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Superconductor Electronics Research

National Competitiveness and Funding Activity

CSET Data Brief

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Introduction

Superconductor electronics (SCE) research could advance a range of commercial and defense priorities, with potential applications for supercomputing, artificial intelligence, sensors, signal processing, and quantum computing.[1] Unlike traditional semiconductor materials, superconductors have zero electrical resistance. This allows processors to move bits without any dissipation of energy, resulting in much lower energy consumption than standard electronics. For now, many technical hurdles remain before SCE achieves commercial viability, and the field as a whole remains relatively small, with around 100 papers published globally per year. But several countries, particularly the United States and Japan, have recognized the promise of superconductor electronics and have funded research in this space for many years (see Table 1 later in this brief).

This brief identifies the countries most actively contributing to superconductor electronics research and assesses their relative competitiveness in terms of both research output and funding. To do so, it leverages CSET's Map of Science, a database that has grouped most of the world's publicly available academic publications into clusters based on citations. After identifying the research clusters most closely associated with SCE-related research, the brief offers country-by-country breakdowns of research productivity and funding data across the two primary SCE-related clusters. Details of this methodology can be found in the next section.

The analysis yields two key findings:

1. **The United States and Japan collectively account for a large majority of output in SCE-related research.** China produces a growing amount of SCE-related research, while the European Union produces a declining amount. The United States is especially dominant in highly-cited SCE-related research.

2. **The United States and Japan also have highly active government funding programs related to SCE.** The United

States and Japan not only produce the most SCE-related research, they also have government funding agencies that promote SCE-related programs. In particular, the United States' global leadership in SCE-related research since 2016 may be related to the activity of the Intelligence Advanced Research Projects Activity's (IARPA) Cryogenic Computing Complexity program, which began in 2014.[2]

These results suggest that government investments in SCE-related research and other emerging hardware paradigms will be an important lever for ensuring the continued competitiveness of the United States and its allies. This is important because skepticism about the U.S. government's ability to promote domestic microelectronics innovation has had negative consequences for American competitiveness in the semiconductor industry in the past.[3] The results also suggest that while the United States and its allies are currently well-positioned to lead in SCE-related research and subsequent commercialization, this could change quickly if China continues to ramp up investment in SCE.

Of course, success in basic research may not equate to subsequent commercial success. If SCE displaces traditional semiconductor technologies for some applications, this could send ripples throughout hardware supply chains, perhaps eroding the dominance of the United States and its allies in the current supply chain.[4] Nevertheless, this brief suggests that allied cooperation and sustained government funding may influence when and where superconducting electronics and other emerging hardware paradigms are developed.

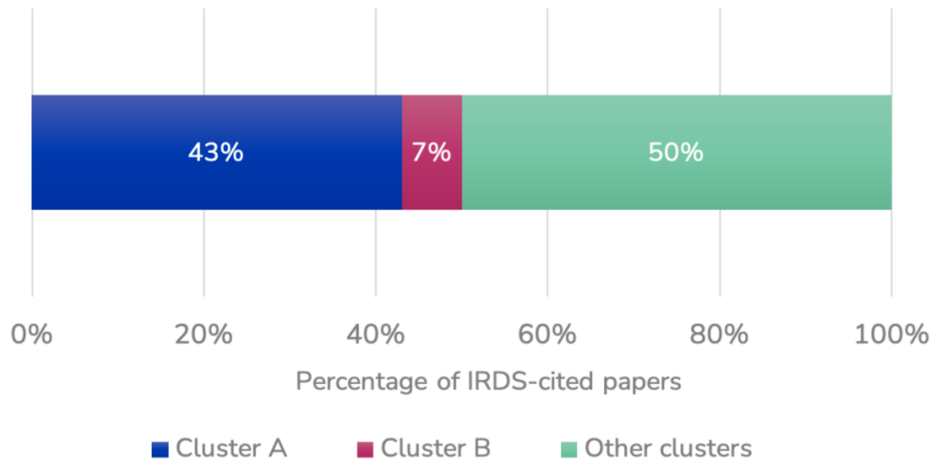
Methodology

To measure funding activity and research output, this analysis draws heavily on statistics derived from CSET's Map of Science, a database of nearly 130 million research publications grouped into more than 123,000 research clusters.[5] Each research cluster contains a set of papers that heavily cite one another, so that a given cluster typically contains research focused on related problems, themes, or methodologies. Once the relevant research clusters have been identified, the Map of Science makes it possible to easily collect statistics on country-by-country research contributions, as well as government funding activity, for the full corpus of papers within a given cluster.

