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Flows and Networks in Global Innovation Systems Among Top R&D Nations

Global Innovation and National Interests Project
Working Paper 7
Draft for Comment

Caroline Wagner, Ph.D.; Kenneth B. Poland, MPA; Xiaoran Yan, Ph.D.
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Executive Summary

Flows of people and information-- networks of interconnected innovators--reveal dynamics about the global information system. Research and development (R&D) capacity, measured by spending, articles, patents, and high-tech trade, has expanded impressively among 25 leading nations examined in this report. Where once the USA held a global leadership position, now, a cluster of nations lead in different features of the innovation system. These leading nations are interconnected in many ways.

Flows of people provide fresh ideas and talent. Prior to the pandemic, North America and the European Union (EU) attracted the largest numbers of visiting scholars. R&D per capita spending is strongly correlated to a nation's attractiveness to visiting scholars. North America and the EU also attracted large numbers of students to study in elite universities, which served as highly attractive assets – although student flows are not tied to, nor do they contribute significantly to R&D. Moreover, educated migrants are attracted to wealthier countries for work, but these movements are not correlated to R&D spending or output.

Trade flows indicate national economic strength and, here, the big change is seen in the growth of China as the largest high-tech exporter. Countries with intensive R&D per capita spending participate in high-technology trade. R&D spending is correlated to high technology trade, although not to capital goods trade. Trade in semiconductors and aerospace products are strongly correlated with R&D/GDP spending. R&D spending correlates to strength in pharmaceuticals for the USA and Asia, but not for the EU.

Patenting is strongly correlated with domestic R&D spending. R&D-intensive nations patent at higher rates than those nations which conduct less R&D. R&D per capita is also correlated to larger numbers of registration of non-resident patents. China reported the largest number of patents filed in 2020--the majority of these were from residents. The USA is the only nation where non-residents file more patent applications than do residents. Japanese nationals filed the largest number of foreign patents in the USA. North America and Europe are highly connected through cross patenting registrations.

Collaboration in R&D is highly active across nations and across the academic and industrial sectors. Small, scientifically advanced nations are the most internationally collaborative as a percentage of their scholarly output. R&D spending is weakly correlated with international collaboration; larger nations are less likely to collaborate internationally as a percentage of all collaborations. Scientific strength is also correlated to cross-sectoral links between academic and industrial sectors. Collaborative research has become the most common form of knowledge discovery, with teams actively linking across borders; cross-border teaming is not limited to the scientifically advanced nations, but involves nearly all nations of the world.

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Table 1 List of Abbreviations

Abbreviation	Full text
GDP	Gross domestic product
GERD	Gross expenditures on research and development
EU	European Union
EU28	European Union of all 28 nations (including UK)
NA	North America
OECD	Organization for Economic Cooperation and Development
R&D	Research and Development
S&T	Science and Technology
STI	Science, Technology and Innovation
UK	United Kingdom
USA	United States of America
WIPO	World Intellectual Property Organization

Shifting Patterns of Innovation & Capacity

Innovation is the engine of economic growth, fueled by flows of people, products, information, and ideas. The innovation system has a regional, national and a global component. Actors and institutions contribute to innovation through research and learning; oftentimes, research and learning occur in specific research settings such as universities or private or government laboratories. Knowledge and innovation diffuse throughout the system in the heads of people as well as through publications, patents, and embedded in equipment. The United States of America (USA) has been the world leader in innovation, however, recently, the position of the United States has seen a relative and an absolute decline compared to other innovative nations. Challenges to US leadership can be seen in science, technology, patenting, high-technology market share, and a number of measures of wellbeing.

The complexity of the innovation system, with many interacting parts and multiple levels, tests any efforts to model or even capture revelatory snapshots of it. Even as we take note of 'globalization,' specific regions of the world such as Silicon Valley, Zurich, Helsinki and Hovestaden, Shanghai, Hong Kong, Singapore, Seoul and Osaka, are standout locations for innovation. In addition to having notable regions that excel at innovation, flows of people and ideas among these places can shed some light on the system's dynamics of knowledge flows and networks. As David Sainsbury points out: "With a narrow view of national competitive advantage involving only input costs and economies of scale, it is easy for policy debates to degenerate into an "us versus them" conflict…..[however] a broader set of forces are at work…"[1] that defy easy characterizations of national capacity.

This paper investigates broader forces within the international innovation system with the assumption that measures of flow and networked communications provide insights into the interdependence as well as the attractiveness of national actors and innovative dynamics. The paper presents indicators of innovation capacity, connection, and flow at the international level for top R&D performing nations (see Box 1). As a rule, greater capacity and flow among and between institutions and nations are strongly correlated to innovative strength—part of the magic is in the location, and part is in the flow. The measures presented here provide insights that can aid in understanding innovation and its many components as inputs to policymaking. This report examines four specific flows and

Box 1
List of Nations and Regions in this Report

Nation	Region
Australia	Asia
Austria	EU
Belgium	EU
Canada	NA
China	China
Czech Rep	EU
Denmark	EU
Finland	EU
France	EU
Germany	EU
Hungary	EU
Israel	EU
Italy	EU
Japan	Asia
Netherlands	EU
New Zealand	Asia
Norway	EU
Portugal	EU
Singapore	Asia
South Korea	Asia
Sweden	EU
Switzerland	EU
Taiwan	Asia
United Kingdom	EU
United States	NA

[1] Sainsbury, 2020, p. 83.

networks related to innovation: 1) mobility of people: students, scholars, and immigrants; 2) the impact of R&D intensity on trade performance in high technology goods and in capital goods flows among nations; 3) relationship between R&D intensity and patent registration at home and abroad; 4) international research collaboration and national performance. Following the broad overview, this report examines the activities and location of ICT and electronics, aerospace, and pharmaceuticals.

National STI Capacity in the Global Framework

Capacity to support and sustain a knowledge system underpins any nation's ability to conduct science, technology and produce innovation products processes and services (hereafter, STI). Growing and maintaining capacity requires monetary and human resources, universities and research infrastructure, and policy support functions. Nations invest billions of public and private dollars into R&D each year: the top seven nations spent an estimated $151 billion in 2020 (PPP constant prices)[2] The subject of this paper focuses on nations whose research and development (R&D) expenditures as a percent of GDP rise above 1.2% (listed in Box 1) as reported by the OECD. (The 25 nations are all OECD member nations except for China, which is a key partner, and Taiwan, which is not an OECD member.) These 25 nations are responsible for close to 90% of the world's R&D spending.

Figure 1 displays three measures for national STI capacity, compared across 40 nations:

1) Comparative spending on R&D as a percent of a nation's gross domestic product (GDP) (position on the x axis); compared to
2) The number of tertiary-level researchers per million population of a nation (position on the y axis);
3) Volume of R&D spending by nation normalized to the USA's total R&D spending (size of bubbles on the graph).

The growth in the global R&D system in the past three decades has been remarkable, shifting from a system dominated by a few wealthy nations to one with many participants, shown in Figure 1. In 1990, of the nations studied here, only three of them—Japan, Germany, and the USA—spent more than 2.5% of gross domestic product (GDP) on R&D. By 2018, 11 nations in Box 1 spent more than 2.5% of GDP on R&D. In 1990, US R&D spending was $232.5 billion compared to the next highest spender, Japan, at $85 billion. By 2018, China and the European Union each spent over $425 billion and to the USA's $551.5 billion. Japan ($173bn) and Germany ($129.6bn) also kept pace with US growth. Six of the nations listed in Box 1 did not report their R&D spending to OECD in 1990: Czech Republic, Hungary, Israel, Norway, Singapore, and South Korea. Now these are leading scientific nations.

In 1990, the list of nations leading in the production of scientific papers were the USA, Japan, and top European countries: China and India both produced less than 2% of world scientific papers. As the European Union grew to 27 nations, the aggregation pushed that region above

[2] OECD, MSTI, 2020. Nations: China, Germany, France, United States, Great Britain, Japan, South Korea.

the United States in total output. Top European nations became more productive over time, as well. China now produces more than 10% of world scientific papers. India has also greatly increased scientific output. Science and technology have transformed the global knowledge system into one with distributed capabilities and multiple centers of leading research. Figure 1 shows 40 nations investing in R&D.

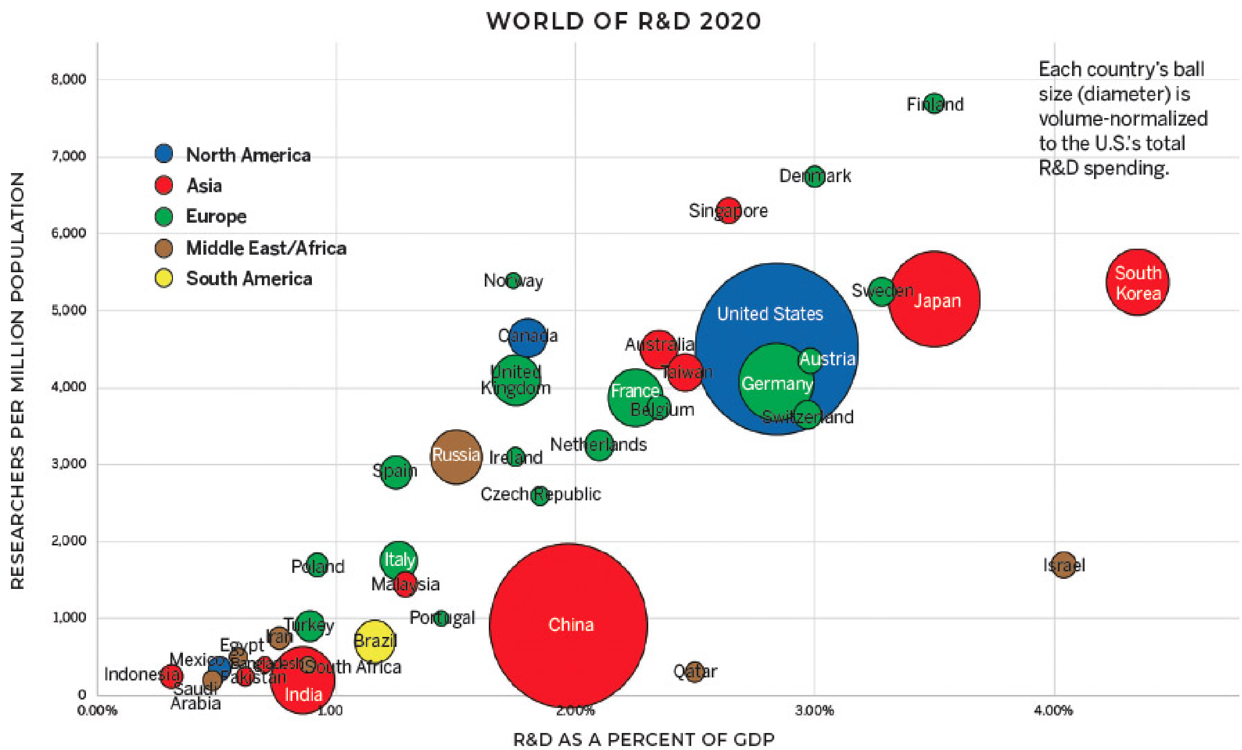

Figure 1 R&D as a Percent of GDP Compared to Researchers per Million Population, 2019, Source: rdworldonline [Note: This figure contains countries beyond those included in our analysis for the sake of comparison.]

