U.S. R&D and Innovation in a Global Context: 2022 Data Update

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Bottom Line: The U.S. position remains strong, but public investments are stagnant: the U.S. is now 6th in total R&D intensity, but 13th in government R&D, 10th in basic science intensity, and only 17th in researchers as a share of the workforce.

China has not yet caught the U.S. in R&D, but it leads the world in published output in math and physical science and engineering, and increasingly produces high-value patents.

Investment in research and development (R&D) – activities to generate new knowledge and create new technology – is a cornerstone input for innovation. This report provides an update of major trends in R&D and related innovation metrics, in light of continuing Congressional interest in U.S. competitiveness.

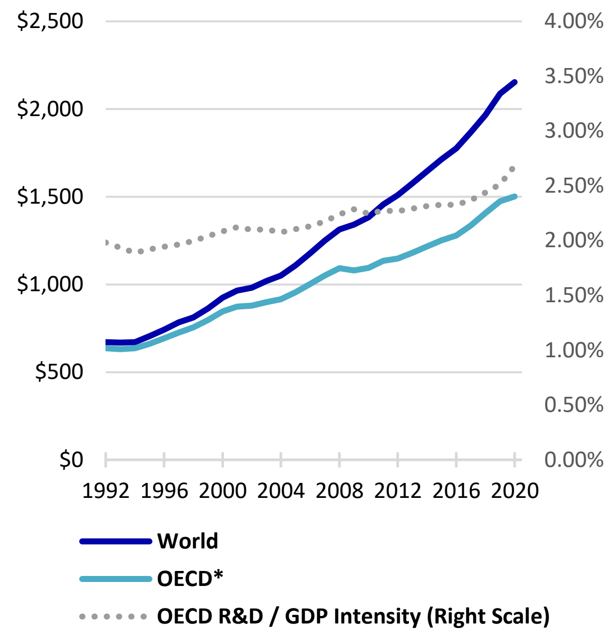
This report relies primarily on new data from the Organisation of Economic Cooperation and Development (OECD), released in late March 2022.[1] For certain topics, the OECD data is supplemented with data from other sources.

1. Aggregate Trends

Adjusted for inflation and cross-economy price differences, global R&D investment has tripled over the past 20 years, from $672 billion in 1992 to over $2.1 trillion as of 2020 (Figure 1). COVID-19 appeared to slow this spending growth somewhat, though global R&D still rose by $65 billion in 2020.

One of the striking things about the trends shown in Figure 1.1 is the expansion in investment from areas beyond the 38 OECD member states, which tend to possess high wealth, highly developed economies. In 1992, OECD members accounted for virtually all global R&D. Since then, OECD R&D has grown, as has its intensity: the share of economic output devoted to R&D in OECD economies has risen from 2.0% in 1992 to over 2.5% today, as seen in Figure 1.1.

Figure 1.1: Total World R&D Since 1992

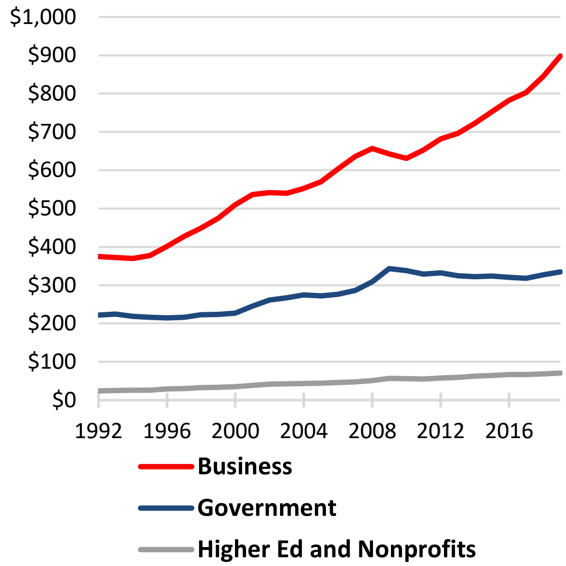


*The 38 OECD members generally possess high levels of income and development. Includes public and private sources.
OECD Main S&T Indicators, April 2022 | AAAS

But 30% of all R&D now comes from *outside* the OECD. What's driving it? Economies like Taiwan and Russia account for some, but over 80% of non-OECD investment today comes from China.

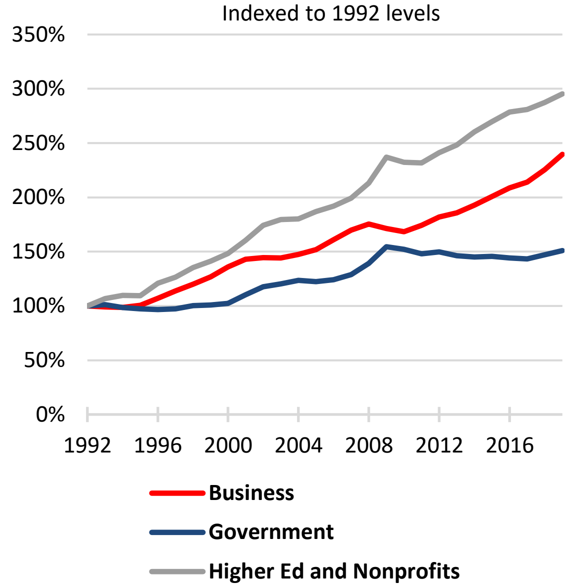
As seen in Figure 1.2 (following page), the business sector is by far the largest funder of R&D in OECD economies, providing nearly $900 billion and accounting for 64% of OECD R&D in 2019. That year, government financing – which refers almost entirely to national government in most cases – accounted for 24% of R&D, and the remainder was composed of universities, nonprofits, and foreign sources. However, since

Figure 1.2: OECD R&D By Funding Sector
(Billions of constant dollars adjusted for purchasing power parity)



AAAS calculation based on OECD S&T Indicators, April 2022

Figure 1.3: OECD R&D Growth By Funding Sector
Indexed to 1992 levels



AAAS calculation based on OECD S&T Indicators, April 2022

1992, relative funding growth has looked somewhat different (Figure 1.3). Over that time, R&D funding from higher ed and other nonprofit institutions has almost exactly tripled in real terms, while industrial R&D financing has more than doubled, and government R&D has only increased by 50%. It appears that a common theme within OECD economies is stagnant government funding since the 2009 financial crisis, with no real growth since then.