However, identifying relevant research clusters within the Map of Science poses some difficult definitional problems. Determining whether a given paper qualifies as "SCE research" requires expert judgment. At the same time, evaluating the relevance of a given cluster (which may contain thousands of papers) by hand would be both impractically labor-intensive and susceptible to the biases of the evaluator. Thus, this paper identifies SCE-related clusters by identifying the clusters that contain the highest percentage of papers cited by the 2020 International Roadmap for Devices and Systems. The IRDS (formerly the ITRS) is a highly-regarded technical roadmap authored by an international committee of technical experts from academia and industry.[6] It has guided the progress of the semiconductor industry for more than two decades, helping the global semiconductor research and development community coordinate on the science and technology breakthroughs needed to continue progress in microelectronics. Importantly, each section of the IRDS—including its discussion of superconductor electronics—includes an extensive body of citations of relevant research.

This analysis starts by identifying which of the 314 papers cited in the IRDS' subsection on superconductor electronics are included in CSET's Map of Science.[7] The Map of Science contained 242 of these 314 IRDS papers. Of these 242 papers, half are spread among two research clusters in the Map of Science—43 percent belong to just one cluster while 7 percent belong to another (see Figure 1). For convenience, these two clusters are referred to as Cluster A and Cluster B, respectively.[8] The group of all publications within both clusters are referred to as "SCE-related research."[9]

Figure 1. Half of IRDS-cited papers in the Map of Science belong to one of two research clusters



Source: CSET Map of Science. Results generated August 11, 2021.

Cluster A contains an especially large number of papers cited in the subsection of the IRDS roadmap focused on logic (i.e. data processing), as well as significant numbers from all other IRDS sub-sections. Cluster B contained papers exclusively from the Fabrication subsection.

Clusters A and B also include many papers not cited in the IRDS, but both clusters appear to be centrally concerned with SCE-related research. IRDS-cited papers made up roughly 8 percent of papers published between 2000 and 2020 in Cluster A and Cluster B. Most of the papers cited by the IRDS were published between 2015 and 2020. In this period, these papers made up 15 percent of Cluster A and 19 percent of Cluster B. Core papers within both Cluster A and Cluster B generally focus on engineering challenges within superconductor electronics.[10]

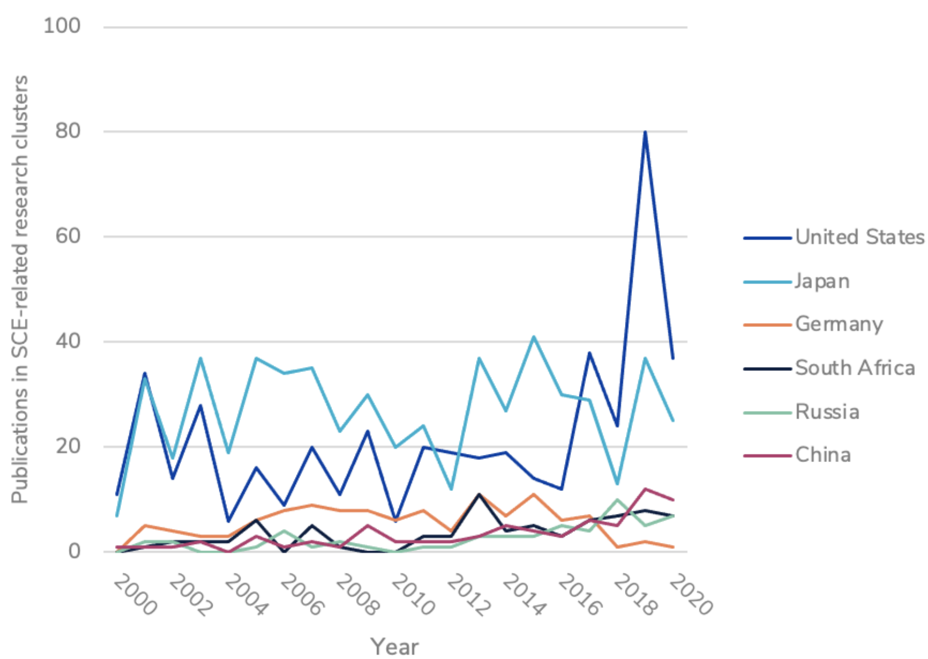
To see how the results would differ by including a larger corpus of IRDS-related papers, Appendix B presents results from conducting the same analysis on the top *three* clusters associated with IRDS-cited papers. For this larger set of papers, the results were broadly similar, but showed more pronounced overall growth over time, as well as modestly differing trends in the productivity of specific countries (see Appendix B).

