Immigration, International Collaboration, and Innovation:
Science and Technology policy in the global economy

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Abstract

The globalization of science and engineering that has characterized the beginning of the 21st century has substantial implications for US science and technology policy. This paper shows that globalization of scientific and technological knowledge has reduced the US share of world scientific activity, increased the foreign-born proportion of scientists and engineers in US universities and in the US labor market, and led to greater US scientific collaborations with other countries. China's massive investments in university education and R&D have in particular made it a special partner for the US in scientific work. The paper suggests that aligning immigration policies more closely to the influx of international students on the supply side and requiring that firms with R&D tax credits or other government R&D funding develop "impact plans" to use their new knowledge to produce innovative products or processes in the US could help the country adjust to the changing global economy.

Globalization of knowledge, knowledge creation, and innovation have widened the framework for assessing the economic effects of science and technology (S&T) policies. As an advanced country at the frontier of knowledge, the US relies on investments in science and technology to improve economic performance and maintain comparative advantage in the high tech industries that employ highly educated workers. Expansion of tertiary education, increases in research and development spending, and the manufacturing and assembly of high tech products in low income countries as well as in other advanced countries challenges the US position at the knowledge frontier[1]. This makes S&T policies more important in determining economic outcomes than in earlier post World War II decades when the US naturally dominated the production and application of knowledge to the economy.

This paper analyzes the globalization of science and engineering and knowledge production in the 21st century and its implications for US science and technology policies.

Section I documents the spread of advanced knowledge and knowledge creation around the world in terms of its impact on the US share of the world's science and engineering activity. It stresses that the rapid catch-up in knowledge-creating activities and production in low-wage developing countries, most notably China, constitutes a major challenge for the US. The catch-up undermines the “North-South” model of trade that posited that advanced countries inevitably have comparative advantage in the production of high value added innovations.[2]

Section II shows that the worldwide spread of science and engineering has “globalized” science and engineering *within* the US by increasing the foreign-born share of science and engineering graduate students and post-docs in US universities and the foreign-born share of the US's science and

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[1] It also benefits the US economy. Products and services produced at lower prices in low-wage countries reduce the costs of consumption in the US. Technological advances beyond or complementary to those in the US can improve US productivity. Expansion of university education and R&D overseas creates jobs for US citizens and augments the supply of high-level immigrants to the US.

[2] Krugman 1979 has the clearest statement of this model. Baumol and Gomory (2000) make the case that loss of comparative advantage in particular high valued or high-tech industries can reduce the well-being of one of the countries. Ruffin and Jones 2007 offer additional insights and a more sanguine view.

engineering work force, and by spurring international collaborations in knowledge production and innovation, which presumptively speeds the rate of knowledge creation and its spread around the world.

Section III examines possible changes in US policies regarding international students, post-doctoral workers and S&E immigrants and regarding the link between technology-based innovations and production. It argues that globalization of knowledge makes S&T policies the "industrial policy" of the 21st century, with broad implications for economic performance. To maximize the benefits of the globalization of knowledge, the US will have to find the appropriate balance between investments that expand the stock of global knowledge and policies that localize a share of the gains in the domestic economy, as other countries will also have to do.

I. Globalization of S&E Activity Across Countries

Not so long ago the US was the *colossus* in producing new science and technology and developing science and technology-based innovations. In 1970, with just 5-6% of the world's population, the US had 29% of university enrollments and over half of science and engineering PhDs, performed 40% of world R&D, and produced 32% of all scientific papers and 57% of the most highly-cited papers.[3] The US accounted for 28% of world GDP in 1970 and had a GDP-per-capita five times the global average.[4]

Investments by the rest of the world in higher education and research in the past half century or so have reduced US predominance in science and engineering. Advanced European countries recovering from World War II increased university enrollments and R&D expenditures from the 1960s to the present. Japan, and later the Asian Tiger economies, did the same. Beginning in the 1990s,

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3 For enrollment data see Freeman, R. (2010) What Does Global Expansion of Higher Education Mean for the United States?" in Clotfelter, Charles editor, American Universities in a Global Market. University of Chicago Press http://www.nber.org/books/clot08-1. For other data see Science and Engineering Indicators 2014

4 http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx#.UxR0FfldXw8.

developing countries substantially expanded their higher educational systems and scientific activity. Despite its low level of GDP-per-capita, China graduated huge numbers of scientists and engineers and poured sufficient money into R&D from the 2000s to 2013 to become a super-power in science and engineering, which will inevitably translate into innovation in high-tech and other sectors.

The rapidity with which China and other developing economies have moved toward the frontier in knowledge creation and in the application of advanced knowledge to the economy is arguably the great surprise of modern globalization. When Americans debated the NAFTA treaty two decades ago, analysts had no notion that in the near future, low-wage countries would increase their supplies of university-educated workers and invest enough in R&D to challenge the US in knowledge and technology intensive sectors. Proponents of free trade promised American workers that the solution to low wage competition from Mexico was university education. Opponents warned of the “giant sucking sound” of factory assembly jobs moving to Mexico to hire low-wage workers.[5]

Post-NAFTA, the proportion of young Americans in colleges and universities increased, driven by an influx of women. But continuing a trend that began as early as the 1970s, the proportion of young persons in tertiary education in other countries increased more rapidly than in the US. From 1970 to 2010, the US share of the world’s university students fell from 29% to 11%. In the 1970s and 1980s, the spread of mass higher education in Europe was the major factor in the decline of the US share of world college enrollments.[6] By 2010, enough advanced countries had expanded their higher educational systems to drop the US from a top position to middle of the pack in the ranking of countries by proportion of young persons in university.[7]

The downward trend in the US share of world university students in the 1990s and 2000s was

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[5] http://en.wikipedia.org/wiki/North_American_Free_Trade_Agreement. http://en.wikipedia.org/wiki/Giant_sucking_sound

[6] See exhibit 1.