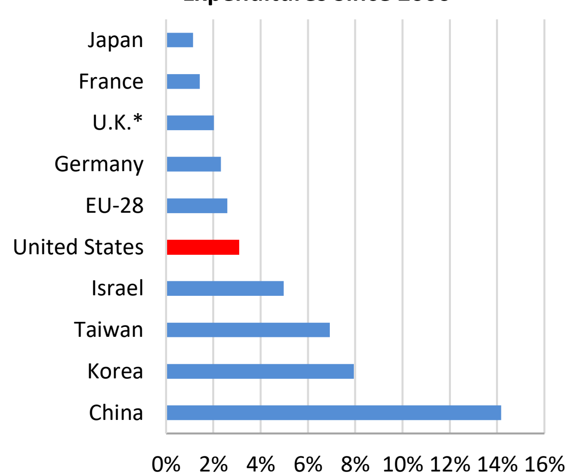
The above graphs cover up through 2019. What has happened over the past two years, in the era of COVID-19? The data remains incomplete, but initial OECD analysis points to a 2020 surge in public R&D across several advanced economies with an unsurprising focus on health, coupled with a parallel decline in private R&D. But both of these appear transient, with 2021 appearing to feature more "normal" investment.[2] For more, see country-level breakdowns in the next section.

2. R&D Investments by Country: China Continues to Gain

The United States has long led the world in R&D spending, but China has gained rapidly in recent years. Since 2000, Chinese R&D investment from public and private sources increased by 14.2% a year on average, an astounding growth rate nearly double that achieved by Korea, and over four times that of the U.S. (Figure 2.1).

As a result of this growth, Chinese R&D reached $563 billion in 2020, $101 billion behind the U.S. (Figure 2.2) and closing the gap somewhat from 2019.

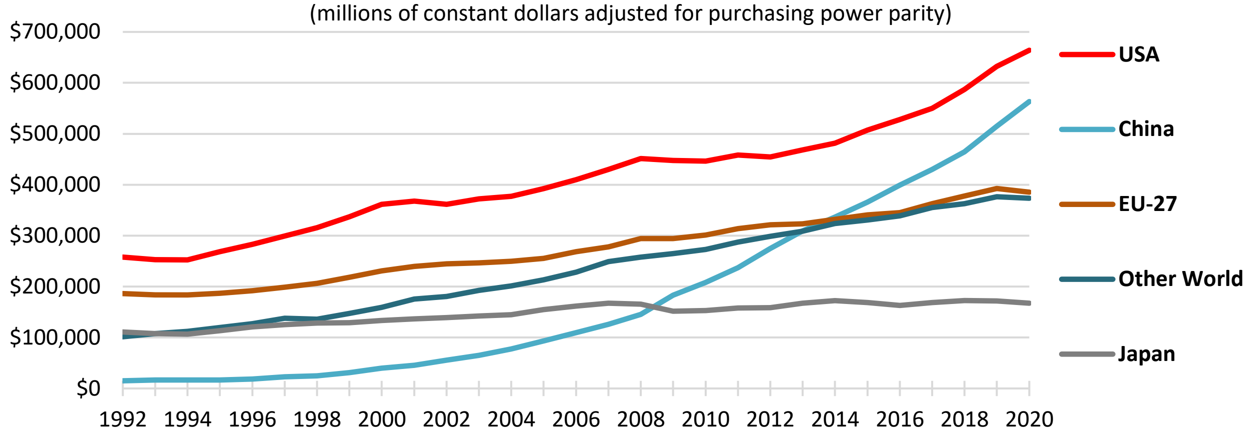
Figure 2.1: Annual Growth in R&D Expenditures Since 2000



Including public and private sources. Analysis based on OECD S&T Indicators data, April 2022. | AAAS

Figure 2.2: World R&D by Country / Region

(millions of constant dollars adjusted for purchasing power parity)



Includes public and private sources. OECD Main S&T Indicators, April 2022 | AAAS

During the pandemic, both Chinese and U.S. R&D saw increases, while aggregate E.U. expenditures saw a decrease. At the E.U. country level, Italy was notably the first country in Europe to be an epicenter of the pandemic, and aggressive lockdown measures and funding redirection curbed scientific output for some time.[3]

In conjunction with the pandemic, the U.K.'s exit from the E.U. also caused significant shifts in R&D funding as U.K. and E.U. scientists abruptly found themselves unable to access funds and projects.[4]

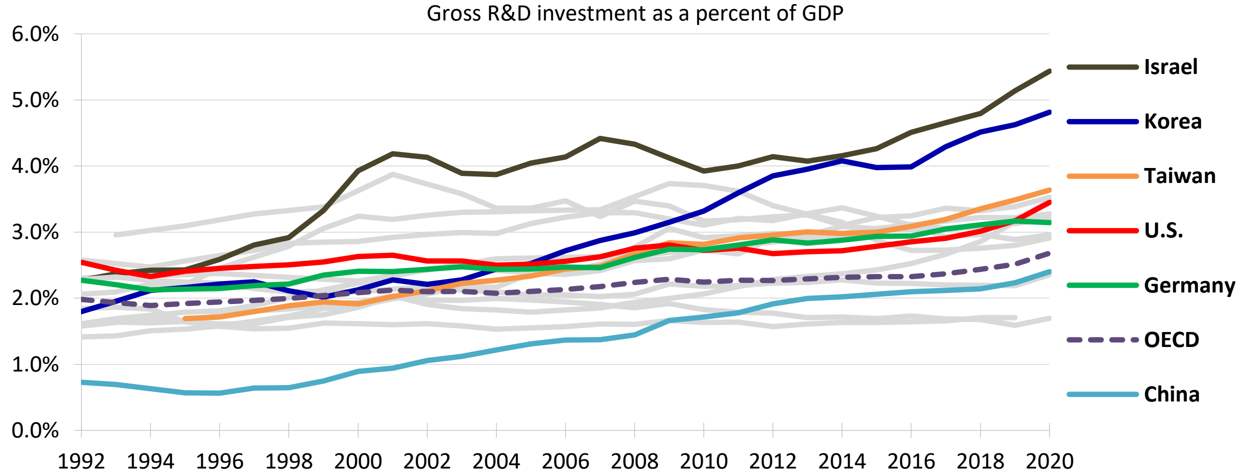
Some countries saw significant gains despite – or perhaps because of – the pandemic. In the E.U., Ireland saw a 6% increase in R&D spending. Under the "other world" category, Taiwan saw a 7% increase in science and Israel and South Korea continued their upward trajectory with a 3% increase each.