Figure 1 reveals a correlation between R&D as a percent of GDP, and researchers per million population. Among the notable observations in this graph:

- standout performance of small, scientifically advanced nations such as South Korea and Israel where R&D represents more than 4 percent of GDP; Finland, Denmark, and Singapore with high productivity for investment and higher percent of technical workforce per million population;
- the proportionately larger contributions of financial resources of the United States and China (greatly increased spending, but with fewer trained researchers)
- the continuing strength of Japan; and
- a strong European cluster.

The OECD reports that, in 2018, the USA placed third behind South Korea and Japan in GERD intensity as a percent of GDP, followed by China and the EU28.

1. People Flows and Migration

Flows of people, ideas, and intellectual property reveal the strengths and attraction of different regions and the capacity of these regions to participate in STI activities. The international mobility of educated people transfers knowledge; attractive locations can reveal research capacity. We collected and created indictors to test the attractiveness of nations and interactions among them for three types of flows: 1) students; 2) scholars (generally visiting scholars); and 3) tertiary-educated migrants, to assess the relationship of these flows to national STI capacity.

1.a. Globally ranked university attraction not due to R&D

Globally ranked universities--such as Oxford University, Stanford University, or ETH Zurich, or Seoul National University--are highly attractive to college and graduate students. By examining the top 500 globally ranked universities (Times Higher Ed) we find that the greater the number of highly ranked universities, the greater the inflow of tertiary-level students. Research universities contribute significantly seeking to study abroad. The locations of research universities remain fixed in place of course, so students are often willing to travel to these places to study at elite institutions, to take advantage of the people, resources, and experience therein. We collected data on the location of the top 500 universities (Times Higher Ed ranking) and data about the number and movement of students from the UNESCO database reporting international flows of students for 2017-2019, prior to the pandemic. By comparing these data, we confirm a statistically significant link between the greater the number of highly ranked universities to the greater the flow of tertiary level inflow of students to that nation. However, our analysis does not show a link between the attractiveness of universities and scientific capacity. The research and development capacity is not a primary reason for students to travel abroad to study.

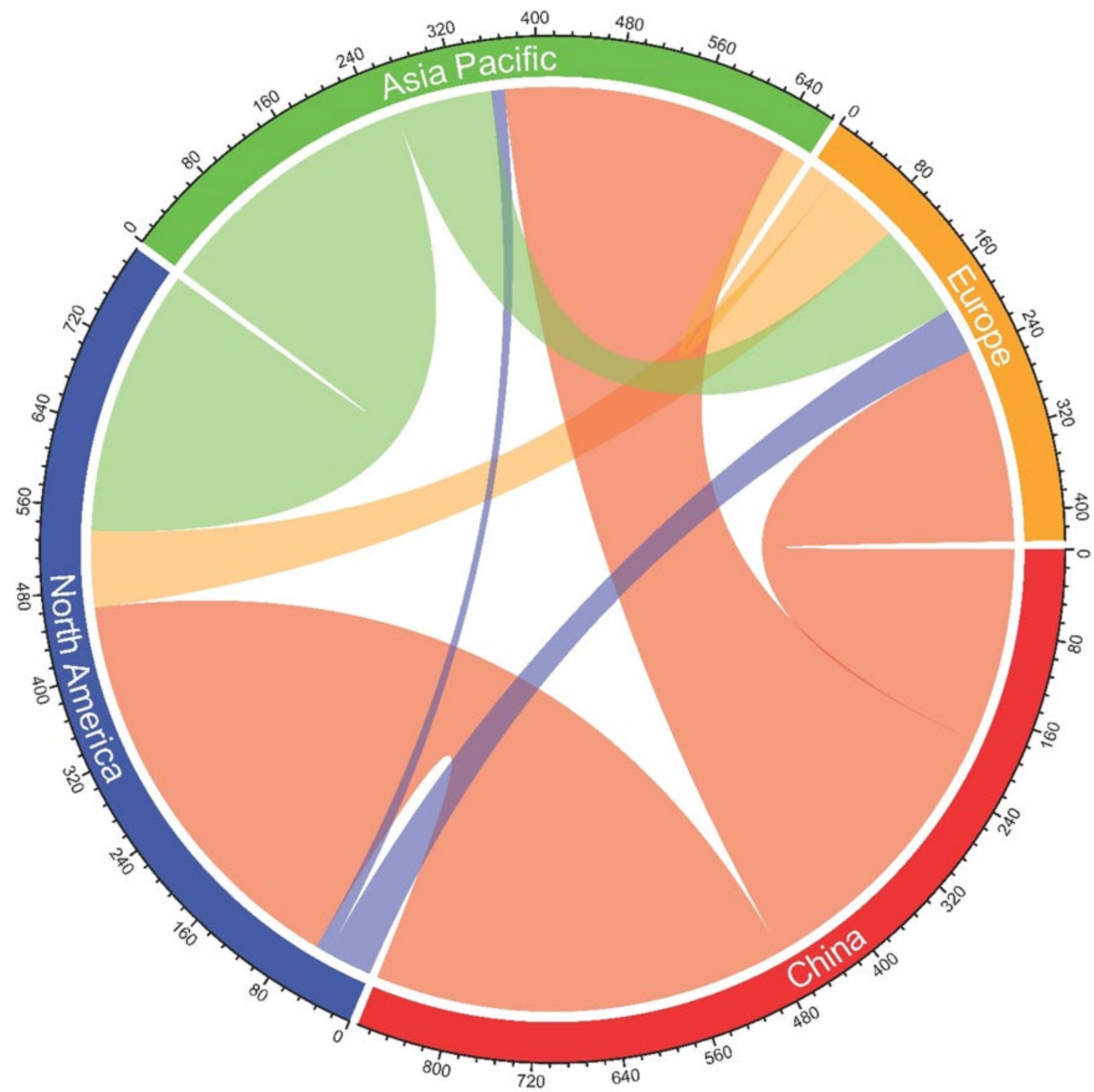

Figure 2 Student Flows in Thousands Across Regions Data: UNESCO [Note: Student inflow data for China, Russia, and Israel were unavailable and are not reflected in this figure.]

Figure 2 shows the flows of students across top countries and then grouped by region. The figure shows that dominance of the flow of students from China over the studied period 2017-2019 to North America and Europe. (We did not have numbers for students going to China.) Contributions of student flows to the United States, for example, were highest from China (300k+), India (135k+) South Korea (53k), Saudi Arabia (47K) and Canada (27k).

1.b. Scholarly flows tied to R&D Strength

National educational and research strength attracts foreign scholars. Scholars often travel to conduct extended visits (such as sabbaticals) with counterparts in foreign laboratories, to use state-of-the-art equipment, to visit field sites to advance their research. We used data on scholarly mobility from the OECD and compared mobility to the receiving nation's R&D and educational strength. We sought correlation between scholarly mobility and R&D spending/GDP spending (hereafter, R&D/GDP) to the attraction of foreign scholars. We found a positive correlation between both educational strength of a nation (measured in rankings) and R&D/GDP. R&D/GDP is a stronger indicator of attractiveness when measured for visiting scholars than for university rankings.

To illustrate scholarly flows, Figure 3 maps scholarly flow between countries from 2006 to 2016 (data from OECD). The data are based on a change in location of scholar's address from one year to the next. (e.g. if a scholar publishes a paper in the USA one year and a paper in Amsterdam the next year, this movement is counted as a scholarly migration from the USA to the Netherlands.) Width of lines reflects numbers of people moving between these nations. The largest global movements are from the UK to North America, and from China to North America, although with fairly reciprocal exchanges in both directions -- especially when compared to student flows, which are highly directional.