[7] OECD, Education at a Glance, 2013 (Paris 2014), table A3.2a shows the US with a graduation rate of 39% of the age group, which is exactly at the OECD average. The US was at the median rate for 25 countries in this table. http://www.oecd.org/edu/eag2013%20(eng)--FINAL%2020%20June%202013.pdf

largely driven by a different phenomenon – expansion of higher education in China, India and other developing countries. In 1970, China had just 47,000 undergraduate students and essentially no graduate students (courtesy of the Cultural Revolution's destruction of higher education). In 1980, China had 1.3 million undergraduates enrolled and 21,000 graduate students. In 1990, it had 2.1 million undergraduates and 93,000 graduate students. In 2000, it had 5.6 million undergraduates and 301,000 graduate students.[8] By 2010, China had increased its enrollments to 30 million students and graduated 6 million persons with bachelor's degrees. The other hugely populous country, India, expanded its higher educational system more slowly but still enrolled 21 million students in 2010. From 1970 to 2010 India more than doubled the number of Indian Institutes of Technology.[9] According to the OECD (2013), Mexico, the focus of the NAFTA debate, had the highest average annual rate of growth of first-time upper secondary graduation rates in among OECD countries in the 2000s and increased tertiary graduation by 6 percentage points between 2000 and 2011. Because the proportion of bachelor's degrees going to science and engineering in most countries exceeds the proportion in the US, increased enrollments and graduates overseas have an amplified effect in reducing the US share of scientists and engineers with bachelor's degrees.

Exhibit 1 measures the globalization of scientific and engineering activity in terms of its impact on the US share of world research and S&E activity, as given from data in various editions of the Science and Engineering Indicators and from the OECD's Main Science and Technology Indicators database. The comparisons for the 2000s are based on comparable statistics that cover nearly identical samples of countries, but some of the figures for the "world" are sparser in earlier years and reported differently, which gives a cruder measure of the trends. The OECD measures of country R&D differ

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[8] Li (2010) tables 8.1 and 8.2

[9] http://en.wikipedia.org/wiki/Indian_Institutes_of_Technology

modestly from the Science and Indicators measures for some countries, and so forth.[10] I deal with this problem by giving several statistics under some of the headings. The changes are sufficiently large to make it clear that global catch-up produced a huge drop in the relative position of the US.

The US share of R&D spending and of researchers dropped sharply in the 2000s, as China expanded its scientific activities extraordinarily rapidly (lines 1 and 2). By 2011 China was the second biggest performer of R&D, accounting for 18% of R&D among the select group, while Japan accounted for 11%. The largest EU performer, Germany, spent 8% of global R&D but the EU in its entirety accounted for 28%.[11] With Asian countries aside from China, Japan, and South Korea increasing R&D substantially and with Brazil increasing its R&D, the concentration of R&D in the US and other advanced countries declined. The OECD's series on the number of researchers follows a similar pattern, albeit subject to problems in the consistency of statistics for some countries, notably China. By 2012 the OECD data show that China surpassed the US in the number of full-time equivalent research personnel.

Lines 3 and 4 turn to the US share of scientific and engineering publications and citations, respectively. The US share of global scientific papers held roughly steady from 1970 through 1990 then fell to 31% in 2000 and to 26% in 2011.[12] The decline in the 1990s resulted largely from expanded activity in other advanced countries, whereas the decline in the 2000s was associated with the huge increase in papers with addresses in China. The increased China share exceeded the absolute value of the decline in the US share and reduced the EU and Japan shares of world papers as well.

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[10] The cost of research varies greatly among countries depending on the wages of researchers and other expenses. A country in which researchers are paid half as much as in another country could spend half as much for the same real activity. In the absence of R&D specific exchange rates, the US National Science Foundation uses purchasing power parities to compare expenditures across countries in comparable units.

[11] Indicators, 2014, table 4-13.

[12] The statistics measure the country share by fractional counts of country addresses/affiliations on papers. This may exaggerate the drop in US as producer of research papers by weighing the contribution of collaborations across country lines equally whereas US based researchers are particularly likely to be the principal investigator which in most fields is the last name on the paper.

From the 1970s through 2000, “Indicators” reports the US share of citations. Thereafter, it reports the US share of articles in the upper 1% of the distribution of papers ordered by their citations. The US share of citations dropped more or less commensurately with the drop in the share of papers from 1990 to 2000. In the 2000s, the share of highly cited papers declined more in absolute and proportionate terms than the US share of all papers, as the rest of the world closed the citation gap. China's increased share of top 1% cited papers fell short of the drop in the US share. Other developing countries, and rapidly growing Korea, Taiwan, and Singapore, explain much of the remaining US drop in highly cited articles. But even with the decline, the US still maintained a remarkably high share of the most highly cited papers.