R&D Intensity: R&D intensity – or R&D as a share of gross domestic product – indicates the relative share of resources devoted to R&D in an economy, providing an indicator of its innovative capacity. For instance, Israel and Korea, the two countries with the most R&D-intensive economies, spend far less on R&D than the United States or China in absolute dollars, but those dollars account for a much larger share of their respective economies, indicating stronger relative focus on science and innovation.

The U.S. is now climbing its way back up the rankings after dropping out of the top 5 in the mid-1990s. As of 2020, the U.S. is 6th in R&D

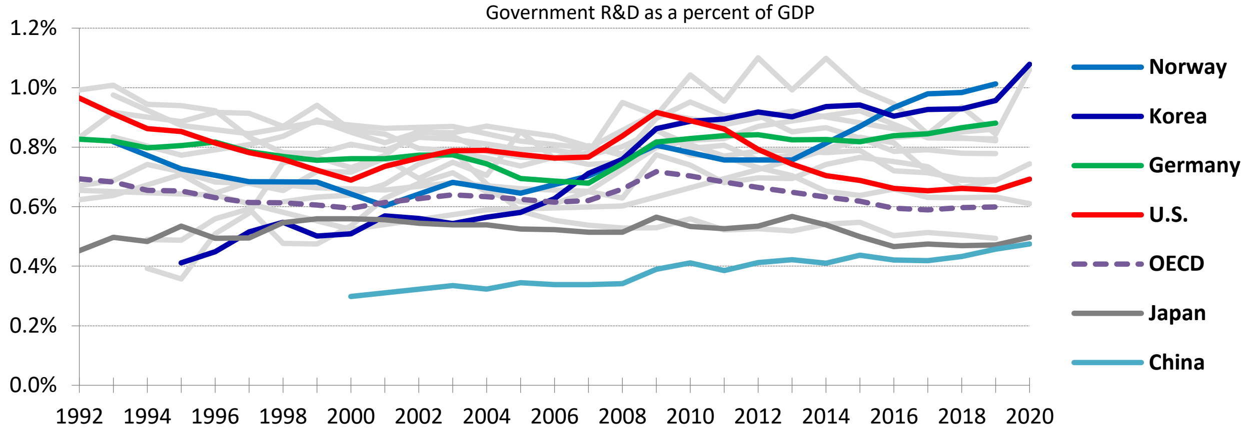
Figure 2.3: National R&D Intensity

Gross R&D investment as a percent of GDP



Source: OECD Main S&T Indicators, April 2022 | AAAS

Figure 2.4: Public R&D Intensity
Government R&D as a percent of GDP



Source: OECD Main S&T Indicators, April 2022 | AAAS

intensity. Israel, Korea, and Taiwan remain at the top, while the U.S. crept back ahead of Germany recently (Figure 2.3). China continues its dramatic upward climb, though it remains well under the 3% mark.

Note that GDP in several economies including the U.S. declined in 2020, which helped to artificially push up R&D intensity estimates. Does this mean U.S. progress is illusory? No: the U.S. also ranked 6th in 2019, the year before the pandemic.

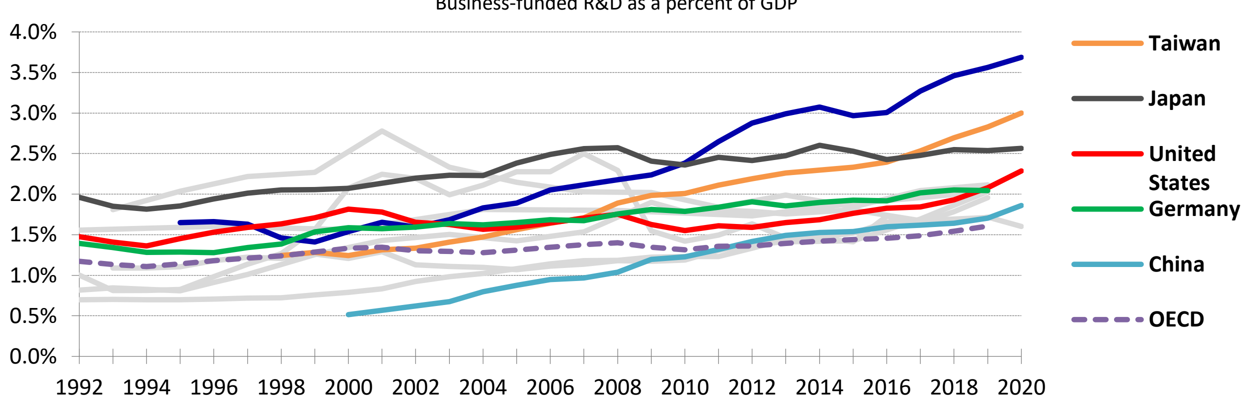
Public and Private R&D Intensity. The preceding section refers to combined R&D expenditure, but what is the picture when we disaggregate public and private R&D? Different economies can have very different compositions of R&D financing: for instance, the Japanese and Taiwanese R&D systems exhibit greater emphasis on R&D from private firms, while in Norway and France, government R&D plays a relatively larger role.

Focusing first on public R&D intensity, the U.S. has fallen in the leadership tables since the 1990s, ranking 13th as of 2019. Global leaders in this category include Norway, Germany, Korea, and Austria.