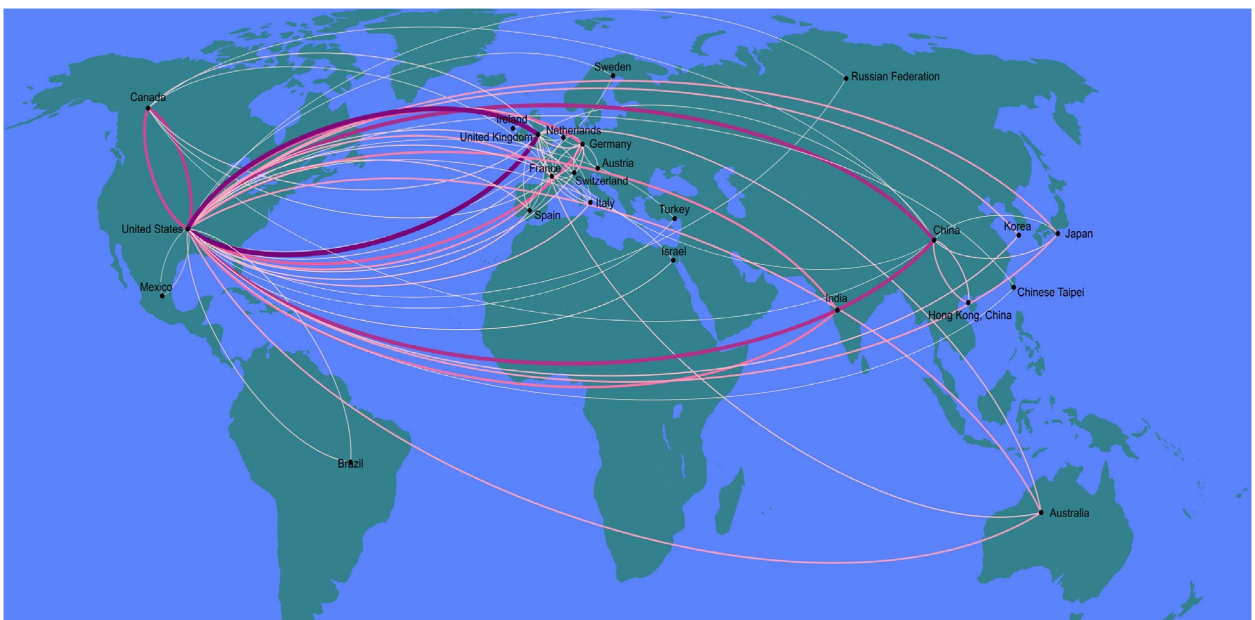

Figure 3 Scholarly Flows across Nations, 2006-2016, Data: OECD

1.c. Migration of educated people not related to R&D strength

In addition to attracting students and scholarly visitors, scientifically advanced nations attract educated migrants. Figure 4 shows flows of university-educated immigrants between 2006 and 2016 (data from OECD). These flows represent immigrants who report having a tertiary-level (university) education. (The data do not contain details as to the field of study represented among educated migrants.) Figure 4 shows the flows on the left, with largest numbers of migrants coming from Asia and Europe going to nations on the right, especially to North America, where Canada has led the United States for the past few years. A test of the relationship between migration and national scientific strength shows a positive relationship between incoming immigration and the citation strength of a nation's scientific output. In the United States, immigrants outperform natives in starting companies and in patenting inventions. No other strong association exists between inflows of educated foreign workers and other STI measures (such as percentages of excellent articles or levels of scholarly output) so counting educated migrants can only be considered a weak indicator of attraction or benefit. (If we limited the analysis to STEM graduates, we would expect to find a stronger relationship between migration and scientific output, but those data were not available.)

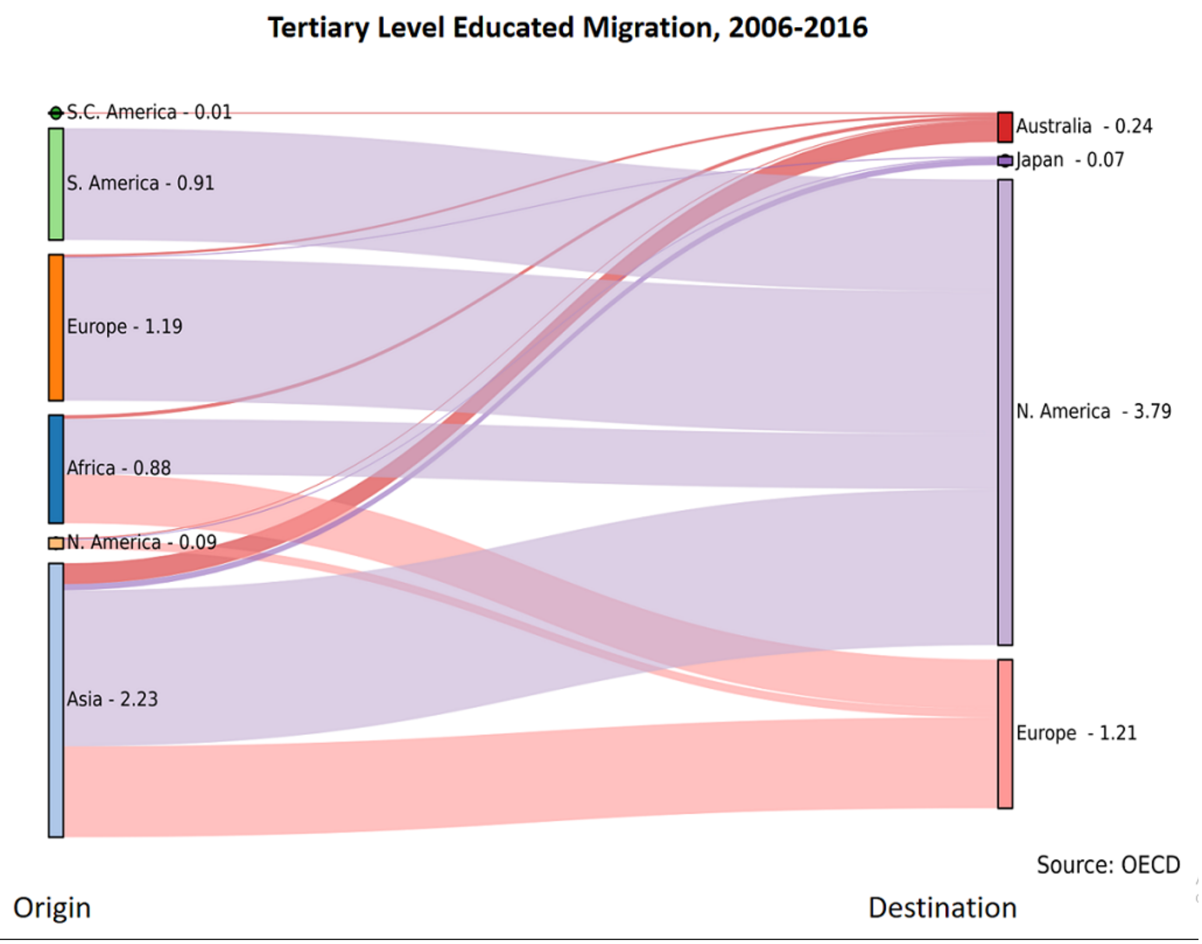

Figure 4 Migration of University-educated Migrants, 2006-2016, Data: OECD

2. Impact of R&D Intensity on Trade: The Flows of Goods Related to Innovation

Trade is highly correlated to national wealth, and high-technology trade brings significant amounts of income to scientifically advanced nations. As David Sainsbury noted, premium products and services command high prices[3]. We compared national R&D spending to the flow of high-technology goods, and capital goods generally to test for a relationship between capacity and output.

2.a. High technology goods tied to R&D investment

Comparing national R&D intensity to trade performance in 2019, we find higher R&D spending per capita associated with a higher proportion of high-technology exports, although only weakly correlated, perhaps because of the existence of global value chains. Figure 5 shows the flows of high-technology goods in 2019. This figure reveals the dominance of China in the export of high-technology goods; the majority of these high-technology exports from China ship to North America. Importantly, global value chains – where value-addition occurs in different proportions along the chain—challenge this interpretation of these measures. China exports the greatest amount of finished high-technology goods, but value is added to these goods along a multinational chain of imports and exports of primary and intermediate goods.

Analysts examine global value chains for patterns. OECD reports that foreign value-added to exports has been dropping since reaching a peak in 2012. Value chains show increasingly regional tendencies in Asia, Europe and the Americas; regional loops have increased since 2012. Smaller nations with low trade barriers--such as the Netherlands or Switzerland--are more likely to use value chains since they cannot cost-efficiently produce the full range of technical inputs or raw materials needed by industry and therefore these countries import more foreign goods from large countries. ICTs/electronics, and motor vehicles[4] are two industries with the most active global value chains.

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[3] Sainsbury, p. 83

[4] Miroudot & Nortström, 2020

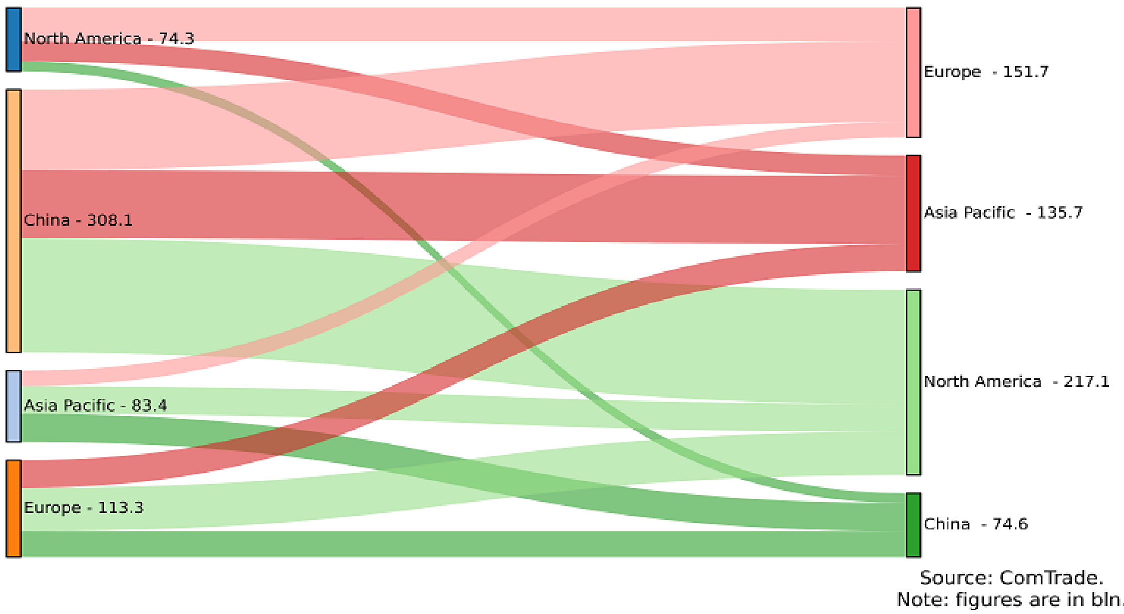

Figure 5 High-technology Trade Flows, 2017, Data: UN ComTrade Database

2.b. Capital goods flows not tied to R&D spending

We also explored the relationship of R&D spending to capital goods flows generally—total goods flows, including but not limited to high technology products. Here we found no relationship between R&D intensity and trade numbers for capital goods. Figure 6 shows the flow of capital goods from regions of the world, visualizing the dominance of Asia over Europe and North America. The development of and trading position for these traded items are not dependent upon a strong R&D base.