Turning to higher education, the exhibit shows that the US share of bachelor's science and engineering graduates and doctorate S&E degrees fell from the 1970s through the 2000s. EU countries expanded doctorate science and engineering programs so rapidly that by 2010 the EU produced nearly twice as many natural sciences and engineering PhDs as the US – a differential that reflects in part the shorter time period for gaining a doctorate in those countries than in the US. In the 2000s, however, the big mover in the production of doctorate degrees was China. China increased its S&E PhD graduates so rapidly that by 2007 the number of students obtaining natural science and engineering PhDs in China exceeded the number obtaining S&E degrees in the US.[13] While the quality of China's graduate training falls short of that in the US, its jump from negligible producer of S&E PhDs to top single country is remarkable. Recognizing its lag in the quality of doctorate education, moreover, China encourages top students to enroll in doctorate programs in the US and other advanced countries and funds PhD students and researchers to spend a year overseas to improve their research skills. The massive increase in S&E doctorate researchers in China promises to improve the country's position in

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[13] It fell short of the total science and engineering degrees due to much larger numbers of social science PhDs in the US.

the knowledge-intensive and high-technology sectors of the economy on which the US relies for economic growth and comparative advantage in trade.

In 1990, virtually no major multinational would consider undertaking R&D in a developing country such as China. Industry-funded R&D was concentrated in the US. In 2000, multinational firms had on the order of 120 R&D centers in China. In 2013, this had expanded to over 1,300 R&D centers in China, with 61% of major multinationals doing R&D reported to have at least one research and development center in China.[14] In 2013, one-fourth of IBM's 12 major research facilities were in developing countries – China (established 1995), India (1998), Brazil (2010), and Kenya (2013).[15] To be sure, companies locate R&D around the world for a diverse set of reasons – to be near the markets of consumers of their products, or to be close to the production plants of their firm or its major suppliers. But the key factor in the spread of multinational research facilities worldwide is the new availability of scientific and engineering workers in developing countries at the lower wages in those countries compared to the advanced countries.

The development of the global solar energy industry provides a striking example of the changing advantages of the US and other advanced countries compared to China in what is becoming a bulwark green technology. When the Obama Administration loaned substantial government funds to US solar manufacturers as part of its sustainable energy policies and spent $9 billion in federal stimulus funds on green energy it did not appreciate the huge advances China had made in the sector, which reduced the prices of solar panels sufficiently to bankrupt several leading edge US firms.[16] The most renowned case was the 2012 bankruptcy of the Massachusetts firm A123 battery, which had received millions of dollars of US government R&D support, to develop innovative batteries that came on the

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[14] See KPMG Innovated in China: New frontier for global R&D China 360 - Issue 11, 31 August 2013

[15] http://www.research.ibm.com/labs/

[16] For the progress of China's firms see Wang, Ucilia, Chinese Manufacturers Cement Their Hold On Global Solar Market Forbes /27/2012 and "180 Solar Panel Makers Will Disappear by 2015 Forbes http://www.forbes.com/sites/uciliawang/2012/10/16/report-180-solar-panel-makers-willdisappear-by-2015/

market at the wrong time. In 2013, the Chinese automaker Wanxiang bought A123, only to sell the grid scale battery part of the firm—which produces large batteries to store power from intermittent energy sources such as wind turbines—to Japan's NEC corporation the following year.[17] The more successful Massachusetts-based multinational Applied Materials built its new private solar R&D facility, which it calls “the world's largest and most advanced,” in Xian, in order “to take advantage of local research talent, manufacturing capabilities, and to be near its largest market.”[18] In a separate development, DuPont agreed to collaborate with China in materials research for Chinese companies' PV panels and systems.[19]

In sum, the US remains the leading country in S&E, but global catch-up has shrunk the US advantage greatly and is likely to continue to do so into the foreseeable future. Whether or not China surpasses the US in R&D spending in the next 10-15 years, as trend extrapolations suggest, the globalization of basic and applied science and of product development has created a new economic world, with implications for US science and technology policy that I explore in section III.

II. S&E Globalization within the US

Globalization affects science and engineering activity *within* countries as well as among countries. Within countries, globalization takes several forms: international students who study in a country other than their country of citizenship; international postdoctoral students or workers in research labs; immigrant/emigrant scientists and engineers who leave one country to work in S&E occupations in another country; and collaborations between domestic researchers across country lines. Each of these forms of globalization has affected science and engineering in the US in major ways.

International students

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[17] http://www.bostonglobe.com/business/2014/03/24/nec-buy-unit-waltham-battery-maker/H3hobthqsnyTR5DGVGER3N/story.html

[18] Quan Barry, Oct 26, 2009 http://blog.appliedmaterials.com/worlds-most-advanced-solar-rd-center
Bradisher, K “China Drawing High-Tech Research from US” NY Times, March 17, 2010
http://www.nytimes.com/2010/03/18/business/global/18research.html?_r=0

[19] http://www.renewable-energy-technology.net/solar-energy-news/us-materials-producer-agrees-rd-deal-china-solar-firm

International students are the fastest growing part of the global higher educational system. Between 1975 and 2010, the number of international students increased nearly seven-fold, producing a growth rate about three times as large as that for tertiary education students worldwide. As the lead scientific country and as a highly desirable location for educated workers in all fields, the US is a major attractor of international students in science and engineering. In 2011, 21% of S&E students enrolled outside their country of origin were enrolled in US institutions of higher education[20]. The top supplying countries for international students were China and India, with Chinese students more concentrated in the sciences and Indian students more concentrated in engineering. Many international students obtain work visas to remain in the US for the early years of their scientific careers while some become permanent immigrants.