The U.S. decline appears to be a product of the extended federal R&D slowdown after the financial crisis and the enactment of the Budget Control Act of 2011,[5] though federal R&D spiked in 2020 in response to COVID-19.

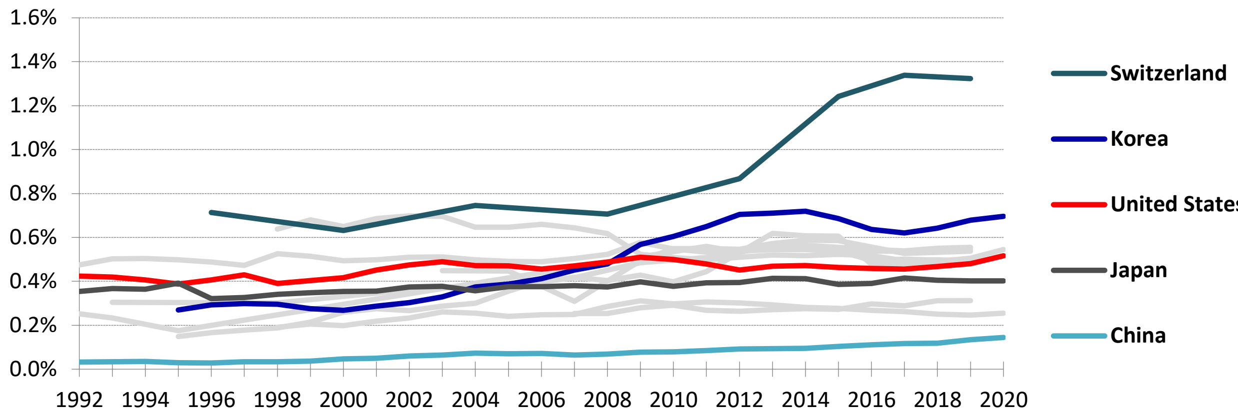
This apparent post-crisis slowdown was not uncommon across the OECD as a whole, as seen in Figure 1.2, but it seems to have been marginally more severe in the U.S. compared to several other economies (Figure 2.4). As mentioned in Section 1, it appears several high-income economies saw a public R&D surge in 2020, with a return to normal expected in 2021.

Figure 2.5: Private R&D Intensity
Business-funded R&D as a percent of GDP



Source: OECD Main S&T Indicators, April 2022 | AAAS

Figure 2.6 Basic Research Intensity
Reported basic research as a percent of GDP



Source: OECD Main S&T Indicators, April 2022 | AAAS

While public R&D investment has not been growing substantially, R&D from the private sector has been increasing. Business R&D remains a long-term relative U.S. strength, as well as continued primacy in the venture capital market.

As of 2019, the U.S. stood at 5th in the global rankings of private R&D intensity. While the U.S. has been on a recent rise, Korea, Japan and Taiwan have maintained their leads, and China has seen a four-fold increase in private R&D intensity in the last twenty years (Figure 2.5).

OECD data suggests the increase in private-sector R&D investment is not uniform across all fields. Between 2019 and 2020, investment increases were realized in software and computer services, and pharmaceutical and biotechnology companies. On the other hand, automotive and aerospace companies saw some reductions.[6]

Basic Science Intensity. In the same way that different economies feature differing mixes of funding sources, different economies can also exhibit tendency toward short-term investment – by focusing more on development spending – or longer-term investment through basic science. Basic science is inherently uncertain with unpredictable results, and the gap between initial investment and economic impact can amount to several years, if ever.[7] The tangible benefits from knowledge gains can also be difficult for individual investors to recoup due to knowledge spillovers. Yet the knowledge generated from basic science can also open the door to new commercial capabilities that are unavailable to more short-term R&D funders, with social returns far larger than private returns. For this reason, basic science has historically been more associated with public investment, while industrial R&D has historically focused marginally more on applied science and development.

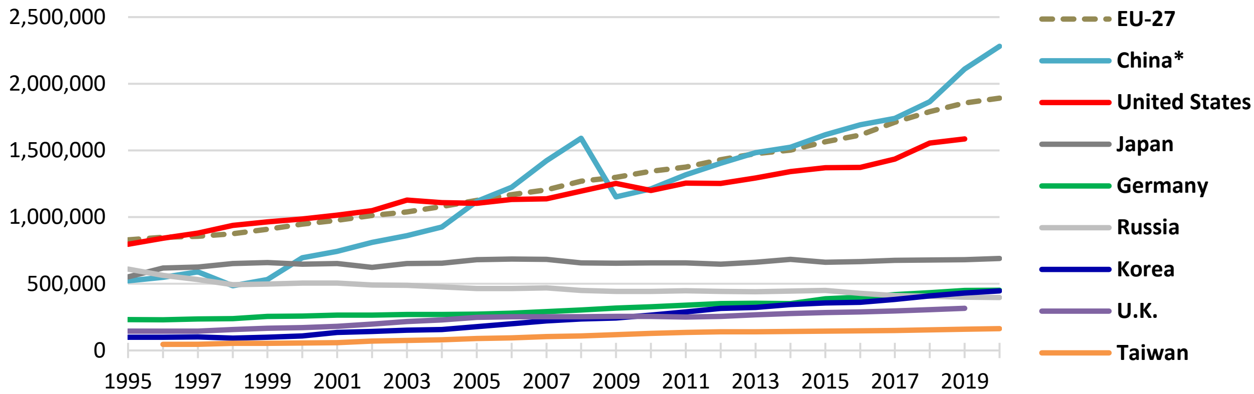
As of 2019, the U.S. ranked 10th in the world in basic science intensity, behind Korea, the United Kingdom, Denmark, and several others. Switzerland's status as the most basic science intensive economy in the world reflects the presence of several world-class research universities and institutions including CERN, home of the Large Hadron Collider.

In spite of the association of government investment with basic science, it appears U.S. basic science intensity has been relatively sustained in the face of recent public R&D declines. This suggests a greater share of basic research is being funded by industry, an observation borne out by domestic survey data.[8]

3. Research Workforce: China Pulls Further Ahead

An innovative economy requires not just investment in R&D, but a workforce capable of performing that R&D and exploiting the knowledge produced by it.

