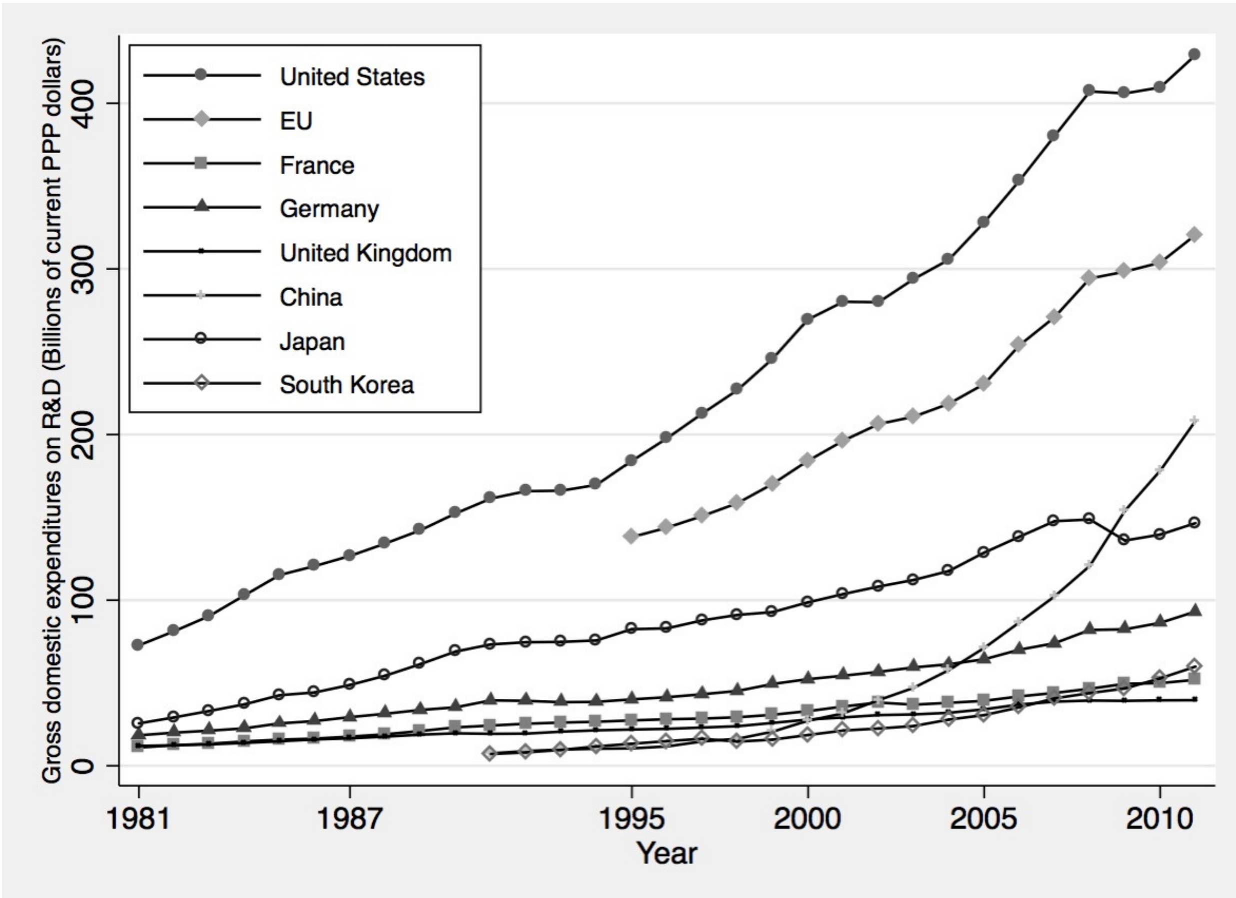
Note: Covariates controlled for in all columns include indicators of number of authors, number of addresses, number of references, language of paper, countries, publication years and fields. Standard errors are in parentheses.

Figure 1. The 2000s Increase in Chinese International Students



Notes: Data are not available for all countries in all years. Data of students going abroad is from www.eol.cn, whose data source is Ministry of Education of the PRC. Data of US students are from open door data. Data of UK is from https://www.hesa.ac.uk/. Higher Education Statistics Agency. Data of Canada is from Canadian Government Department of Immigration. Data of Australia is from Australian Government Department of Immigration and Border Protection. The data of UK Canada, Australia are collected by www. eol.cn.

Figure 2: Gross Expenditures on R&D, by Country and Area, 1981-2011



Notes: The figure is from Science and Engineering Indicator (2014). The data source is Organization for Economic Co-operation and Development Main Science and Technology Indicators (2013/1). EU = European Union; PPP = Purchasing Power Parity. Data are not available for all countries in all years.