Exhibit 2 shows the foreign-born proportions of undergraduate and graduate US enrollments; of bachelor's, master's, and PhD S&E degrees; and of post-doctoral students/workers. Although 33.2% of foreign-born undergraduates were enrolled in S&E in 2012, they make up just 4.4% of bachelor's degrees in science and engineering.[21] The percent in engineering exceeds that in the natural or social sciences but is still in single digits (6.3%). International students are relatively more important in graduate science and engineering, where they make up around one-third of graduate enrollments, one quarter of S&E master's degrees, about one-third of S&E PhDs, and over half of post-docs. There are field differences in the foreign-born share of degrees and post-doctorate workers. The foreign-born share of PhDs is lower in the biological sciences (27.4%) than in physics (45.4%) or engineering (56.2%). The foreign-born share is lower in the social/behavioral sciences (19.7%) than in the natural sciences (31.4%), but 60.4% of doctorates in economics went to foreign-born persons.[22] Among post-

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[20] Ruiz, 2013

[21] Science and Engineering Indicators 2014, table 2-19, p 65

[22] Science and Engineering Indicators, 2014, Appendix table 2-31

doctoral students the foreign-born proportion is 60% in engineering compared to 30.3% in psychology[23]. Without the foreign-born, many US labs would close or shrink massively, at least in the short run.

The US treats all applicants for student visas (and other non-immigrant visas) as potential immigrants who must convince the consular officer that they do not intend to immigrate and that they have stronger reasons to return home than to seek to move to the US.[24] But this is a pro forma declaration, as many international students stay in the US and work for years. Exhibit 3 gives two measures of the tendency for foreign-born PhDs to work in the US after graduation: intention to work in the US upon graduation, from the Survey of Doctorate Records, where about three-fourths of graduates report that they intend to work in the US as post-docs or at other jobs; and five-year "stay rates" -- the proportion of doctorates with temporary visas that social security records show actually worked in the US five years after they obtained their doctorate degree. These data show that two-thirds of PhDs in a given years' graduating cohort work in the US over the next five years. The rates are highest, though declining, for China and India, and lower, but rising, in South Korea, Mexico, and Brazil. The broad consistency between the intentions of foreign-born doctorates to work in the US and ensuing actual work behavior implies that responses to the question on intentions, which the Survey of Doctorates asks each year, is a good leading indicator of future behavior.

The attractiveness of the US to foreign students and the tendency of many of those students to work in the US thereafter enlarges the S&E labor supply. To the extent that foreign-born graduates choose their country of work by comparing careers in their home country or other non-US locations to possible careers in the US while US graduates focus primarily on US opportunities, the greater the

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[23] NSF Graduate Students and Postdoctorates in Science and Engineering: Fall 2011 Detailed Statistical Tables | NSF 13-331 | September 2013 http://www.nsf.gov/statistics/nsf13331/pdf/nsf13331.pdf table 34

[24] See NAFSA, the association of International Educators, advice to persons seeking student visas. http://www.nafsa.org/Find_Resources/Supporting_International_Students_And_Scholars/Network_Resources/International_Student_and_Scholar_Services/10_Points_to_Remember_When_Applying_for_a_Nonimmigrant_Visa/

foreign-born share of doctorate S&E programs, the more sensitive is the supply to changes in market conditions.

Immigrant scientists and engineers

Exhibit 4 moves from enrollments and degrees to persons working in S&E occupations. It gives figures for all college graduates and for persons differentiated by level of degree. Foreign-born persons make up a substantial and increasing share of working scientists and engineers, with smaller shares for persons at the bachelor's level than for master's and doctorate graduates. In 2011, 19% of bachelor's scientists and engineers were foreign-born. While this is less than half the foreign-born proportion of master's and PhD graduates, it far exceeds the foreign-born proportion of US S&E bachelor's graduates. Since the number of foreign-born workers in S&E occupations is the sum of the number of non-US trained immigrant scientists and engineers in the US and the number of US-trained foreign-born S&E immigrants, the bachelor's proportion primarily reflects immigration of foreign-trained bachelor's degree scientists and engineers to the US.[25] In addition, while the foreign-born shares of master's and PhD S&E workers are close to the foreign-born shares of graduates with those degrees, substantial numbers of US-educated persons at those degree levels return to their home country or other overseas destinations, so that the final number of foreign-born scientists and engineers with PhDs and master's degrees also depends substantively on immigration of persons trained overseas. The single most important factor that foreign-trained immigrants say brought them to the US is job/economic opportunities (29%). The second most important factor relates to family situations (23%), followed by scientific or professional infrastructure (11%) and educational opportunities (10%) [26]

Given that most foreign-born university graduates obtain their highest degrees outside the US, it would be reasonable to expect that the number of foreign-trained foreign-born scientists and engineers

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[25] To a lesser extent this also reflects the greater likelihood that foreign-born persons with US S&E bachelor's degrees work in S&E occupations than do their native-born peers.

[26] Science and Engineering Indicators 2014, p 2-54 for persons who received both degrees abroad

working in the US would far exceed the number of US-trained foreign-born scientists and engineers. The opposite is true. Exhibit 5 shows that in 2005, the majority of foreign-born scientists and engineers in the country were US-trained. Science and Engineering Indicators 2014 shows a similar pattern for 2011, with two-thirds of the foreign-born scientists and engineers working in the United States having obtained their highest degree in the United States, with nearly half having also received their first bachelor's degree in the US. Among foreign-born PhD scientists and engineers in the United States, 58% got their PhD in the US, though most of these obtained their bachelor's outside the country. Only one-quarter of foreign-born scientists and engineers with an advanced degree received both their first and highest degree abroad and thus first came to the US on immigrant visas rather than student visas.