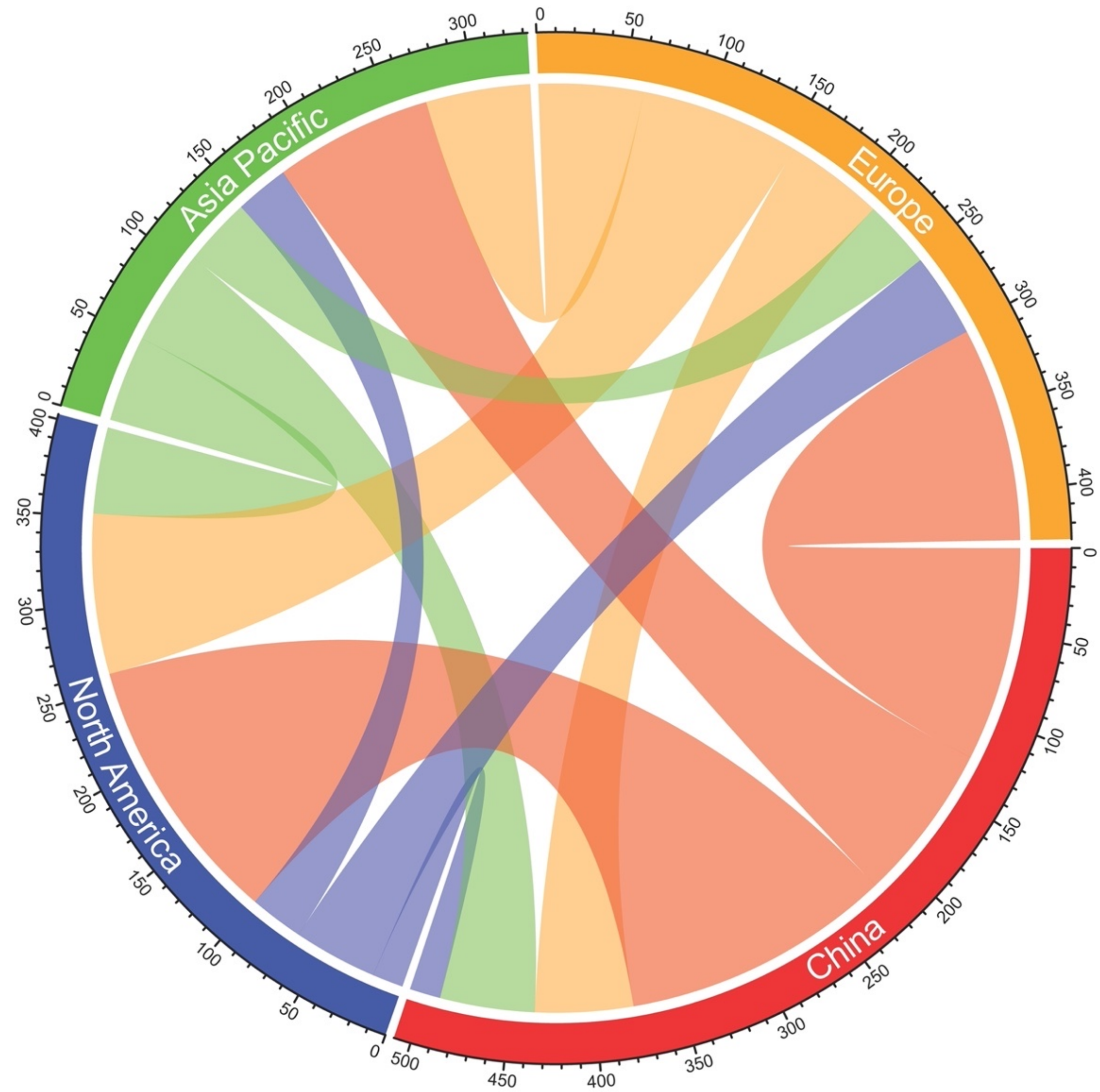

Figure 6. Capital Goods Flows between Regions in Billions of USD, 2019; Data: UN Comtrade Database

3. Orientation to Foreign Innovation

In addition to the movement of people, knowledge flows across regions through patent registrations. Patents and patent families[5] reveal capacity of national STI profiles. Openness to innovation can be measured by examining which national actors maintain an international orientation in the process of licensing and registering intellectual property. R&D-intensive nations tend to patent at higher rates than those nations which conduct less R&D. Patent applications worldwide have risen rapidly over the past decade. In 2018 according to WIPO, 3.3 million patent applications were filed worldwide. This represents a 5 percent increase over the year before, largely because of the exceptional growth from Chinese companies and institutions. China's patent office received 1.5 million patent applications (or 46.4 percent of all patent applications filed worldwide) in 2018; the overwhelming majority of these filings were from domestic actors. In comparison, the United States patent office received nearly 600,000 applications with just under 300,000 listed as domestic applications, and just over 300,000 foreign applications in the same year. Japan's patent office received just over 300,000 patents total, and South Korea had about 200,000 total.

With the exception of the USA, for most nations, residents file the majority of patent applications. Companies planning to export high-value products often register the associated intellectual property in foreign offices to protect exports. US applicants filed the largest number of patents abroad. Japanese nationals filed the largest number of foreign patents in the USA. For those filing foreign-oriented patent families, inventors in USA and Japan created by far the largest number of patent families.

Figure 8 illustrates the cross-patenting activity by region for 2019 (data from WIPO). Europe and North America are much more likely to be the location of non-resident patent applications. China's external patent registration is focused on North America and Europe; much less activity is focused back on China. Europe links to North America. Solid links can be seen between Europe, the USA, and other Asian nations.

[5] A patent family is a set of interrelated patent applications filed in one or more offices to protect the same invention.

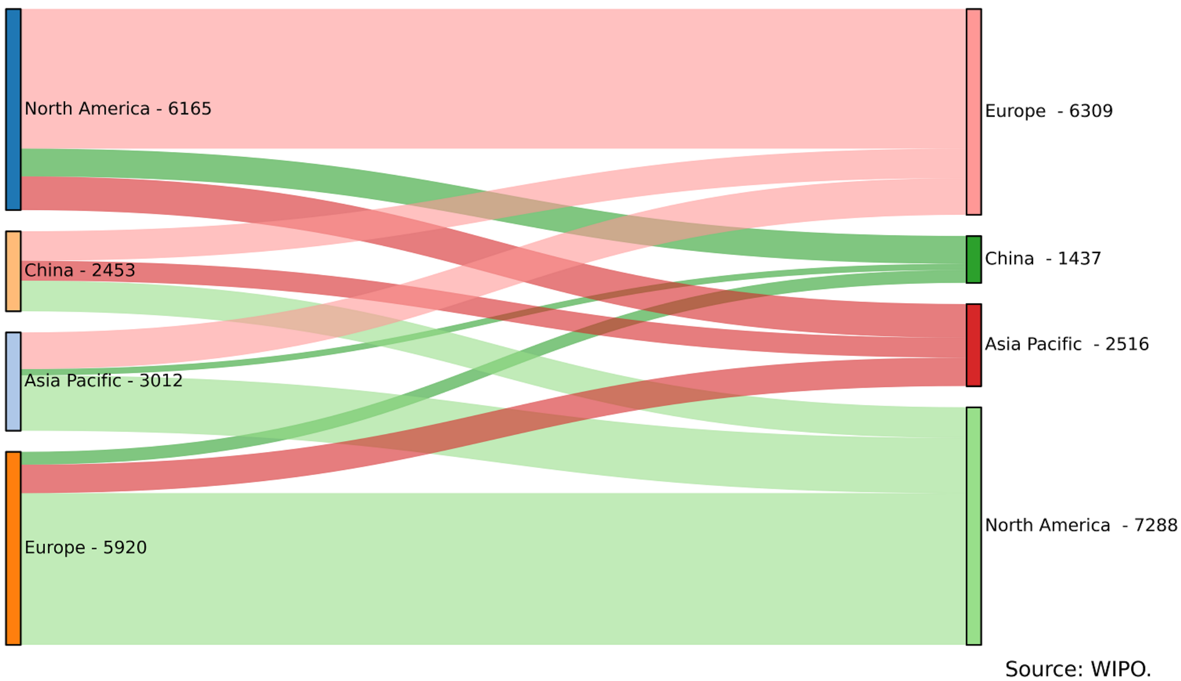

Figure 6 Patent Registration across National/Regional Lines, Data: WIPO

To gain insight into national orientation towards international innovation, we collected data on patent families to view relationships between R&D spending and patent registration. Analysis showed that higher R&D per capita for a nation results in greater numbers of patent families registered outside that nation. Similarly, we expected to find that nations with high R&D per capita are attractive to foreign inventors. Analysis showed that higher R&D per capital spending in a nation correlates with a higher proportion of foreign owned, or non-resident, patents registered in that nation.

When patenting behavior is examined using GDP as an indicator, rather than by total numbers, the list of leading nations changes. South Korea filed the greatest proportion of patents for its GDP. China followed with the second highest ratio to Korea, followed by Japan, Germany, and Switzerland. The USA ranks sixth in this list of GDP patent registration, followed by Finland, Denmark, and Sweden[6].

4. International Research Networks and National Strengths

In addition to the movement of people, knowledge flows across regions through collaborations on research and commercialization projects - even when research partners are located in different nations. Using coauthorships on published scientific or engineering articles, we examined the relationships between academic-academic, academic-industry, and industry-

[6] WIPO 2019

industry connections, expecting different patterns among them. Links between academic institutions often follow elite reputations, with collaborators interested in linking to those in highly reputed institutions. Links between academia and industry transfer basic knowledge from academia into market-oriented applications in business; these links generally follow scientific or engineering strength reflected by citations rather than business strength, but an elite component operates for business, too. Published articles from industry to industry are relatively fewer in numbers among the published literature, usually less than 12-15 percent of all articles. Industry-industry links closely correlate to both scientific and industrial capacity and tend to be highly disciplinary, although less focused on elite ties than the academic work.

Scientific and engineering publications in scholarly literature reveal knowledge creation and interdependency among nations. For many years, the United States was the standout leader in numbers of publications, citations, and elite prizes. This is no longer the case. Table 2 shows the productivity levels for regions and nations of the world. The EU28 (including the UK) publishes the largest number of papers. China has overtaken the USA in numbers of papers. The table shows data on top S&T-producing nations for 2018, indicating the dominance of China and the rapid growth of other nations compared to the USA.

Table 2 National Production of Science and Engineering Articles by Nation, 2008-2018, Data: National Science Foundation drawing upon Scopus [Note: Nations in light grey type are not included in this report]

Rank	Region or Country	2008	2018	Annual Growth Rate, 2008-18 (%)	2018 world percentage (%)
-	World	1,755,850	2,555,959	3.83	-
1	China	249,049	528,263	7.81	20.67
2	United States	393,979	422,808	0.71	16.54
3	*India*	*48,998*	*135,788*	*10.73*	*5.31*
4	Germany	91,904	104,396	1.28	4.08
5	Japan	108,241	98,793	-0.91	3.87
6	United Kingdom	91,358	97,681	0.67	3.82
7	*Russia*	*31,798*	*81,579*	*9.88*	*3.19*
8	Italy	56,157	71,240	2.41	2.79
9	South Korea	44,094	66,376	4.17	2.60
10	France	66,460	66,352	-0.02	2.60
11	*Brazil*	*35,490*	*60,148*	*5.42*	*2.35*
12	Canada	53,296	59,968	1.19	2.35
13	*Spain*	*44,191*	*54,537*	*2.13*	*2.13*
14	Australia	37,174	53,610	3.73	2.10
15	*Iran*	*17,034*	*48,306*	*10.99*	*1.89*
-	EU	528,938	622,125	1.64	24.34

Source: National Science Foundation, *Science & Engineering Indicators*, 2020

Table 2 further shows average growth rates in scholarly output was highest for India, Iran, and Russia (greyed out in the table)—three nations not covered in this report. Among the nations covered in this report, average annual growth rate was highest for China and South Korea. The EU28 outperformed China and United States in percentage share of world articles, a data point closely correlated to R&D/GDP spending.

