June 2021

Research Security, Collaboration, and the Changing Map of Global R&D

CSET Policy Brief

CENTER for SECURITY and EMERGING TECHNOLOGY

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Executive Summary

The global map of research has shifted dramatically over the last 20 years. Annual global investment in research and development has tripled and the United States' share of global R&D funding and total research output is diminishing. The open research system, with its expanding rates of investment and interconnectedness, has delivered tremendous benefits to many nations, but it has also created new challenges to research integrity and security.

Our data shows significant variations across countries in how much, and in what ways, they rely on their collaborative links to the global research network. A more nuanced understanding of those differences is critical for assessing the unique cost/benefit calculations behind decisions to limit open engagement to address security concerns.

Takeaways:

- The United States has lost its leadership position in the scientific literature across many research fields, not only to China, but also to the European Union, over the last 20 years.
- Traditional U.S. partners, and particularly the Five Eyes countries (including the United Kingdom, Australia, and Canada) have significantly increased international research collaboration over the last 20 years, while China's level of international collaboration has remained essentially flat.
- Strategies requiring U.S. allies to "decouple" from China in key fields of R&D will potentially hurt Five Eyes partners far more than either the United States or the European Union.
- Collaboration levels vary significantly by both country and research field, so strategies for research security will need to be fit-for-purpose. A one-size-fits-all approach to research security and international collaboration will not be effective.
- New strategies are needed for the United States to assess and leverage new knowledge produced in other parts of the global research system for its economic and national security. These new strategies should be grounded in up-to-date information about the dynamic map of global research.

Introduction

The global R&D system has undergone significant changes in just 20 years, with total global R&D investment tripling since 2000 to over $2.2 trillion per annum. The distribution of global R&D investment has also shifted—in 1960, U.S. R&D accounted for almost 70 percent of the global total, by 1995 it was down to around 40 percent, and today it is close to 25 percent. Simultaneously, China's R&D has grown to an almost equivalent level. The rest of the world now accounts for half of global R&D, over $1 trillion spread among a heterogenous group of countries.[1]

While funding for R&D is important, it is just one input. This paper uses bibliometric data—data on research publications—to provide an alternative, output-based perspective on change over the last 20 years. Bibliometric data provides a means of examining change over time in the global production of new knowledge, leadership in key fields of research, and rates and patterns of international collaboration among researchers.

Total research output globally has seen impressively steady growth since World War II, growing at an annual rate of approximately 8-9 percent, representing a doubling of scientific literature every nine years.[2] Changes in the distribution of global R&D investment have led to shifts in the production of knowledge and subsequently to shifts in global leadership in specific fields of research. There are common discussions in science policy communities about the rise of international research collaboration, and while this is true in the aggregate, we see a significant amount of variation by country.[3] The bibliometric data shows that while Australia, the European Union, and the United States have all grown significantly more collaborative over the last 20 years, China's level of collaboration over the same period is relatively flat.

Why does this matter? Growth and change in the global research system can bring significant benefits for countries (including access to a larger pool of ideas, talent, and technologies), but there is also increasing awareness of significant new research security risks arising from the global research system, including foreign interference, the theft of intellectual property, and the use of R&D

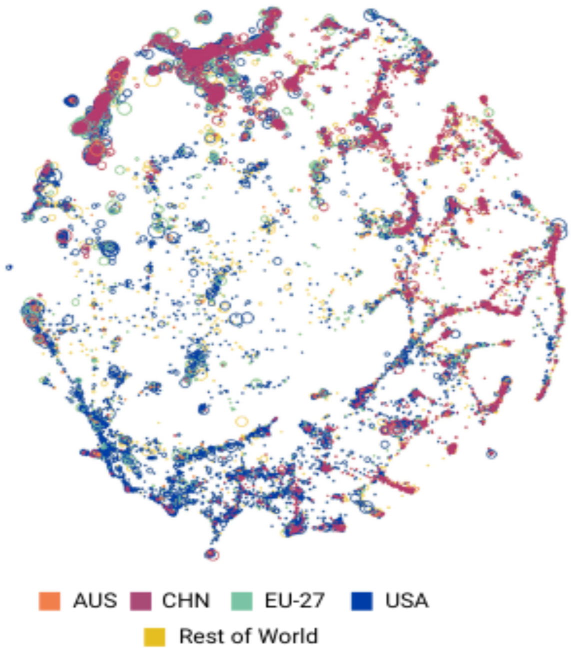
to advance authoritarian goals. An effective response to these security risks in international research collaboration will require an up-to-date and nuanced understanding of the changing global research system.