Figure 3.7: Total Researchers (FTE) by Country / Region



*Counting methodology changed in 2009. Source: OECD Main S&T Indicators, April 2022 | AAAS

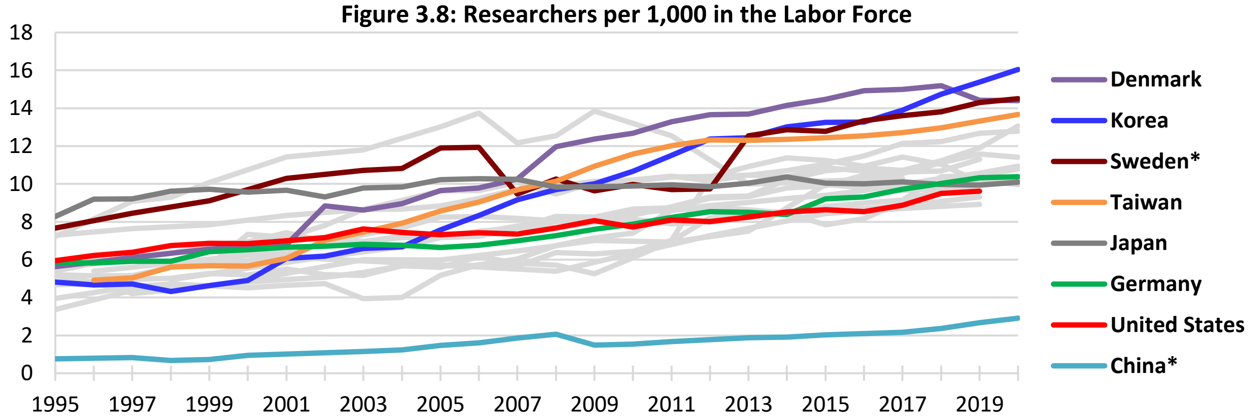
As measured by OECD, China's total headcount of full-time researchers has increased rapidly (including since 2009, when China's accounting definition of "researcher" was brought into accordance with OECD guidelines). The most recent data, covering up to 2020, indicates that there are now over two million fulltime-equivalent Chinese researchers, while U.S. researchers now number just above 1.5 million fulltime-equivalent (Figure 2.7).

Relatedly, China also continues to close the gap in science and engineering (S&E) doctoral degrees, though the United States continues to produce the greatest number. As of 2018 – the most recent year for which comparable data is available, as provided by the National Science Foundation (NSF) – the U.S. produced 41,071 S&E doctorates, while China produced 39,768. India is 3rd with 26,890 S&E doctorates.[9]

Notably, U.S. totals in researcher workforce and degrees may soon be impacted by a recent shift in the movement of foreign talent: for the first time in 20 years the United States may not be the world's top work destination.[10]

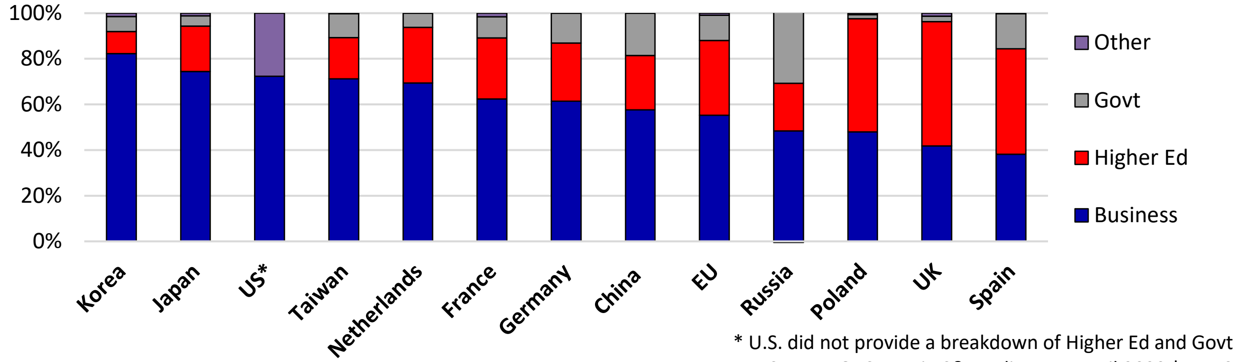
As with R&D, some of the U.S. dominance in the researcher workforce is partly thanks to economic scale. Figure 2.8 adjusts researcher workforce to account for total labor force, which makes clear the U.S. is much less researcher-intensive than several other economies. World leaders Denmark and Korea have over 50% more full-time research personnel per worker than the United States, which ranks 17th in the world and 15th in the OECD as of 2019. That year, the last for which the U.S. provided data, there were an estimated 9.6 U.S. researchers per thousand U.S. workers, as compared to Korea's 15.4. On the other hand, while China has made strides to increase its research workforce, it still has

Figure 3.8: Researchers per 1,000 in the Labor Force



*Includes changes in researcher headcount methodology in prior years.
AAAS analysis based on OECD and World Bank data, April 2022 | AAAS

Figure 3.9: Researchers by Sector
Calculated from 2019 FTE Equivalents



* U.S. did not provide a breakdown of Higher Ed and Govt
Source: OECD Main S&T Indicators, April 2022 | AAAS

substantial ground to make up compared with global leaders.

The researcher workforce varies across sectors for different economies (Figure 2.9). The U.S. joins Korea and Japan as major economies with particularly high proportions of researchers in the business sector.