4.a. International collaborations across academia

Scientific and engineering research collaborations—measured by counting coauthorships--have been growing at a rapid pace for several decades. Those occurring at the international level have been growing even faster than collaboration as a whole. It is increasingly common for scientific articles published in journals to include authors from multiple countries. Depending on counting methods, over 60 percent of all articles in natural sciences and engineering are coauthored, and among these, about 50 percent of them are internationally coauthored. Often, coauthorships include three or more nations. These connections can be studied as a network of connections where knowledge is being created and exchanged in flows from one place to another. (We assume that participating parties contribute and benefit equally.)

Table 3 shows the top collaborating partners for the most active R&D nations in 2019, with data from Web of Science. Academic partnerships across nations, reflected in publications, closely correlate to the size of nations in the nations observed for this study. China and the USA were one another's largest collaborating partners in 2019. China ranks among the top three collaborating partners in nine of the 18 nations listed in Table 3, the USA appears as a top partner for 13 nations. The frequency with which China and the USA appear on the list reflects the numbers of collaborators available to work with others, as well as their funding capacity, visualized in Figure 8. European nations show preferences for regional collaborators. The USA shows a Pacific orientation with China, Japan, and Canada as top partners. The results demonstrate a combination of regional linkages, the influence of size of the cooperating nation's STI system on preference, and the role of STI excellence in choosing partners.

Table 3. Top Collaborating Partners of R&D-intensive Nations, 2019, Data: Web of Science (CADRE)

Nation	Cooperator #1	Cooperator #2	Cooperator #3
Australia	China	USA	UK
Austria	Germany	Japan	UK
Belgium	UK	Germany	Netherlands
Canada	China	USA	Switzerland
China	USA	Germany	UK
Denmark	Germany	Sweden	USA
England	China	USA	Germany
Finland	Germany	USA	Poland
France	Germany	USA	Switzerland
Germany	USA	China	Russia
Israel	USA	China	Germany
Japan	USA	China	Germany
Netherlands	Germany	UK	USA
Singapore	China	USA	Japan
South Korea	Germany	USA	Japan
Sweden	Germany	UK	China
Switzerland	Germany	Italy	USA
USA	China	Japan	Canada

Figure 8 shows academic collaborations across nations by region, where each of the represented nations gets a full count for participation in coauthored articles. It is possible to see strong links between North America and the European Union (minus the UK), as expected. China has a strong connection to North America. The UK bridges North America and the EU. The

Rest of World (ROW) is strongly connected to Europe, the UK, and North America but much less so to China.

As noted above, China has become the most frequent partner with the USA in science and engineering. In 2019, the two nations had 27,000 collaborative papers in Web of Science. The topics of these papers, in descending order by numbers of papers were chemistry, engineering, materials, physics, environment, computer science, and energy. Chinese nationals working in the United States coauthored perhaps one-quarter of these papers[7]. Researchers with academic addresses, not industrial linkages, coauthored the vast majority of these papers. A similar pattern emerges between Europe and China.

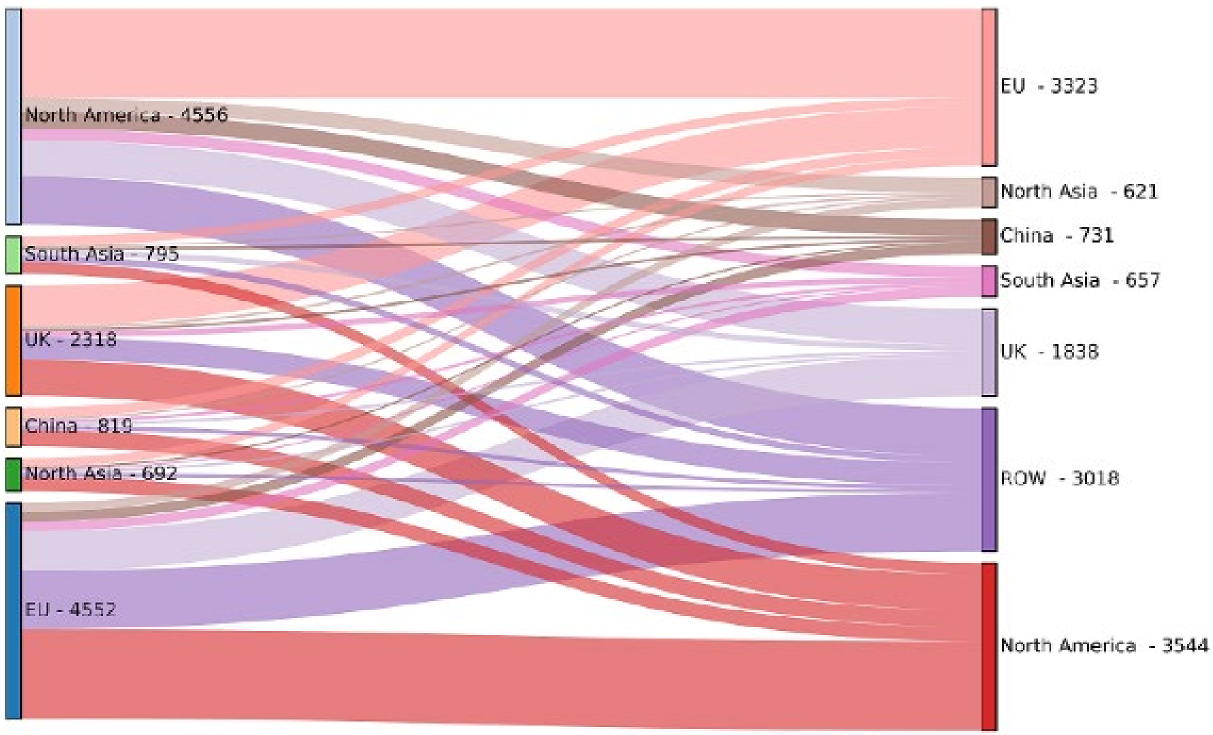

Figure 7 Collaborations across Regions in Academic Science and Engineering Publications, Data: Web of Science/CADRE

4.b. Academic-industry links

Theory suggests that basic knowledge diffuses from academia to industry for more practical applications and market innovations. Figure 9 shows the links derived from scholarly

[7] Cao et al., 2019

publications between academia on the left, by region, to industry on the right[8], by region. Europe holds a commanding position in the 'export' of academic knowledge to industry. The industrial partners are largely in Europe but also in North America, and less so in China and other Asian countries. North American academics also have robust connections to European industry. Overall, Europe appears to be the source of the largest tranche of academic literature being used by industry, and European industry appears to be the largest user of academic links, perhaps influenced by specific European Commission support to the creation of these linkages over three decades.

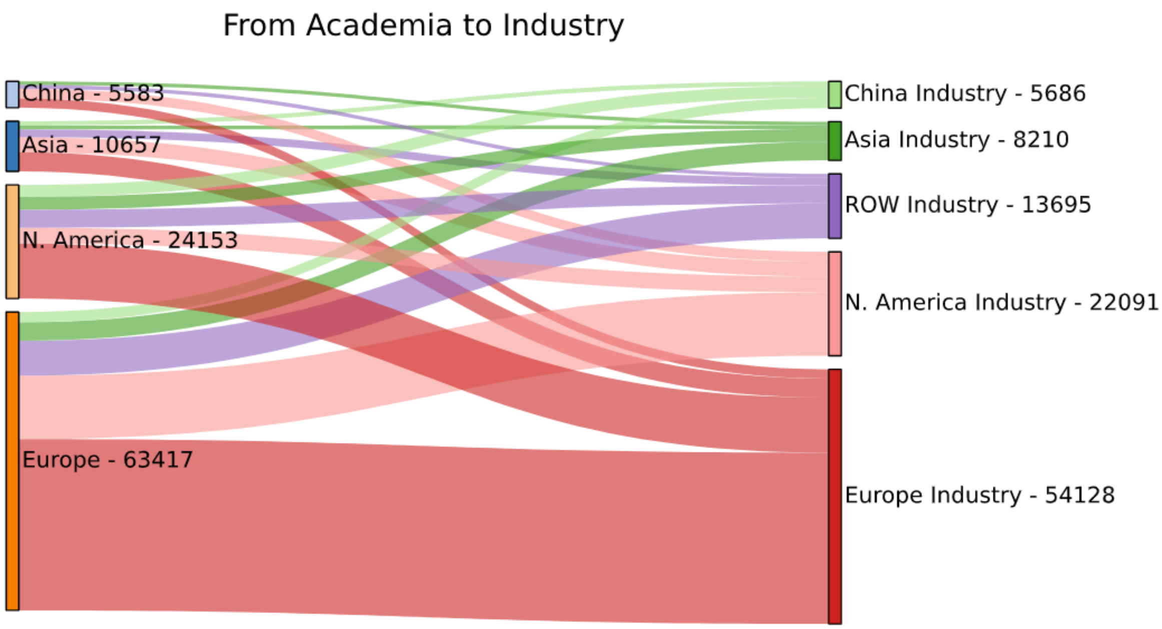

Figure 8 Academic-Industry Collaborative Links by Region, 2019, Data: Web of Science

4.c. Industry-industry links in basic research

Figure 10 shows industry-industry linkages across regions. As noted, industry publishes less than one-quarter of all scientific or technical publications. Among these, industry-industry links are the smallest category. These works are important indicators of basic research in industry, and cross-national links present an indicator of capacity. The vast majority of industry-industry links are within the nation or the geographic region. Figure 10 illustrates links across regions when industry collaborates across regions. Even here, it is possible to see strong regional connections. Across regions, North America and the EU are more likely than Asia to work with the Rest of World partners. The USA is more likely than other regions to be working with China. The UK and North America have strong ties in industry-industry links.