The world of research is not monolithic. R&D analysis often tends to focus on inputs at an aggregate national level, but this policy brief shows that there is significant variation in patterns of growth and collaboration across countries and also across different fields of research. The map of global research is irrevocably changed—no one country will dominate all fields of research in the twenty-first century in the way that the United States did for much of the twentieth century. Governments, academic and industrial research organizations, and individual researchers are faced with increasingly complicated assessments about the benefits and risks of international collaboration in a dynamic environment. Our data shows that a one-size-fits-all approach is likely to do more harm than good. New strategies will require a more detailed evidence base to support more nuanced decision-making.

Mapping global research

The conversation around global leadership is often framed as a bilateral discussion of the United States losing ground to China over the last 20 years, but when we look at the scientific publication data, we see a more complex picture. We analyze research publications from the Scopus database via a clustering model that groups publications based on their direct citation links.[4] Figure 1 displays the map of global research, where each dot represents a research cluster of publications and each cluster is colored by the country with the most publications.

Figure 1. Map of global research: Scopus 1999–2019



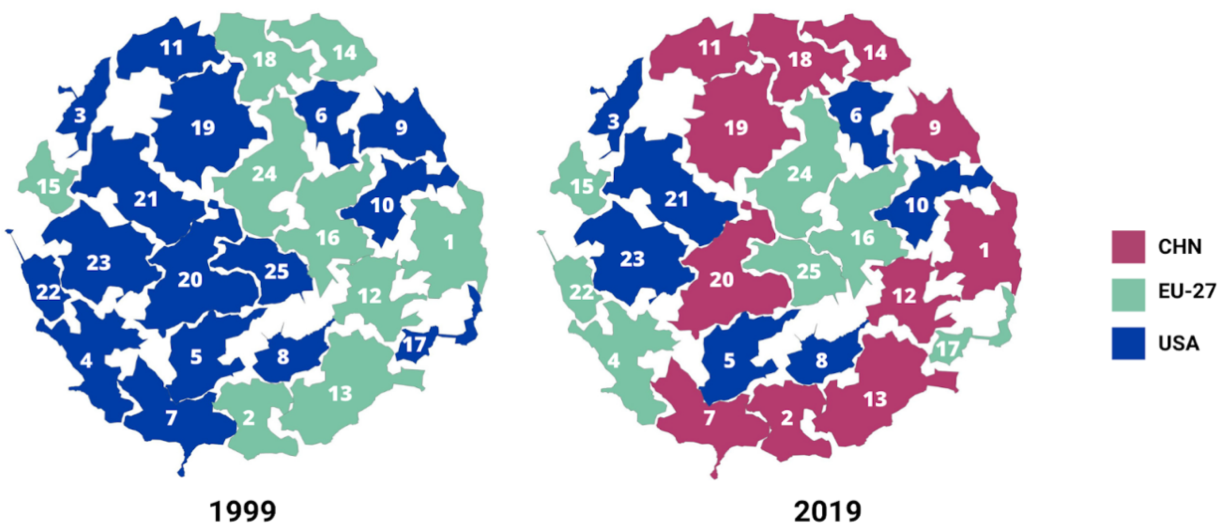
Source: Scopus.

In order to understand research publication output more generally, we use hierarchical clustering to aggregate clusters into broader regions of research as shown in Figure 2 (see Appendix for more details on the regions in Figure 2). We display two snapshots of the region-level map of global research, one in 1999 and one in 2019, to show the changes in publication output by country over this time period. Each region is labeled by taking the most common phrases from the journal titles where papers in the region are published.

China has clearly had a significant rise in productivity. As seen in Figure 2 below, it is also clear that the United States has lost its dominant global position overall. But the European Union also remains an important bloc in global research. We focus here on the European Union, rather than on individual European countries, because the European Union countries can take a coordinated policy approach and adopt a coordinated research funding strategy.

We observe a shifting of leadership in some areas from the European Union to China (e.g., physics/space physics, immunology and oncology, and automation and electrical engineering, etc.) but also from the United States to the European Union (e.g., condensed matter physics/chemistry, psychiatry/psychology, education, and history/culture/philosophy). This more nuanced picture creates interesting opportunities to assess specific technical areas of competition and potential alliances between the United States and the European Union. With further analyses, it would also be possible to map current policy priorities and investments against shifts in the global research landscape.