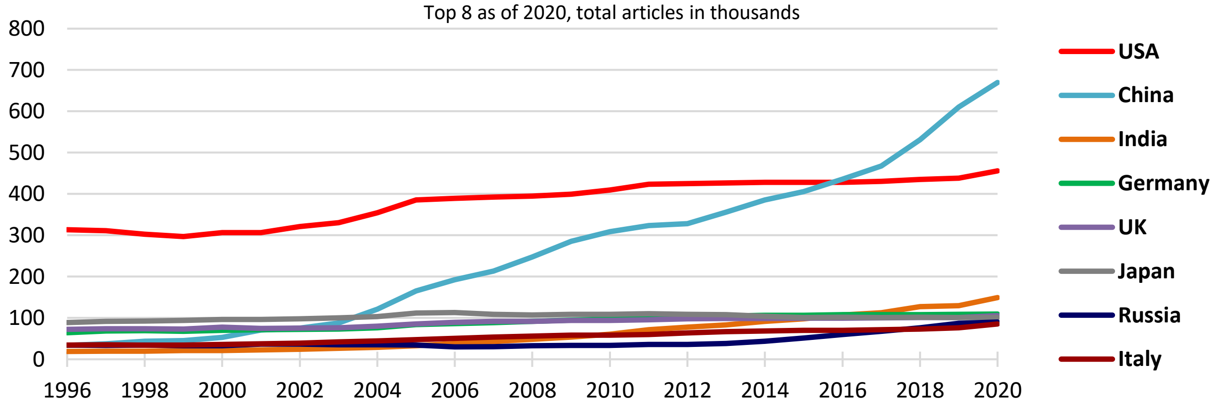
These distinctions are important when one considers the roles that each sector typicaly plays in the innovation lifecycle. For instance, while government and higher education researchers have historically partaken in a varied research portfolio including basic and applied research and development, business researchers tend to stay closer to developmental work, though there has been a recent increase in industrial basic science, as mentioned earlier. The sector mix might also suggest varying national capacity to generate new breakthroughs, to share and disseminate knowledge through norms of open science, or to translate new discoveries into societal application via commercial products, clinical treatments, and the like. Some countries have adapted policies and investment strategies to address the sectoral research balance, such as Japan's goal to establish a major fund for university research.[11]

4. Scientific Publications: U.S. Dominant in Life Sciences, Surpassed in Physical Sciences

One common measure of scientific output and performance is the publication of original peer-reviewed research articles in scientific journals. Such articles are the most common form of sharing new theories or experimental discoveries.

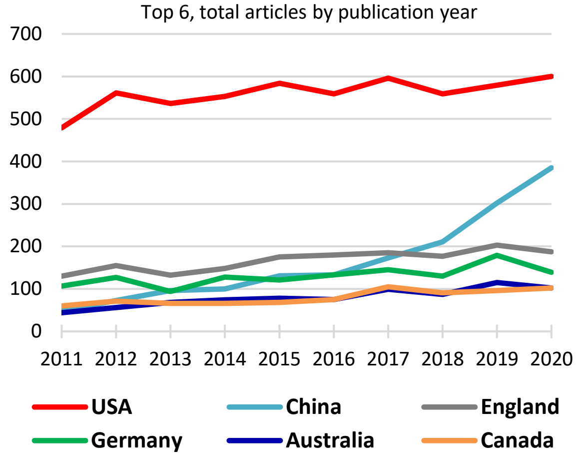
Total Publications. Figure 4.1 shows total science and engineering articles and conference proceedings from the top eight science-publishing countries. The underyling data is taken from NSF's 2021 indicators report on publications output, which in turn was based on data from Scopus, a leading database.[12]

Figure 4.1: Science & Engineering Publications
Top 8 as of 2020, total articles in thousands



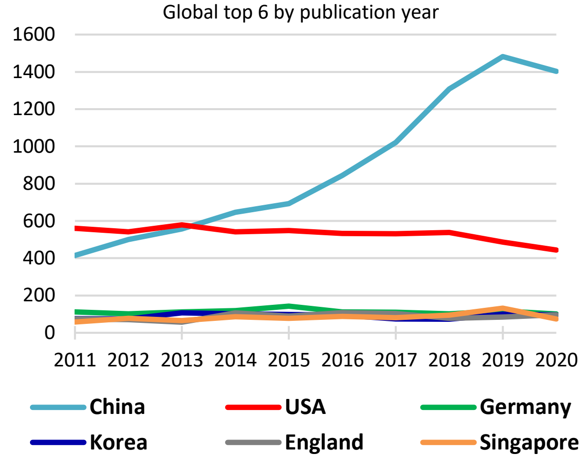
Based on data from NCSES Indicators, October 2021. | AAAS

Figure 4.2: Highly-Cited Biological Sciences Publications



Based on Web of Science data, accessed April 2022 | AAAS

Figure 4.3: Highly-Cited Chemistry Publications

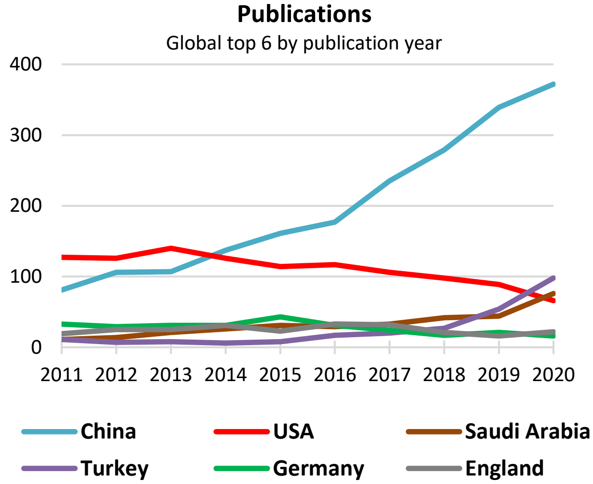


Based on Web of Science data, accessed April 2022 | AAAS

As with R&D, China's progress in publication output is quite striking, especially in light of the United States' dominance over other advanced economies. Chinese science and engineering publications have grown by more than 13% percent annually over this time. According to this data, China surpassed the U.S. in total publications in 2016 and shows no signs of slowing, with the total 2020 count near 700,000.

As can be seen, others lag substantially in raw count. India at #3 is an interesting case, as India's R&D intensity stood at less than 0.7% of GDP as of 2018, according to UNESCO data.[13] This puts it well behind other investment powerhouses like Germany and Korea, yet it seems to publish quite a bit more.