Why are international students such a large source of immigrant scientists and engineers?

One reason is that students who come to the US self-select from persons who are especially attracted to the US and presumably have a high penchant to immigrate if the opportunity arises. What do these self-selected students find especially attractive about the US? The single most popular reason that foreign-born persons who obtained an initial degree abroad but who gained a highest degree from a US university give as the reason for coming to the country is educational opportunity (27%).[27] For the present and foreseeable future, the US has a comparative advantage in higher education that attracts many students from around the world.

Initial preferences toward living in the US aside, another factor likely to induce international students to immigrate to the US is their accrual of US-specific knowledge, including business and social connections (from friends to marriage partners). Absent direct evidence on the causal impact of studying in the US on future location of work, I use analyses of the European Union's Erasmus Program – a scholarship program that funds short study periods for EU students to study in other EU

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[27] Science and Engineering Indicators 2014, p 3-54

countries – to assay the effect of overseas educational experience on working abroad. Parey and Waldinger (2008) estimate that being in the Erasmus program increases the likelihood of working overseas by 20 percentage points.[28] Since Erasmus funds short periods of study, its estimated impact is likely to be a lower bound on the effect of international study in the US on migration decisions of international students.

In sum, immigrant scientists and engineers to the US come largely from international students, which makes the attractiveness of US higher education and policies toward student visas an intrinsic part of policies toward the immigration of scientists and engineers.

International collaborations in research papers

Scientific research has moved from lone investigators to collaborative research, producing an upward trend in authors per paper (Jones, Wuchty and Uzzi, 2008; Wuchty, Jones and Uzzi, 2007; Adams, Black, Clemmons, and Stephan, 2005). Papers with larger numbers of authors garner more citations and are more likely to be published in journals with high impact factors than papers with fewer authors (Lawani, 1986, Katz and Hicks, 1997; deB. Beaver, 2004, Wuchty et al., 2007; Freeman and Huang, 2014a), which offers a potential productivity justification for increased collaborations. In the past two or so decades the trend in co-authorship has extended across country lines, with a larger proportion of papers coauthored by scientists from different countries (Indicators, 2014; Adams, 2013).

Exhibit 6 examines the pattern and change in internationally co-authored papers and the position of the US and its main collaborating partners in these collaborations in 1997 and 2012. The columns "share of S&E articles internationally co-authored" records the ratio of articles with two or more international addresses relative to all articles for the specified group. The shares increase for the world, the US and other countries, though only modestly for China and South Korea, whose numbers

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[28] Oosterbeek and Webbink, 2009; Grip, Fouarge and Sauermann, 2008; Dreher and Poutvaara, 2008 find similar magnitudes for being an international student on working in a foreign country for EU students.

of articles increased largely through within-country collaborations. Internationally co-authored articles are a larger share of articles for European countries and for Canada and Australia than for the US and Japan, presumably because the US and Japan have much larger researcher populations, which creates a larger pool for intra-country collaborations. In both years the share of internationally co-authored papers for all the countries exceeds the internationally co-authored share for the world, in most cases by large amounts. How can this be? The reason is that 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 a count of one for each country.

The columns "US share of international collaborations" record the ratio of papers in which one or more authors has a US affiliation and one or more has an affiliation to another country, divided by the total number of international collaborations for the relevant entity. The US is a huge contributor to international collaborations worldwide, with 43.8% of world collaborations in 1997 and 43% of world collaborations in 2012. That the US maintained its share of world collaborations in a period when the US share of papers fell markedly is indicative of the US position as a hub of world science. In 2012, the countries with particularly large US shares of international collaborations were South Korea, Canada and China. The surprise relative to 1997 and earlier years is China, whose collaborative research with the US increased greatly in the 2000s. The fact that the 47.5% US share of Chinese collaborations in 2012 exceeds the 43% US share of all international collaborations shows that the US-China link exceeds the US average collaborative link.

The columns "Country shares of US international collaborations" give the ratio of the number of papers in which the given country's affiliation appears along with a US address, divided by all US international collaborations. The country shares are lower than the "US shares" because the number of papers by US-based scientists far exceeds the number of papers in the other countries. The most striking change in these columns is for China, which increased its share of US international collaborations fivefold to become the leading collaborator for US scientific papers.

The huge increase in China-and-US collaborations suggests that the two countries are developing a “special relationship” in science and engineering. Because many international students and post-doctoral students in the US are Chinese, the tie between US and Chinese researchers extends to collaborations within the US. Freeman and Huang (2014a) find that 14% of the names on research papers with only US addresses in the late 2000s were Chinese names, the vast majority of whose names and initial indicate that they were born outside the US (Xu Wang rather than Andrew Wang). Moreover, while papers with only Chinese addresses have few US names, some highly productive researchers in China have US-research experience, having studied or worked in the US and written papers with US-addresses. The decision of the Chinese government to fund Chinese students and faculty to spend up to one year studying and working in the US and other advanced countries has fueled the growing link between the US and China.

What is the impact of international collaborations on the quality of scientific papers and US science in particular?