Figure 2. Global leadership by publication output in 1999 and 2019



1: Condensed Matter, Chemistry, Physics **2:** Cancer, Immunology, Oncology **3:** Statistics, Information, Computer
4: Psychiatry, Psychology, Surgery **5:** AIDS, Infectious Diseases, Public Health **6:** Mechanical Engineers, Engineering, Heat
7: Cardiology, Ophthalmology, Obstetrics **8:** Infectious Diseases, Neuroscience, Infection **9:** Materials Science, Materials, Engineering
10: Applied Physics, Engineering, Materials **11:** Signal Processing, Pattern Recognition, Computer Vision
12: Ecology, Evolution, Biological Sciences **13:** Biotechnology, Food Science, Food Chemistry **14:** Physics, Space Physics, Cosmology
15: Management, Finance, Economics **16:** Biogeosciences, Oceans, Space Physics **17:** Chemistry, Organic Chemistry, Biochemistry
18: Automation, Electrical Engineering, Decision **19:** Engineering, Management, Industrial Engineering **20:** Philosophy, History, Politics
21: Economics, Law, Management **22:** Education, Higher Education, Learning **23:** Education, Law, Psychology
24: Environment, Energy, Management **25:** History, Culture, Philosophy

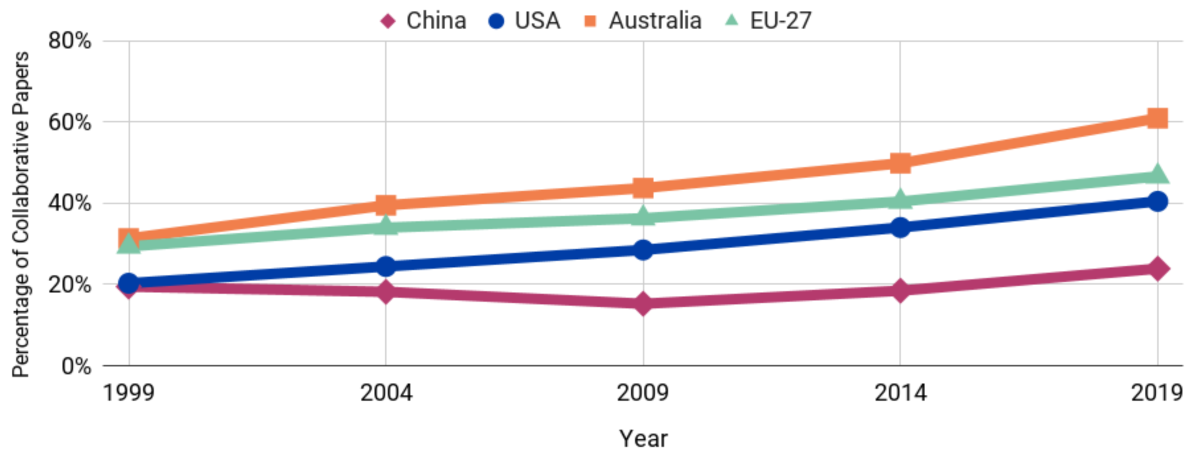
Source: Scopus.

Understanding patterns of international collaboration

As global research output has grown and globalized, patterns of international collaboration in research have changed significantly, and in many cases have allowed countries to tap into a much larger pool of ideas, talent, infrastructure, and technologies. Countries demonstrate different rates of international collaboration, reflecting different strategies or cultures for maximizing the effectiveness of their own domestic investments in R&D. But this international connectedness now raises new concerns about research security and foreign interference.

We focus on China, the European Union, and the United States to show trends and patterns across the major global research actors, and on Australia to highlight differences for a smaller country that has high levels of international collaboration with the major powers (see Figure 3 below). In this paper, we define international collaboration using the country assignments from the addresses of author affiliation organizations, exclusively considering international collaboration on publications (i.e., a publication with authors belonging to organizations in the same country is not considered here). International collaboration rates are calculated as the number of papers with more than one author affiliation organization country, divided by total number of papers for each country respectively. We use Scopus data[5] from 1999 to 2019, and we label the aggregation of the 27 European Union countries as EU-27.[6] Overall, we see that all analyzed countries have become more collaborative over time, but some countries show significant growth in rates of international collaboration (Australia) while others (China) have hardly grown at all over that period, despite massive increases in investment and output.