Figure 4.4: Highly-Cited Mathematics Publications



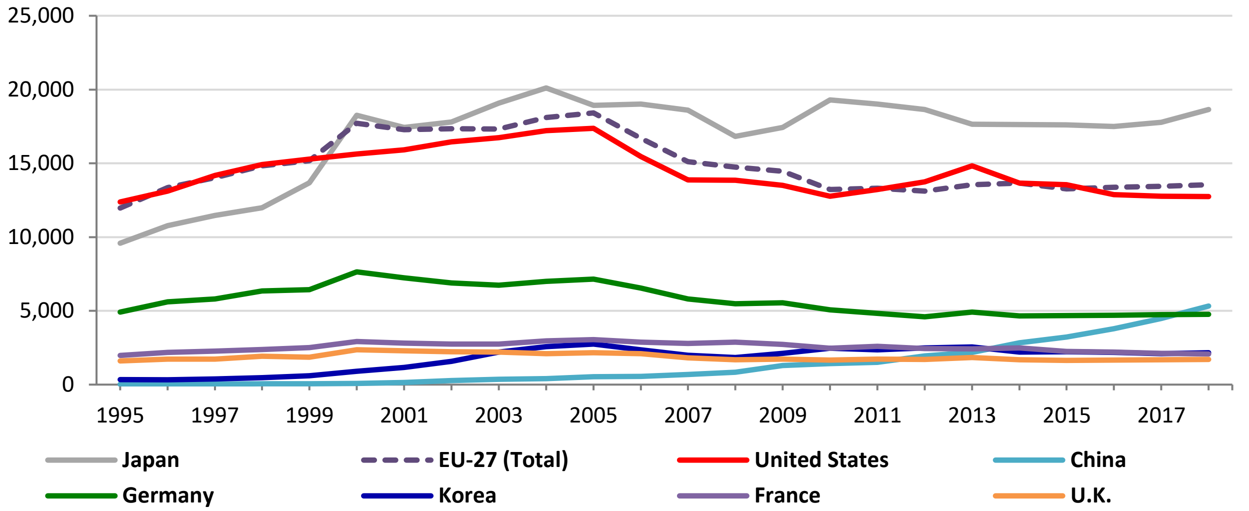
Based on Web of Science data, accessed April 2022 | AAAS

Influential Publications. Beyond raw numbers, NSF also reports estimates of highly-cited articles, referring to articles in the top 1% most-cited publications in each field that year.[14] Citations are not a perfect metric, but are often seen to be a proxy indicator of scientific impact or influence. As Wang and Barabasi (2021) write, studies of citations suggestion they "correlate positively with other measures of scientific impact or recognition, including awards, reputation, peer ratings, as well as the authors' own assessments of their scientific contributions."[15]

According to the NSF figures based again on Scopus, 1.8% of articles with U.S. authors are among the most highly-cited science and engineering articles globally. This is reasonably high in global terms, though it does rank the U.S. behind several high-income R&D funders including the U.K., Australia, and Italy, among others. China ranks well below at 1.2%, though as with other Chinese metrics this represents marked improvement from two decades ago.

However, when comparing highly-cited papers by scientific discipline, the picture becomes more interesting and nuanced. We present data on three (out of many) disciplines in Figure 4.2, 4.3, and 4.4. For these, we rely on direct data from

Figure 5.1: Triadic Patent Families



Source: OECD, Main Science and Technology Indicators, April 2022 | AAAS

the Web of Science, another authoritative database. Note that for these, articles are only ranked against others in the same discipline. That means that, for instance, chemistry papers are not ranked against materials science papers. Calculations are only available for the most recent ten years.

The basic picture that emerges is this: United States scientists remain highly influential in several fields. However, the highest relative influence is in the life sciences (as seen in Figure 4.2 covering biological disciplines). On the other hand, Chinese scientists have achieved far greater influence in the fields of physical science and engineering. This includes chemistry (4.3), where China surpassed the U.S. in highly-cited articles in 2014, and mathematics (4.4).

5. Patenting: Japan Maintains Lead While China Rises

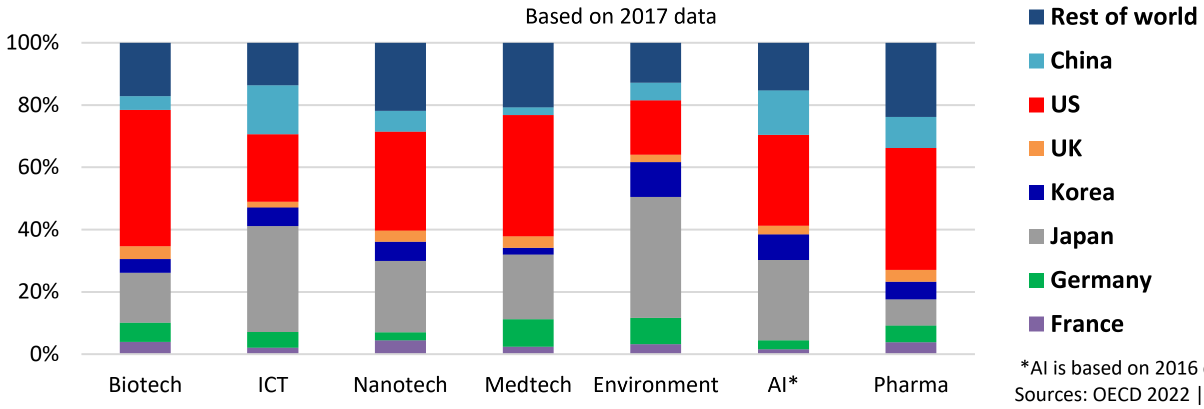
What about the ability for economies to take these inputs (resources and talent) and knowledge outputs (publications) and convert them into useful, commercial inventions with economic value? One metric to assess this performance is data on patents, which assign ownership of the intellectual property derived from new knowledge. This is not a perfect metric, to be sure, partly due to the preponderance of low-value patents. However, for international comparisons, one solution to the low-value problem may be use of "triadic" patents. Triadic patent families refer to patents for the same invention registered by the inventor in the patent offices in the U.S., Japan, and the European Union. These multilateral patent families tend to capture more economically valuable inventions, leaving out junk patents that may only be filed in the single patent office of the filer's home country.