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[8] Industry was identified by suffixes such as "corp," "LLC," and "inc." The list of suffixes was developed in Europe, and it may have weighted the search in favor of European nations.

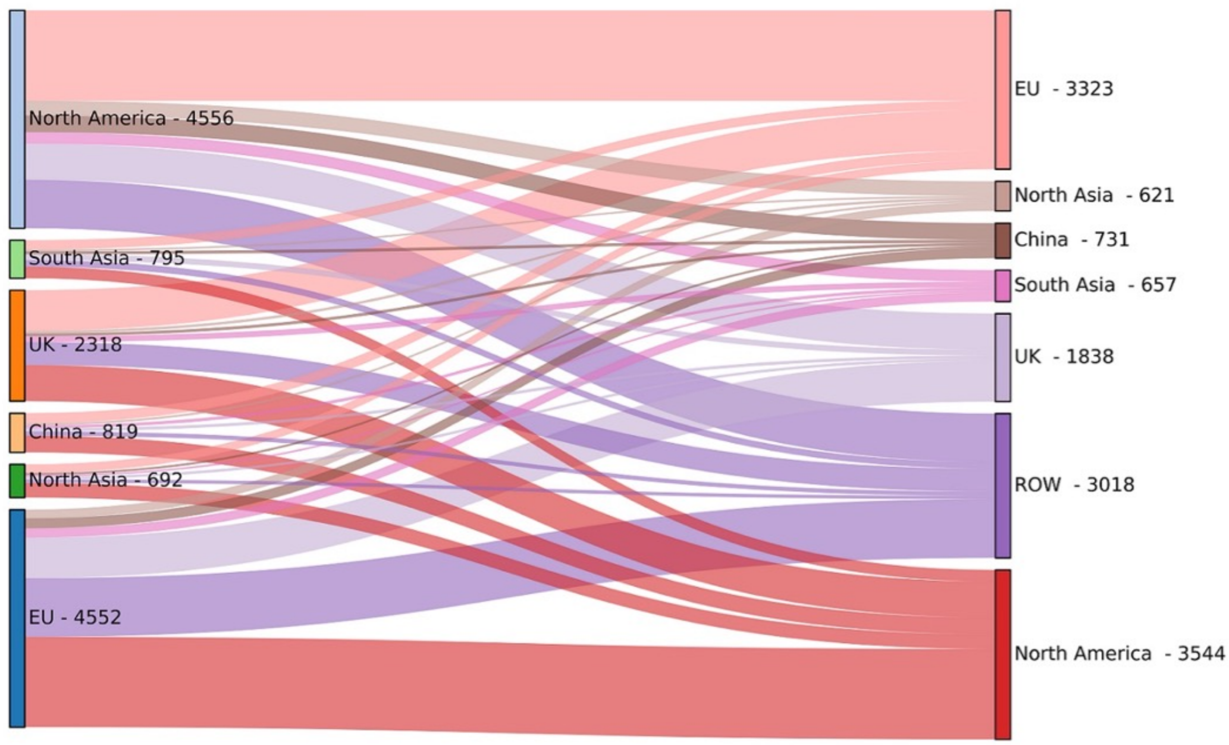

Figure 9 Industry-Industry Links in Science and Engineering Publications by Region, 2019, Data: Web of Science

4.d. Citations counts across regions

Citations to published works reveal the impact of a paper, serves as a proxy for quality, and indicates co-dependency; citations are a reflection of the value placed on that work by others, indicating the utility of ideas for later publications or applications. Citations reflect reputation, as well, and thus are not always a sign of 'novelty' or even of quality. Figure 11 shows the aggregated citation counts for elite work—those articles in the top 10% most highly cited articles--for the EU28, USA, and China. In the 2010s, the EU28 topped the USA. When citations are normalized and aggregated, four nations best the United States in garnering citations to their work: Singapore, Switzerland, Netherlands, and Denmark. Germany is on par with the United States. China is represented by the curved line below the EU with a nearly exponential rise in the appearance of articles in the top 10% most highly cited list. China still lags considerably when measured against the top 10% most highly cited works, but its position has been growing slowly upwards.

The more open a nation is to exchange and communication in scholarly work, the more likely that nation is to lead in science and engineering; citations reflect this tendency. In earlier work, we analyzed publication and citation data for 36 nations, along with government expenditures on science. We found that although government spending on research and development (R&D) does correlate with the number of publications produced, it does not correlate with citation impact. What does correlate with citation impact is a country's openness to exchanges discussed in this report—movement of people, openness to trade and knowledge exchange, and connections of researchers across borders.[9]

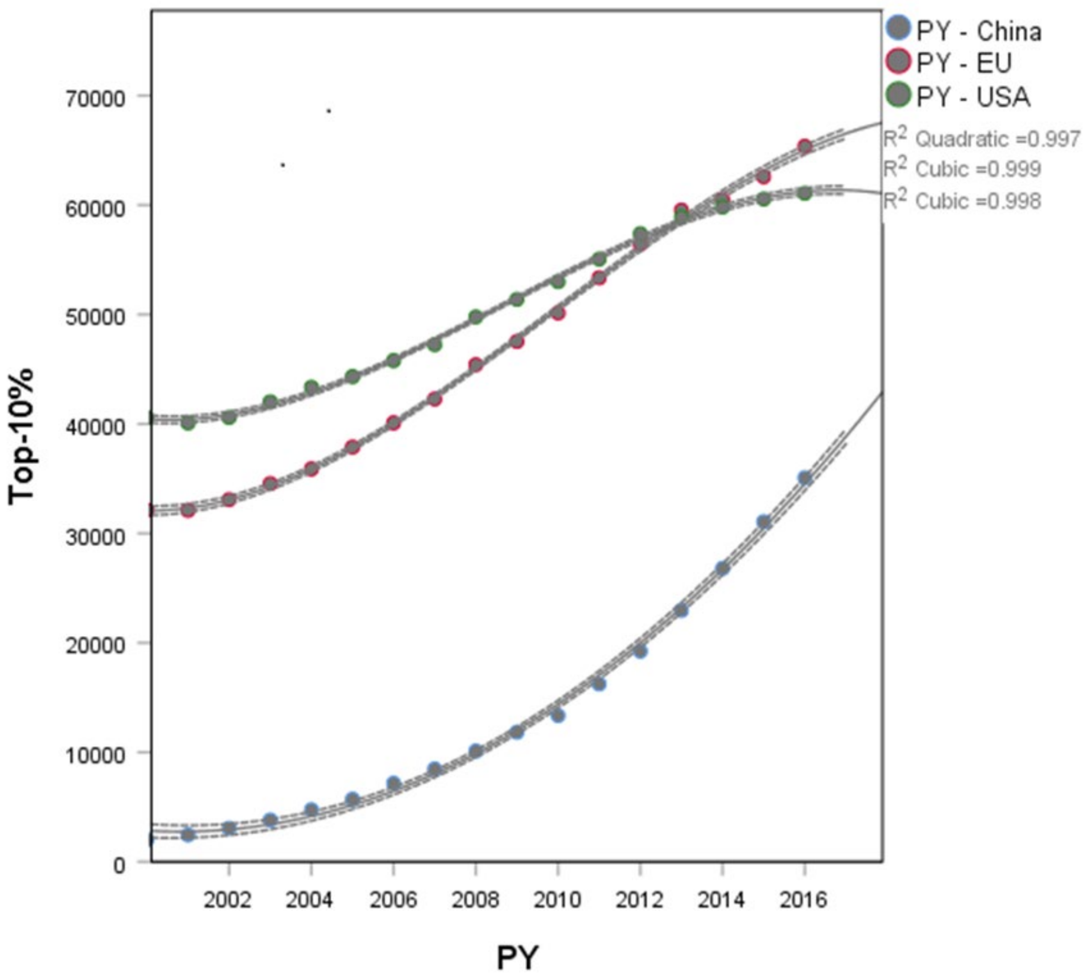

Figure 10 Aggregated Citations to Articles in the Top 10% Most Highly Cited Research Articles, 2002-2016, Source: Leydesdorff, Wagner and Bornmann, forthcoming, Data: Web of Science

Figure 12 shows the network of interconnections where we isolated only those nations examined for this report (Box 1). Here, one sees that the top R&D producing nations are deeply and intensively connected to one another. The USA retains a place as the most centralized nation in the network, partly due to size, and partly due to its historical leadership. Nations on the periphery are ones that are increasingly connected to the core groups. (Once visualized, it would be possible to see nations such as Indonesia, Colombia, and South Africa connecting to the core group.) When we measure the centrality of each nation in the network, we find a strong correlation between R&D/GDP to centrality. Centrality in a network conveys an important informational advantage—the central position means much of knowledge flows

[9] Wagner & Jonkers, 2018

through that node, enabling it to stay on top of developments throughout the network. The strength of centrality and its relationship to R&D/GDP demonstrates the benefits of strong investment and interconnectedness.