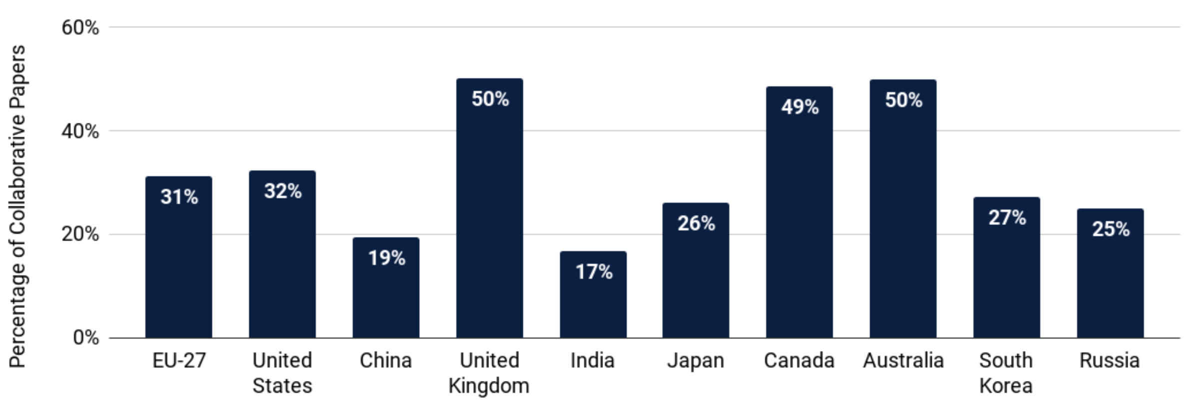
Figure 3. Percentage of collaborative papers by country over a 20-year period



Source: Scopus.

We look more closely at the top research producing countries/blocs in Figure 4, which displays the percentage of collaborative papers out of the total number of research publications for each top producing country/bloc. Figure 4 shows that the three countries with the highest levels of international research collaboration are the United Kingdom, Australia, and Canada, which are predominantly English-speaking U.S. allies. All have benefited greatly from an increasingly internationalized research system and have been able to leverage benefits far beyond their size from higher levels of global integration.

Figure 4. Variable rates of international collaboration across top 10 research producing countries/regions (1999–2019)

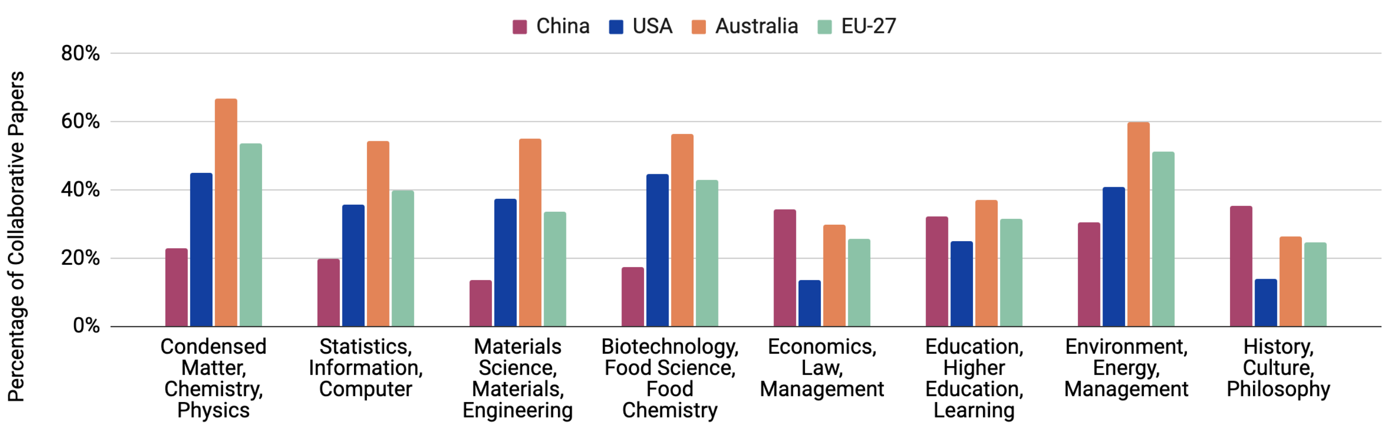


Source: Scopus.