It is well-established that papers with international collaborators are published in higher impact journals and obtain more citations than papers with solely domestic collaborators (Katz and Hicks (1997), Rigby (2009), Adams (2013). This pattern suggests that international collaborations add a special synergy to research, but two differences between the international and domestic collaborations invalidate this interpretation of the evidence. The first difference between international and domestic collaborations is in the number of co-authors. International collaborations average more authors than single country collaborations. Given that numbers of authors is associated with greater impact factors and citations, the international collaboration edge could simply reflect numbers of authors on those collaborations. Regressions of impact factors and citations on whether papers in Nanoscience and Nanotechnology, Biotechnology and Applied Microbiology, and Particle and Field Physics have international addresses or not show that introduction of numbers of authors changes the sign on the variable for international collaborations from positive to negative (Freeman, Ganguli, and Muricano-Goroff, 2014). At least in these fields international collaborations look better because they are bigger than domestic collaborations.

The second difference relates to the attributes of persons and countries in any collaboration. International collaborations between researchers from the US, a top country in impact factors and citations, and researchers from countries lower in those outcomes, are by the arithmetic of averages likely to produce lower impact factors and citations for international collaboration than for domestic collaborations for the US, and conversely for the country with lower average outcomes. Who collaborates with whom in international collaborations should matter in the impact factors and citations associated with international collaborations.

Examining impact factors and citations for collaborations between the US and China, Freeman and Huang (2014b) find such patterns with some twists that illuminate the incipient special research relationship between the two countries. On average, US-China collaborations have impact factors and citations that lie between the high impact and citation numbers for the US (including collaborations with other countries) and the relatively low – but increasing – impact factors and citations for China. The twists are that researchers in China with US research experience (defined as having an earlier paper solely with a US address) have higher impact factors and citations on their China-addressed papers, which suggests that the Chinese researchers increase their research skills working in the US; US-addressed papers with a Chinese first author gain higher impact factors and citations than other US addressed papers, suggesting that US research gains from attracting some of China's best and brightest young post-docs and graduate students; and Chinese researchers with US experience have higher impact factors and citations when they work in the US than when they work in China. A natural interpretation of these patterns, consistent with Khan and McGarvie (2012)'s finding that the Foreign

Fulbright Program requirement that students funded by the program return to their home countries before applying for a work visa in the United States reduced their scientific productivity, is that the US has an exceptional research climate for scientific work.

III. Conclusion: "A policy, a policy – My kingdom for a policy"

Today's world of global science and engineering diverges greatly from the World War II/Cold War period when the US started to take science and technology policy seriously.[29] The spread of knowledge discovery and knowledge throughout the world has changed the nature of the global economy and comparative advantages in high tech and knowledge intensive activities. Developing countries have the human resources to produce scientific and technical breakthroughs and ability to produce innovative goods and services that economists once viewed as the province of advanced countries. In the US, the S&E workforce increasingly consists of immigrant scientists and engineers, many of whom come to the country as international students. Chinese students and researchers and scientific collaborations with China have become critical in US scientific activity.

The US has considerable assets in the global knowledge economy: the world's preeminent higher education system,[30] which draws the best and brightest students from around the world; a research enterprise with sufficient quality and quantity to be the hub of global research and international collaborations; a successful innovation system protected by intellectual property rights and a business culture that encourages start-ups to translate research findings into goods and service. The danger to the US from the global expansion of knowledge and scientific and engineering expertise,

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[29] Roosevelt appointed Vannevar Bush the first science adviser to the President in 1939. The US established the Office of Science and Technology policy in the White House in 1976. Congress established the Office of Technology Assessment (OTA) from 1972 to 1995
http://en.wikipedia.org/wiki/Office_of_Science_and_Technology_Policy.
http://en.wikipedia.org/wiki/Office_of_Technology_Assessment

[30] The US has a disproportionate share of top universities in every global ranking. See, for example, the ratings by world universities by Center for World-Class Universities at Shanghai Jiao Tong University, which place 8 of top 10 in US http://www.shanghairanking.com/ARWU2013.html. The Times rankings have 7 of top 10 in US http://www.timeshighereducation.co.uk/world-university-rankings/2013-14/world-ranking, but its reputation rankings have 8 of 10 top in US. http://www.timeshighereducation.co.uk/world-university-rankings/2014/reputation-ranking

is that other countries, particularly those with lower wages and labor costs, will produce an increasing proportion of the science and engineering-based innovations and reduce the US's comparative advantage in science-based discovery and its application to the economy, adding a trade x technology twist to the economic problems facing many US workers.

This section offers some ideas on possible directions for US S&T policy in this new world. It suggests ways in which the country could enhance the movement of scientific and technological innovations into production in the US and ways in which the country could align immigration policies with policies toward international students to maintain the US position as a major creator of scientific and technical knowledge.

The starting point for assessing the economics of S&T policy is recognition that in a world where economic growth and comparative advantage depend critically on science and technology, S&T policy should focus more on the potential economic impacts of science and engineering than it did in earlier times, when its main purpose was to give expert input to decision-makers on complex scientific and technical issues. In a global knowledge-based economy where trade treaties restrict measures to protect industries, policies toward R&D are one tool for societies to try to shape the future state of the economy – a new *industrial policy,* as it were. If the government puts more money into the basic research that underpins industry A, which induces it to do more R&D and receive greater R&D tax credits, or if the government favors advanced products from industry A in its procurement policies or regulations, industry A will prosper. By contrast, an industry competing with A would suffer. From this perspective, the country's research portfolio and accompanying S&T policies will influence the future composition of output and employment.