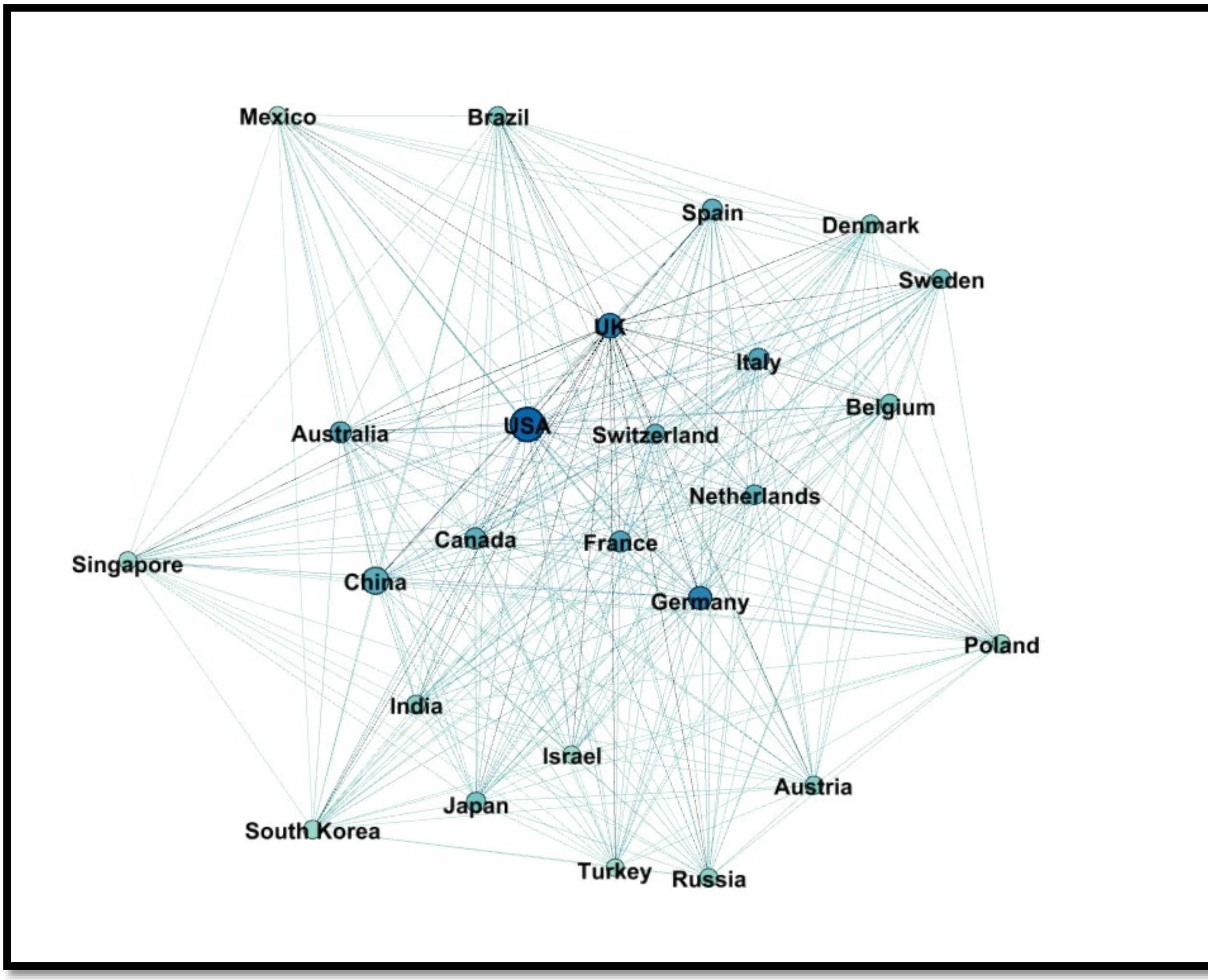

Figure 11 Network of Nodes and Edges of Collaboration in S&T across Top R&D Nations, 2019, Data: Web of Science (CADRE)

The Case of Pharmaceuticals

The pharmaceutical industry--including research, development, clinical trials, production and sales--is critical to many nations, particularly so in the time of COVID-19 pandemic. In a 2017 study of the industry[10] examining patent applications with the United States Patent and Trademark Office (USPTO), the European Patent Office (EPO) and triadic patent families, consisting of related applications filed at all three of the USPTO, EPO and the Japan Patent Office (JPO), analysts found that R&D is correlated to patenting activities for the USA and Japan, but not for the European Union. However, for the six non-European countries in the dataset

[10] Kumazawa, 2017

(Australia, South Korea, Mexico, Romania, Singapore and Taiwan), R&D spending always had statistically significant effects on all three types of patent applications in the industry. The results were more pronounced when the United States and Japan were also included. China, Brazil and India were excluded due to missing R&D data.

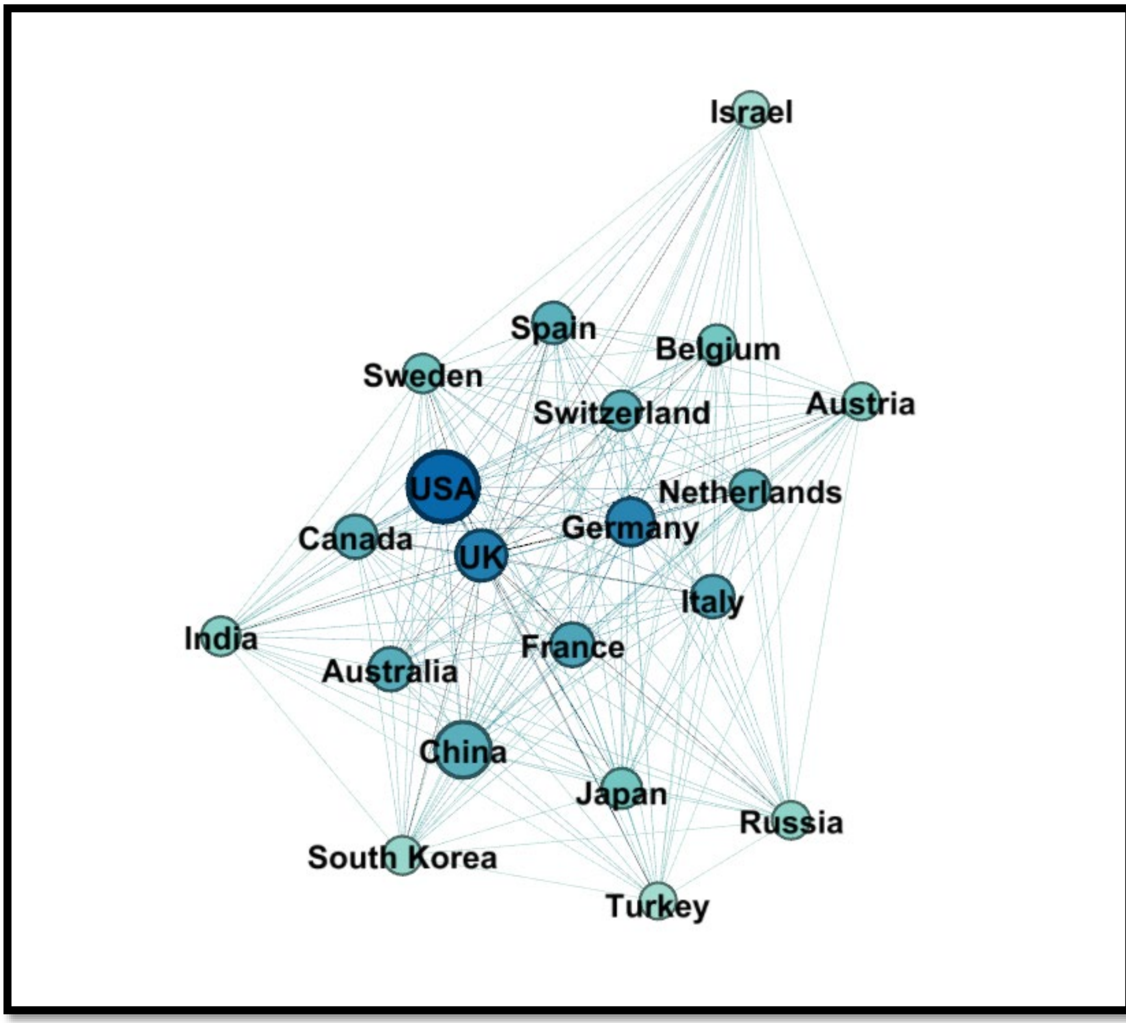

Figure 12 R&D Network of Pharmaceutical Coauthorships (Node size and darker shading indicate a higher number of coauthorships), Data: Web of Science (CADRE)

Figure 13 depicts international collaboration in pharmaceutical coauthorships among the top 20 R&D nations in 2019. As can be seen, the network is tighter than the one seen in Figure 12, suggesting less external collaboration (outside the network). The United States is central to international collaboration on pharmaceutical research. US researchers collaborated on 226,574 international studies; researchers in China, the closest contender, published 134,201 papers with international coauthors. England (100,956), Germany (82,225), and France (57,038) were closest behind China. Interestingly, despite its high number of international coauthorships, China is less central to the network than several European counterparts. The US, England, Germany, France, Italy, and Australia comprise a central, particularly dense, and interconnected collaborative community in pharmaceutical research. That being said, the R&D-20 countries as a whole also comprise a relatively dense pharmaceutical collaboration network.

Conclusions and Observations

Investments in the past two decades have transformed the STI world from one dominated by the United States to a distributed world of strengths in many regions. Researchers, students, and innovators in North America, Europe and Asia are interconnected through collaborative research, patent filings, trade, and exchanges. Prior to the COVID-19 pandemic, interdependence among nations had grown substantially to include international collaborations, cross-filings of patents, global value chains in high technology production, shared funding of large-scale research infrastructure and flows of people.

The ranking of nations producing the greatest number of scientific articles shows change over the decade between 2008 and 2018. With 24% of all published work, the EU produces the largest number and greatest percent of scientific and technical articles, followed by China at 21%--a new position for that nation. The United States produces 17% of all articles. The EU has overtaken the USA in citation strength of elite published articles. The EU also leads in number of academic-industry collaborations. When measured by R&D as a percent of GDP, seven nations outspend the USA by investing more than 2.7% of GDP in R&D: South Korea, Israel, Japan, Finland, Denmark, Sweden, and Singapore. Twenty-two nations out-invest China. South Korea and Taiwan are the most R&D-intensive nations, according to the National Science Foundation.

The statistical analyses of the data showed that the following measures were statistically significant when compared to R&D spending per capita:

- Numbers of scholarly visitors weakly correlates to R&D spending
- High technology trade weakly correlated to R&D spending
- Nations with higher R&D spending are more likely to attract non-resident patents
- Pharmaceutical sales are correlated to R&D spending.

Other features that did not correlate to R&D spending include the following:

- Attraction of students
- Attraction of educated migrants
- Trade in capital goods.

Patenting showed the greatest change in the time we examined, with China rapidly rising to the nation with the most patent applications. China was less likely than other advanced nations to have non-resident patent applications, however. The USA was the only nation attracting more non-resident patent applications than national ones. Japan actively patents in the United States as well as in other foreign nations. South Korea showed greatest strength in patenting as a percent of GDP.

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Appendix 1. List of nations and their regions covered in this report

The list differs from Box 1 in that the list of nations included in each of the analyses sometimes changed based upon what data was available. Data was not always available for each nation. Some of the analysis included Mexico, Brazil.

Country	Region
Australia	Asia
Austria	EU
Belgium	EU
Canada	NA
China	Asia
Czech Republic	EU
Denmark	EU
Finland	EU
France	EU
Germany	EU
Hungary	EU
Israel	EU
Italy	EU
Japan	Asia
Netherlands	EU
New Zealand	Asia
Norway	EU
Portugal	EU
Singapore	Asia
South Korea	Asia
Switzerland	EU
Taiwan	Asia
UK	EU
United States	NA

Appendix 2. Initial hypotheses and analytical methodology

Data Sources

Data for this report were obtained from published datasets provided by the following organizations: The United Nations Educational, Scientific and Cultural Organization (UNESCO); the Organization for Economic Co-operation and Development (OECD); and The World Bank (TWB). Some specialized data were obtained from other sources, as noted in the individual descriptions below. For annually collected data, the most recent year with the fewest missing values was used for analysis – with a few exceptions discussed below. Data sources are specified for each variable.