Despite its rapid growth over the last 20 years, China has a much lower rate of international collaboration. This could be explained in two ways—either it is still growing, and its rate of collaboration might be expected to continue to rise in the future, or it has a deliberate strategy to limit collaboration in certain areas or until it has achieved a strong international position. Further analysis using this data would support more detailed assessments for specific countries and specific fields of research. To give one example: in some research fields where the United States retains a global lead (e.g., computer science/statistics), China's rate of collaboration is lower than its overall average, but in other fields (e.g., infectious diseases/public health), China's rate of collaboration is higher than average. Further analyses using this data could also compare China's rise and strategy to that of other leading countries over time, such as Germany, Japan, and the United States.

It is also important to note that rates of international collaboration vary significantly by field of research, as well as by country. In Figure 5, we display a sample of research regions spanning STEM disciplines and the humanities/social sciences. This demonstrates that nations may have different strengths and strategies for different fields of research. For example, China collaborates more in the humanities and social sciences, while the United States and Australia collaborate more in the physical sciences.

Figure 5. Rates of collaboration by research region and by country (1999–2019)

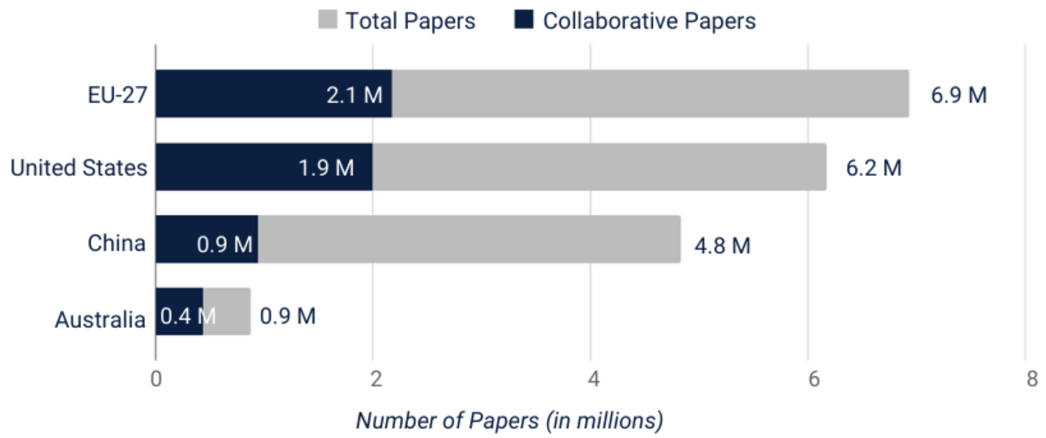


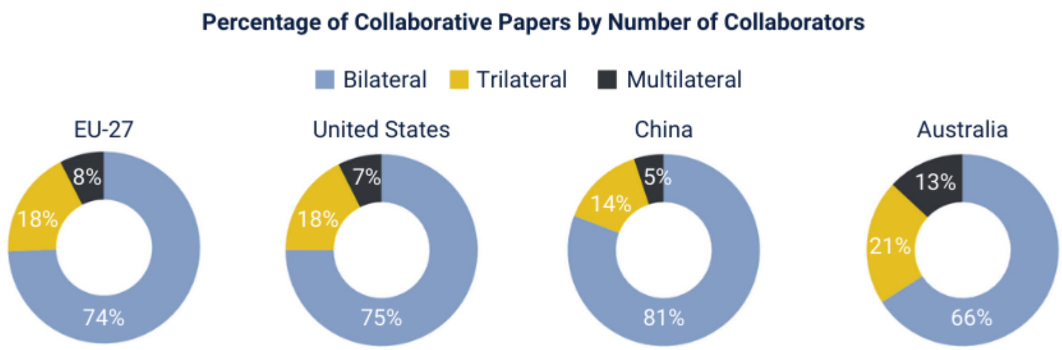
Source: Scopus.