Since the 1990s, if not earlier, the US research portfolio has been more heavily invested in biological and medical sciences than any other major R&D spending region or country. In 2011, the US spent 51.6% of its research moneys on the biomedical fields, compared to the EU spending 43.3%, Japan spending 42% and China spending just 26% of its research moneys in that area.[31] In large part, the exceptionally high spending on biomedical sciences reflects the Clinton Administration's late 1990s policy of doubling the NIH budget and Senator Arlen Specter's support of the doubling in budget deliberations. In the late 2000s the concentration of ARRA money on NIH was due in large part to the continuing desire of Senator Specter to enhance the biomedical sciences. These expenditures affected the educational and career decisions of science students, the direction of scientific research, and the types of immigrant scientists and post-doctoral students that have come to the country. Whether we judge the resulting portfolio of R&D moneys as ideal or not, there should be better ways to determine R&D budgets that can influence the future direction of the economy. Political factors invariably affect the allocation of funds, but science and technology policy should bring more economics to bear in assessing that research portfolio and helping guide decisions.

The biggest danger to the US from the globalization of knowledge and knowledge-creation is that production of innovative goods and services developed by US research expenditures will keep moving from the US to lower wage countries, adversely affecting many US workers. What policies might enhance the ability of the US to hold its own in this terrain?

On the supply side, the response of students to fellowship policies offers a possible way to affect their educational and career decisions in ways that would strengthen the link from innovation to production. When the NSF nearly doubled the value of Graduate Student Fellowships in the late 1990s and early 2000s, the number and quality of applicants rose sharply, which seemed to raise graduate students enrollment, broadly (Freeman, Chang, and Chiang, 2009). The Obama Administration's increase in the number of NSF rewards in the late 2000s has been associated with an increase in graduate enrollments and PhDs by the US-born and permanent residents eligible for those awards that

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[31] Science and Engineering Indicators, 2014, table 5-21

are roughly consistent with the predictions in the policy paper that underpinned that decision (Freeman, 2006). Given this evidence, and the potential benefit from increased efforts to translate scientific findings into production in the US, I propose that the country consider a new set of fellowships for master's or doctorate graduates specializing in the transformation of knowledge into US production. Such a program would produce scientists and engineering specialists in what the NIH calls “translational sciences.”[32]

On the firm side, many national and state regulations require firms to make environmental impact statements if their actions are likely to significantly affect the quality of the human environment.[33] In a different arena of public concern the government requires government contractors and subcontractors to take affirmative action to prevent discrimination against employees or applicants for employment on the basis of "color, religion, sex, or national origin,” where affirmative action may include outreach campaigns, targeted recruitment, and employee support programs. These programs have affected the way business thinks about its activities in both areas.

To focus business thinking on increased production of R&D based goods and services in the US, the government could consider requiring federal contractors or firms that benefit from R&D tax credits or receive direct government support for R&D to develop impact statements about the likely effects of technological advances and innovations and to make affirmative action plans for ways to produce those products in the US rather than overseas. If such impact statements had the same effect on corporate thinking as environmental impact statements and affirmative action statements, they could potentially influence the location of production of innovative products and processes.

The combination of fellowships to develop science and engineering expertise in translation of

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[32] The sluggish translation of biomedical science findings into drug development or other medical practices sufficiently upset NIH that in 2011 the agency established the National Center for Advancing Translational Sciences to transform the translational science process so that new treatments and cures for disease can be delivered to patients faster.

[33] http://en.wikipedia.org/wiki/Environmental_impact_statement

research findings into product development and of corporate impact statements with consideration of US-production would gave these initiatives better chance for success than if they were introduced by themselves.

International students and immigration

In a world where knowledge creation and the application of science- and engineering-based knowledge is a comparative advantage of the US, it makes little economic sense to place hurdles in the way of international students' becoming permanent citizens or residents and working in the US. Such hurdles lower the attractiveness of the US as a destination for international students relative to countries such as Australia and Canada and others whose policies seek to attract such students by offering them a leg up in immigration. It loses the spillover payoffs of US education and research experience from international students working in the US for extended periods of time, if not permanently.

Given general agreement in the Congress and elsewhere that modernizing immigration policy to ease the path of international students to work in the US is in the country's interest, I will limit my comments to the nature of the debate. Policy discourse in this area often presents the situation as a win-win. This exaggerates the benefits of admitting more STEM or other highly-educated immigrants to the US and downplays the costs. The basic economics of immigration indicates that much of the benefits accrue to the immigrant (which is why they want to come) and that greater supply of competitors adversely affects US workers in the same field as the immigrants (Borjas, 2006). There is no need for exaggeration, however, to make the case that in a world in which science and technology are critical in economic growth and comparative advantage, that the US would gain in those activities by allowing as many of the best and brightest from overseas who come to the country for education to continue their work in the US if they so desire. As long as the US maintains world leadership in university education and research, with researchers doing better work in the US and US-educated researchers doing better work elsewhere in the world, it is likely that aligning US immigration policies with its international policies is in the world's interest as well.

Science and technology policy can make the US and world better today in ways that it never could have done before.