Methodology

We began our analysis with the six hypotheses shown in the table below along with their associated measures. For each hypothesis, we conducted an Ordinary Least Squares regression on the collected measures to test for a statistically significant relationship.

Hypothesis	Description	Dependent Measures	Independent Measures	Observed Correlation
1	Education enterprise influence on global talent flows.	Tertiary-level student inflow.	Top 500 universities.	+
		Tertiary-level student outflow.	Top 500 universities.	0
2	Impact of country R&D intensity on trade.	High-technology exports.	R&D expenditure per capita.	+
3	Association between R&D intensity and involvement with foreign innovation.	Triadic patents.	R&D expenditure per capita.	+
		Domestic ownership of foreign patents.	R&D expenditure per capita.	+
4	Impact of Pharma R&D on Pharma value chain.	Pharmaceutical patents.	R&D expenditure per capita.	0
		Medical technology patents.	R&D expenditure per capita.	0
		Clinical trials.	R&D expenditure per capita.	0
		Pharmaceutical patents.	R&D expenditure (Pharma)	+
		Medical technology patents.	R&D expenditure (Pharma)	+
		Clinical trials.	R&D expenditure (Pharma)	+
5	Importance of immigration to R&D outputs.	Researcher inflow.	Percent Excellent Articles	0
		Researcher inflow.	FWCI.	+
		Researcher inflow.	Normalized scholarly output.	0
6	Relevance of R&D intensity to Capital Equipment International Trade	Capital goods inflow	R&D expenditure per capita.	0
		Capital goods outflow.	R&D expenditure per capita.	0

Table 4: Hypotheses, Measures, and Correlations. Observed correlation only shows a direction for results with statistical significance at the 90% confidence interval or above. See full results table below for additional information.

Dependent Variables

These dependent variables describe various flows into and out of a country; these include high-tech goods, students, innovations, and other flows related to the research and development sector. Ultimately, these flows represent the accumulation or diffusion of talent, innovation, and technology across target countries.

Capital Goods Inflow and Outflow. The flow of capital goods into a country is reflected by the aggregate cost insurance and freight (CIF), a measure of the expenses paid by the seller to secure goods in transit to the buyer (Twin, 2020). Likewise, the outflow of capital goods from a country is measured by aggregate freight (or free) onboard (FOB). The FOB defines the destination of goods and specifies precisely the point at which goods transfer ownership, which party is liable should errors occur, etc. It also contains cost information related to the CIF (Nickolas, 2019). For this study, aggregate CIF and FOB measure capital goods imports and exports for a country, respectively. These data originated from the UN Comtrade Database (United Nations, n.d.) and reflect figures from the year 2019.

Domestic Ownership of Foreign Patents. This variable measures the number of domestically owned patents of inventions created abroad for a country; it does not differentiate between the countries of origin for these inventions. These data were obtained from the OECD.Stat Database (Organization for Economic Co-operation and Development, 2020) and represent the year 2018.

High-technology Exports. High-technology exports describe products with intensive research and development (R&D) costs; for this measure, these exports include products from the aerospace, computers, pharmaceuticals, scientific instruments, and electrical machinery sectors. Exports from each of these sectors is calculated as a percentage of all manufactured exports and combined into a weighted average for the country. These data are provided by The World Bank but originate from the United Nations (UN) Comtrade Database (United Nations, n.d.); they reflect exports for the year 2018.

Patent Families. A patent family is a set of interrelated patent applications filed in one or more offices to protect the same invention. Data on national registrations and patent families was gathered from the World Intellectual Property Organization (WIPO) Indicators report, 2019.

Pharmaceutical and Medical Technology Patents. Patents are classified into a field of technology by the World Intellectual Property Organization (WIPO). One measure in this study combines the aggregate number of patents granted in two of these fields – “pharmaceuticals” and “medical technology” – for the years 2017, 2018, and 2019, in each country. Another measure utilizes the same approach using only the “pharmaceuticals” field. All data were obtained from the WIPO Intellectual Property Data Center (World Intellectual Property Organization, n.d.).

Researcher Inflow and Outflow. Researcher inflow describes the number of foreign researchers entering the country as a percentage of all national researchers. Conversely, researcher outflow describes the number of departing domestic researchers as a percentage of all national researchers. These data were obtained from the OECD Science, Technology, and Industry Scoreboard (Organization for Economic Co-operation and Development, n.d.) for the year 2015.

Tertiary-level Student Inflow and Outflow. These two variables measure the aggregate inflow of all post-secondary students to and from the country. Data were obtained from the UNESCO Institute for Statistics (UIS) (UNESCO Institute of Statistics, n.d.).

Independent Variables

This section defines and describes each independent variable used in the study; these variables correspond with research and development capacity in a target country, conceptualizing them as the drivers of various flows (e.g. high-tech goods, students, etc.) into and out of that country. Data sources are specified for each variable.

Excellent Articles Percentage. Jonkers and Sachwald (2018) provide a measure for the “excellence” of research in a country, addressing a missing perspective in innovation research that sometimes focuses only R&D intensity via expenditures. This measure calculates the percentage of publications in a country that are rated in the top ten percent of the worldwide most-cited documents in the United States, European Union 28, and China. Values for the year 2016 are used in this study.

Field-weighted Citation Impact (FWCI) is a method of normalizing citations by field of science. Different disciplines have varying citation practices, intensities, and counts. FWCI is calculated first by field, and all articles classified in that discipline have their citation rate divided by the average citation rate for the field. The rates can then be aggregated into groups; at the highest aggregation, we can view how nations compare against one another in citation strength. FWCI used in this report were calculated by Elsevier.

Normalized Scholarly Output. Scholarly output is operationalized as the total number of citations credited to publications of scholars within a particular country. For this study, scholarly output is normalized per 1000 full-time employees (or equivalent). The number of full-time employees was obtained from the OECD. Scholarly output was provided by Elsevier. Normalization is done by Elsevier.

Number of Top-500 Universities. Hosting top-ranked universities is an indicator of a thriving higher education enterprise. For this measure, data were obtained from the Times Higher Education (THE) World University Rankings for the year 2019. Each country was assigned a value equal to the number of institutions within its borders that ranked within the top 500 institutions on the THE rankings.

Per Capita Gross Domestic Expenditure on R&D (GERD). This is the total gross domestic expenditure on research and development in a country normalized by the population of the country and reported in purchasing power parity dollars (PPP$). Data were obtained from the UNESCO UIS (UNESCO Institute of Statistics, n.d.) database; the most recent data for the year 2018 were missing values for several countries, so data from 2017 were used instead.

Total Business Enterprise Expenditure on R&D (BERD) for Pharmaceuticals Sector. This measures the total BERD expenditures on pharmaceuticals in millions of current purchasing parity dollars (PPP$) for the year 2017. These data were also obtained from the UNESCO UIS (UNESCO Institute of Statistics, n.d.) and are missing values for 2018. Hence, this study uses data from 2017.

Results Table

VARIABLES	(Hypothesis 1) Student In	Student Out	(Hypothesis 2) High-Tech Exports	(Hypothesis 3) Triad Patents	Domestic-Own	Pharma Patents	(Hypothesis 4) Med & Pharma Patents	Clinical Trials	(Hypothesis 5) Researchers In	(Hypothesis 6) Capital Goods In	Capital Goods Out
Top 500 Universities	7,594***	322.4									
	(441.2)	(1,673)									
R&D Spending Per Capita			0.00490*	1.574**	0.966***	-0.983	-2.335	0.0178		156.3	122.9
			(0.00264)	(0.763)	(0.284)	(1.310)	(3.252)	(0.558)		(115.4)	(109.4)
R&D Spending (Pharma)						0.385***	1.348***	0.273***			
						(0.0630)	(0.156)	(0.0281)			
Percent Excellent Articles									0.0688		
									(0.0893)		
FWCI									5.951***		
									(1.378)		
Normalized Scholarly Output									-3.52e-06		
									(9.91e-06)		
Constant	-4,233	77,281	12.77***	-46.56	-155.5	1,817	4,206	1,632**	-4.031**	217,976*	238,538**
	(15,827)	(54,547)	(2.700)	(781.0)	(291.1)	(1,409)	(3,497)	(624.7)	(1.707)	(118,211)	(112,056)
Observations	18	22	46	46	46	29	29	29	33	46	46
R-squared	0.949	0.002	0.073	0.088	0.208	0.596	0.749	0.795	0.580	0.040	0.028

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Appendix 3. Sources for student, patent, and goods flows

Students

Data were obtained from the UNESCO database on Global Flow of Tertiary-Level Students for 2017-2019.

Patents

Data were obtained from the OECD.Stat database; they describe foreign ownership of domestic inventions for the year 2018; we conceptualize these as patent outflows.

Capital Goods

Data were obtained from the UN Comtrade Database; they describe annual goods flows using BEC for the year 2019. Specifically, these are exports as reported by the exporter in US$. Capital goods is the sum of two BEC commodity codes (41 and 521), as suggested by UN Trade Statistics.

BEC Code 41: Capital goods (except transport equipment).

BEC Code 521: Transport equipment, other, industrial.

Pharmaceutical Goods

Data were obtained from the UN Comtrade Database; they describe annual goods flows using SITC Rev. 4 as reported for the year 2019. Specifically, these are exports as reported by the exporter in US$. Pharmaceutical goods consists of one SITC commodity code (5419).

SITC Code 5419: Pharmaceutical goods, other than medicaments.

High-technology Goods

Data were obtained from the UN Comtrade Database; they describe annual goods flows using SITC Rev. 4 as reported for the year 2019. Specifically, these are exports as reported by the exporter in US$. High-technology goods is the sum of five SITC commodity codes (792, 5419, 75, 76, 87), as suggested by OECD.

SITC Code 792: Aircraft and associated equipment; spacecraft (including satellites) and spacecraft launch vehicles; parts thereof.

SITC Code 5419: Pharmaceutical goods, other than medicaments.

SITC Code 75: Office machines and automatic data-processing machines.

SITC Code 76: Telecommunications and sound-recording and reproducing apparatus and equipment.

SITC Code 87: Professional, scientific and controlling instruments and apparatus, n.e.s.