The collaborative research discussed above includes not only bilateral cooperation, but also trilateral and multilateral cooperation (defined here as four or more nations). Figure 6 displays the country-level details on total papers versus collaborative papers, as well as a breakdown of how many different countries (by organization) were present as collaborators on a paper. Some countries (such as Australia) have much higher levels of multilateral collaboration than larger countries, suggesting a more networked engagement with global research. Australia has more multilateral collaboration in some fields of research (computer science/stats, engineering, applied physics, space physics, ocean and biogeosciences and environment/energy) than trilateral collaboration. By contrast, this is not true for the United States in any field of research.

Further analyses using this data could also help to differentiate between different modes of international collaboration—for example, collaboration centered around a major piece of international research infrastructure as distinct from researcher-driven collaboration. It could also map existing patterns of international research collaboration against significant alliances and networks, such as NATO and the Quad.

Figure 6. Share of collaborative papers and number of collaborators by country





Source: Scopus.

Implications for policy and strategy

The reality of shifting leadership in research plays out in a world where the annual global investment in R&D has more than tripled since 2000 and the United States' share of global R&D funding as well as its dominance of research output are diminishing. The open research system, with its expanding rates of investment and interconnectedness, has opened up tremendous benefits to many nations by expanding the pool of ideas, talent, and technologies that they can draw upon to innovate. But with a number of countries eschewing the post-World War II norms of that global research system, it is also being manipulated through means such as foreign interference, theft of intellectual property, and breaches of research integrity.

Our data on global research publications shows significant variation across countries in how much, and in what ways, they rely on their links to the global research network, and those levels of reliance will be critical in understanding the unique cost/benefit calculations behind any decisions to limit open engagement to address these new security concerns. The world of research is not monolithic, and a one-size-fits-all approach to research security and international collaboration will not be effective—and is likely to be counterproductive.

Governments, academic and industrial research organizations, private laboratories, and individual researchers are all faced with increasingly complicated assessments about the benefits and risks of open international collaboration in a dynamic environment. These assessments are not only specific to the mission of the organization in question (for example, companies and national laboratories may need to enforce tighter restrictions than open university campuses), but also the field of research and the partner organization/country in question. New strategies will require a more detailed evidence base to support this more nuanced decision-making.

We believe that a more detailed examination of this changing map of global research can help in addressing important questions such as:

- How is global leadership changing in key areas?
    - In light of this change, does the United States have an up-to-date plan for where it needs to lead, follow, and watch? And is the United States investing domestically in the corresponding areas?
- Where does international collaboration really matter? And where are the greatest risks?
- Where is the United States collaborating with the wrong partners?
- Where should the United States lean in and drive closer collaboration with allies and like-minded partners in areas of mutual priority?

- What are the potential implications for U.S. partners if the United States pursues a “decoupling” between itself and China in key areas of R&D?

In response to concerns about research security and the use of R&D by authoritarian regimes, there is a desire among democratic countries to strengthen collaboration in key areas of research and technology and reduce collaboration in others. While strengthening partnerships among like-minded countries will be valuable, it is critical to understand that the cost of pulling back from certain kinds of international collaboration will potentially be much greater for allies than for the United States, particularly within the Five Eyes community.

As the United States continues to develop R&D strategies at the national level, alliances cannot simply be taken for granted. The assumption that closer collaboration among a group of like-minded countries will be able to replace existing patterns of international collaboration with a much broader set of partners ignores the complex map of global research and the strategies of U.S. partners. Allies should prioritize working together to develop the evidence base to better understand the bilateral and multilateral reality of current entanglements between nations and develop specific strategies to mitigate the costs of any decoupling. Approaches might include building new firewalls and better leveraging national laboratory systems for research that—for national security reasons—must be kept within a more contained development space.

As the United States government reflects on changes in the global research system and its diminishing leadership in many fields, it will require new strategies for working with other nations and leveraging the open system for the good of the United States.[7] This is not a skill the United States has had to exercise for many decades and will require targeted prioritization of where the nation will be able to lead, informed by realistic assessment of the global research landscape. In some fields of research, the United States will have to let others lead, but in other specific areas, it may decide to invest to retake the lead.

This requires a true open source analysis capability that integrates domestic and international knowledge and technical status. This cannot be tied solely to the intelligence community and must engage stakeholders outside of the federal government including industry and academia. Beyond prioritization, this capability would allow the rapid identification of international knowledge and technology of most value to U.S. economic and national security.

This challenge will also require clarity about the desired outcomes that can be delivered through advances in research, science, and technology. One approach for developing new, fit-for-purpose strategies for collaboration is to incorporate frameworks that assess new technologies and their impact on both allied and adversarial goals.[8] It would then be possible to map the clustered research literature to selected technology areas and integrate this knowledge into relevant strategies for desired strategic outcomes.