Exhibit 1: US Percentage of World Research and Scientific Activity, 1970-2011 and Change in Share Compared to Change in Share of China, 2000s-2011

	US level/World level in Percentage Units 1970-2011					Change in % 2000 to 2011	
	1970	1980	1990	2000	2011	US	China
1. R&D spending							
a) All countries, Indicators					32		
b) Major R&D countries*		45	43	45	38	-7	+13
c) All countries, OECD		44	36	40	33	-7	+14
2. Researchers				22	20	-2	5
3. S&E papers	38	37	37	31	26	-5	+8
4. S&E citations	50	53	50	43			
articles in upper 1% citation				57	46	-11	+6
5. S&E bachelor's							
a) Relative to select countries	25	23					
b) Relative to world				14	10	-4	+14
6. S&E PhDs							
a) Relative to select countries	56	52	41	34			
b) Relative to world				22	16	-6	+5

Source: National Science Board, Science and Engineering Indicators, 1982, 1987, 2002, 2014

*"World" limited to EU, US, Japan, South Korea, and China

1 – a for all countries, Science and Engineering Indicators, 2014, table 4-4;

b for major RD countries, Appendix table 4-13, with 1981 for 1980, EU estimated on basis of France, Germany and UK relative to total EU for 1995;

c Downloaded from http://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB, with 1981 for 1980 and missing years for a few countries extrapolated/interpolated from data for nearest years

2 Total researchers, FTE Downloaded from http://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB, Data for earlier years too spotty, with no figures for Russian Federation and other major non-OECD countries

3 Science and Engineering Indicators, 2014, appendix table 5-26. Earlier years from Science and Engineering Indicators, 1982, 1987, 2002

4 Science and Engineering Indicators, 2014, appendix table 5-57, Earlier years from Science and Engineering Indicators, 1982, 1987, 2002

5 Science and Engineering Indicators, 2014. Earlier years from Science and Engineering Indicators, 1982, 1987, 2002

6 Science and Engineering Indicators, 2014. Earlier years from Science and Engineering Indicators, 1982, 1987, 2002

Exhibit 2: Percentage Foreign-Born or with Temporary Visa of US S&E Graduate Enrollments and Degrees, 1970-2011/12

	1970	1980	1990	2000	2011/12
1. Graduate students, full-time, in science and engineering*		22.5%	33.9%	36.3%	36.3%
2. Bachelor's Degrees, Engineering		3.8%	3.6%	3.8	4.4
3. Master's Degrees		16.4	22.6	25.8	26.0
4. Doctorate Degrees,	18.4	26.4	31.8	30.4	34.2
5. All Post-doctoral Workers		38.6	51.1	58.2	62.9
6. Post-doctoral in university jobs for US doctorates only	17.5	18.3	39.1	43.0	49.0

* This excludes medical students

Source:

1. NSF Graduate Students and Postdoctorates in Science and Engineering: Fall 2011 Detailed Statistical Tables | NSF 13-331 | September 2013 http://www.nsf.gov/statistics/nsf13331/pdf/nsf13331.pdf tables 5 and 8

2.Science and Engineering Indicators 2014, table 2-23; Science and Engineering Indicators 2002, appendix table 2-17, with 1981 for 1980 and 1991 for 1990

3.Science and Engineering Indicators 2014, table 2-30; Science and Engineering Indicators 2002, appendix table 2-23, with 1981 for 1980

4.Science and Engineering Indicators 2014, table 2-31;

5 Graduate Students and Postdoctorates in Science and Engineering: Fall 2011 Detailed Statistical Tables | NSF 13-331 | September 2013 table 27 and 3.

6 Science and Engineering Indicators 2014, table 5-17

Exhibit 3: Five Year Stay Rates and Plans to Stay in US, by Graduating Class

	1996-1998	2000-2002	2004-2006	2008-2011
Stay Rates	61	65	64	--
Plans to Stay	68	73	76	75
Stay rates by country				
China	96	95	87	--
India	90	86	81	
Europe	58	67	61	
South Korea	29	43	42	
Japan	32	37	39	
Mexico	31	33	37	
Brazil	26	32	35	

Source: Stay rates, Finn 2012, averaged for consistency with plans-to-stay data in Indicators, 2014, table 5-32. Indicators, 2002 figure 2-21.

Exhibit 4: Percent Foreign-Born in S&E Occupations, by Education Level, 1990-2011

Foreign-Born	1990	2000	2011
All College Graduates in S&E		22.4	26.2
Bachelor's	11.00%	16.5	19.0
Master's	19.00%	29.0	34.3
PhDs	24.00%	37.6	43.2

Source: Science and Engineering Indicators 2014, table 3-27.

Exhibit 5: Proportions of US Science and Engineering Workers that are Foreign-Born and the Proportion of the Foreign-Born that Have Highest Degree in the United States, 2005

	Foreign-Born Share of Workers	Share of Foreign-Born with Highest Degree in US
Bachelor's	15.2%	54.3%
Master’s	27.2%	68.5%
Doctorates	34.6%	64.00%

Source: NSB, 2008. Table 3-8.

Exhibit 6: Shares of International Co-authorship US and Major Collaborators with US

	Share of S&E articles internationally co-authored		US share of Country's Intl Collaborations		Country's Share of US Int'l Collaborations	
	1997	2012	1997	2012	1997	2012
World	15.7%	24.9%	43.8	43	---	--
US	19.3	34.7	--	--	---	--
China	25.7	26.7	35.1	47.5	3.2	16.2
UK	31.0	55.1	30.0	35.2	12.4	14.3
Germany	35.5	55.5	29.9	31.0	13.3	13.3
Canada	33.5	50.2	53.0	48.9	12.1	11.4
France	37.3	58.2	28.4	28.5	8.9	8.8
Italy	36.1	51.1	32.2	34.0	6.8	7.4
Japan	16.4	30.0	44.4	37.1	9.9	6.8
Australia	29.4	52.4	36.1	32.9	4.3	6.0
South Korea	27.6	30.8	51.5	53.9	2.8	6.0

Source: Tabulated from Indicators 2014, Appendix table 5-41 and 5-56

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