The most recent available data on triadic patent families runs through 2018, and is shown in Figure 5.1. The basic story is this: Japan remains the largest producer of higher-value triadic patents – perhaps not surprising given the corporate orientation of their investments (Figure 2.5) researcher workforce (3.9) cited earlier. The United States remains at second, and the trends for these two countries and other prominent producers of triadic patents appear fairly stable. As with other metrics, the most notable and obvious development is the rise of China, with an enormous increase in triadic patent families since 2000 and a 6x increase just in the past decade, from 828 triadic patent families in 2008 to over 5,000 by 2018.

This data refers to total patent family counts. What about adjusting these data to account for varying sizes of the economy, as done with R&D

Figure 5.2: Triadic Patents by Topic

Based on 2017 data



*AI is based on 2016 data.
Sources: OECD 2022 | AAAS

in Section 2? The picture that emerges is very different: per billion dollars of GDP, Japan continues to dominate the charts at 3.7 triadic patent families, followed by Korea (1.25) and Germany (1.20) – all the highest IP-intensive economies. The U.S. rate of triadic patent family production has been declining, down to 0.61 in 2018, which is also below France and Taiwan. China, on the other hand, has seen a marked increase in its triadic patent/GDP intensity, from 0.23 families per $1 billion in 2013 to 0.38 per $1 billion in 2018.

There is some interesting variation in patent performance by sector as well. While Japanese inventors produce more triadic patents than their American counterparts overall, in 2017 U.S. inventors accounted for the majority of triadic patent families in the biomedical fields, and narrowly beat out Japan in AI-related technologies. In turn, Japan led in information and communication technologies (ICT) and environmental technologies (Figure 5.2).

6. Conclusion

What takeaways can be drawn from the above metrics?

One obvious point is that the U.S. remains in a dominant position, party due to scale of the domestic economy. The U.S. is first or second in total R&D expenditures, scientific publications, researcher count, and triadic patents.

But U.S. performance is somewhat less dominant when adjusted for scale: for instance, the U.S. is currently 6th in R&D intensity, 10th in basic science intensity, and 17th in researchers relative to the overall labor force. The R&D intensity ranking does represent a recent improvement thanks to industrial investment, but public R&D relative to the economy remains stagnant. Such stagnation is not uncommon across high-income economies, but it has been worse in the U.S.

At the same time, competition from others continues in both scale and intensity, especially from China, which has seen a 20-year R&D growth four times that of the U.S., and which now accounts for over 80% of non-OECD R&D. Other economies continue to invest as well, with Korea, Germany, Taiwan, and others achieving high rankings in R&D and researcher intensity.

The U.S. also appears to be effective at turning resources into ideas and commercial inventions. However, the challenge from China to U.S. science and innovation preeminence appears particularly acute. In terms of scientific advances, China has well surpassed U.S. influence in the physical sciences and engineering fields, and is gaining in the life sciences, an area of traditional U.S. dominance. China is also now third globally in higher-value triadic patents, a dramatic improvement from earlier performance.

Ultimately, the U.S. is not in a poor position – far from it. But if U.S. science and technology leadership is to be maintained, policymakers must take a proactive approach to investment policy.

[1] Main Science and Technology Indicators. (2022, March). OECD. https://www.oecd.org/sti/msti.htm

[2] OECD (2022). "OECD Main Science and Technology Indicators. R&D Highlights in the March 2022 Publication", OECD Directorate for Science, Technology and Innovation. http://www.oecd.org/sti/msti2022.pdf

[3] Bianchi, F., Dama, E., Di Nicolantonio, F., Baldassarre, G., Guerriero, I., Torchiaro, E., Bruno, A., Blandino, G., Allavena, P., Chiarugi, P., Sozzi, G., D'Incalci, M., & Normanno, N. (2021). COVID-19 epidemic strongly affected cancer research in Italy: a survey of the Italian Cancer Society (SIC). *ESMO open*, *6*(3), 100165. https://doi.org/10.1016/j.esmoop.2021.100165

[4] Gibney, E. (2021, January 5). *What the landmark Brexit deal means for science*. Nature. https://www.nature.com/articles/d41586-021-00009-y

[5] Hourihan, M. (2021, January 19). *The Budget Control Act May Have Cost Over $200 Billion in Federal R&D*. American Association for the Advancement of Science. https://www.aaas.org/news/budget-control-act-may-have-cost-over-200-billion-federal-rd

[6] OECD (2022).

[7] For instance, Ahmadpoor and Jones (2017) found that the impact lag can reach two decades for more abstract fields of knowledge like pure mathematics. See Ahmadpoor, M., & Jones, B. F. (2017). The dual frontier: Patented inventions and prior scientific advance. *Science*, *357*(6351), 583–587. https://doi.org/10.1126/science.aam9527

[8] Federal R&D Budget Dashboard, American Association for the Advancement of Science. https://www.aaas.org/programs/r-d-budget-and-policy/federal-rd-budget-dashboard

[9] National Science Board, National Science Foundation. 2022. Higher Education in Science and Engineering. Science and Engineering Indicators 2022. NSB-2022-3. Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20223/.

[10] *Decoding Global Talent, Onsite and Virtual*. (2021, March). Boston Consulting Group. https://www.bcg.com/publications/2021/virtual-mobility-in-the-global-workforce

[11] Kajimoto, T. (2021, November 8). *Japan unveils $88 bln university fund in growth strategy*. Reuters. https://www.reuters.com/world/asia-pacific/japan-panel-urges-govt-launch-88-bln-university-fund-2021-11-08/

[12] National Science Board, National Science Foundation. 2021. Publications Output: U.S. and International Comparisons. *Science and Engineering Indicators 2022*. NSB-2021-4. Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20214/.

[13] UNESCO Institute for Statistics, data as of September 2021, accessed via World Bank: https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?locations=IN

[14] National Science Board, National Science Foundation. 2021. Publications Output: U.S. and International Comparisons. *Science and Engineering Indicators 2022*. NSB-2021-4. Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20214/.

[15] Wang, D., & Barabási, A. (2021). *The Science of Science.* Cambridge: Cambridge University Press.