These are new ways of working that all countries will need to develop in order to leverage maximum benefit from the changed global research system.

Appendix

Details on the regions that make up the research clusters used in Figures 1 and 2.

Table 1.

Region ID	Region Description	Num. of RCs	Num. of Papers
1	Condensed Matter, Chemistry, Physics	5,145	1,430,622
2	Cancer, Immunology, Oncology	3,818	903,664
3	Statistics, Information, Computer	3,283	1,988,232
4	Psychiatry, Psychology, Surgery	4,736	1,346,968
5	AIDS, Infectious Diseases, Public Health	2,537	1,423,553
6	Mechanical Engineers, Engineering, Heat	2,891	1,161,812
7	Cardiology, Ophthalmology, Obstetrics	4,222	1,053,957
8	Infectious Diseases, Neuroscience, Infection	2,543	747,056
9	Materials Science, Materials, Engineering	3,917	1,099,793
10	Applied Physics, Engineering, Materials	2,477	1,392,890
11	Signal Processing, Pattern Recognition, Computer Vision	2,832	948,000
12	Ecology, Evolution, Biological Sciences	3,816	814,582
13	Biotechnology, Food Science, Food Chemistry	4,689	507,998
14	Physics, Space Physics, Cosmology	3,263	1,611,170
15	Management, Finance, Economics	2,380	1,402,619
16	Biogeosciences, Oceans, Space Physics	4,025	915,110
17	Chemistry, Organic Chemistry, Biochemistry	2,397	545,518
18	Automation, Electrical Engineering, Decision	2,833	647,745
19	Engineering, Management, Industrial Engineering	3,611	900,810
20	Philosophy, History, Politics	3,324	516,023
21	Economics, Law, Management	3,369	298,002
22	Education, Higher Education, Learning	2,465	218,803
23	Education, Law, Psychology	1,830	405,520
24	Environment, Energy, Management	2,882	254,161
25	History, Culture, Philosophy	2,093	163,014

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Acknowledgments

For significant support in the data analysis and science mapping visualizations, we would like to thank Richard Klavans, Kevin Boyack, and Caleb Smith. For feedback and assistance, we would like to thank Caroline Wagner, Andrew Hebbeler, Dewey Murdick, Catherine Aikens, Alex Friedland, Andrew Imbrie, Igor Mikolic-Torreira, Shelton Fitch, and Lynne Weil.

Document Identifier: doi: 10.51593/20210004

Endnotes

[1] Beethika Khan, Carol Robbins, and Abigail Okrent, "The State of U.S. Science and Engineering 2020" (National Science Foundation | National Science Board, January 15, 2020), https://ncses.nsf.gov/pubs/nsb20201.

[2] Lutz Bornmann and Rüdiger Mutz, "Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references," *Journal of the Association for Information Science and Technology* 66, no. 11 (November 2015): 2215-2222.

[3] Caroline S. Wagner, Travis A. Whetsell, and Loet Leydesdorff, "Growth of international collaboration in science: revisiting six specialties," *Scientometrics* 110 (2017): 1633–1652.

[4] We use the research cluster model presented in Richard Klavans, Kevin W. Boyack, and Dewey A. Murdick, "A novel approach to predicting exceptional growth in research," *PLOS ONE* 15, no. 9 (September 2020), which clusters scientific publications based on direct citation links.

[5] We use SCOPUS data because of its reliable clean and structured format, as well as having a research clustering generated from its publications. In future work, we plan to conduct similar analyses using CSET's merged scholarly literature dataset.

[6] For the EU-27 collaboration publications, we treat the aggregate EU-27 as a single entity and do not consider intra-EU collaboration. The United Kingdom is not included in the EU-27.

[7] Caroline S. Wagner, "The Shifting Landscape of Science," *Issues in Science and Technology* 28, no. 1 (2011), https://issues.org/wagner/.

[8] Margarita Konaev, Husanjot Chahal, Ryan Fedasiuk, Tina Huang, and Ilya Rahkovsky, "U.S. Military Investments in Autonomy and AI: Costs, Benefits, and Strategic Effects" (Center for Security and Emerging Technology, October 2020), https://doi.org/10.51593/20190044.