Findings

The United States and Japan lead in SCE-related research

Over the last two decades, the United States and Japan have produced the most SCE-related research analyzed here.[11] Figure 2 shows the number of SCE-related publications produced by the top six countries that have been most active in the field since 2000. Results show that the combined research output of the United States and Japan made up more than half of all SCE-related research for the last two decades, with the United States surpassing Japan in SCE-related research productivity in 2016. Russia and China's contributions to SCE-related research clusters have somewhat increased over the past decade. Germany's contributions to SCE-related research, on the other hand, appear to have modestly declined in recent years. Surprisingly, the SCE-related research output of South Africa, not typically recognized for a leading role in science and technology, is similar to that of Russia and China.

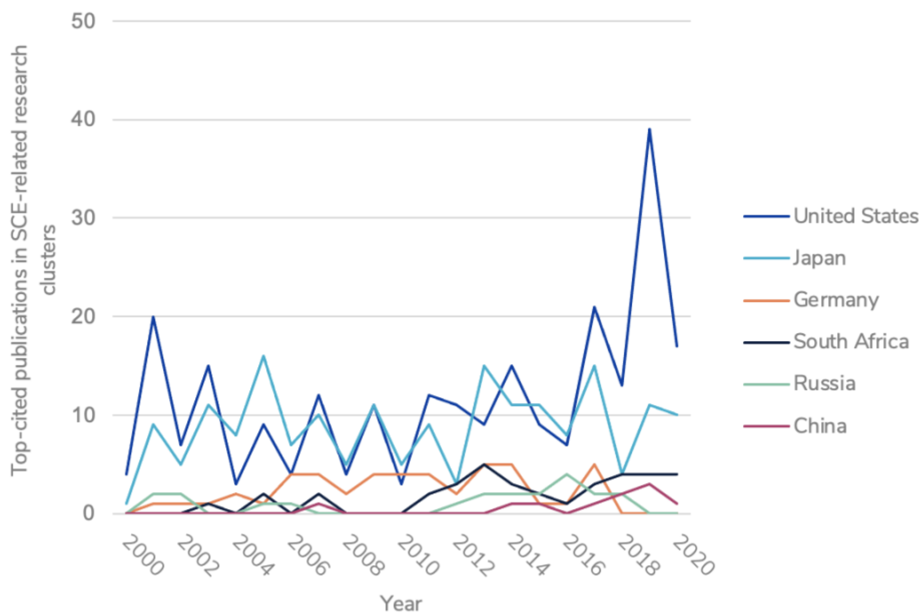
Figure 2. The United States has recently overtaken Japan in SCE-related research productivity



Source: CSET Map of Science. Results generated August 11, 2021.

Of course, not all research is created equal. Most papers in a given field are seldom cited, while a handful are highly influential. Figure 3 below analyzes publication trends within the most highly-cited quartile of SCE-related research in our dataset.[12] Trends are broadly similar to those seen in Figure 2, with Japan and the United States accounting for a preponderance of highly-cited publications. However, U.S. research is especially strong on this metric, particularly since 2018.

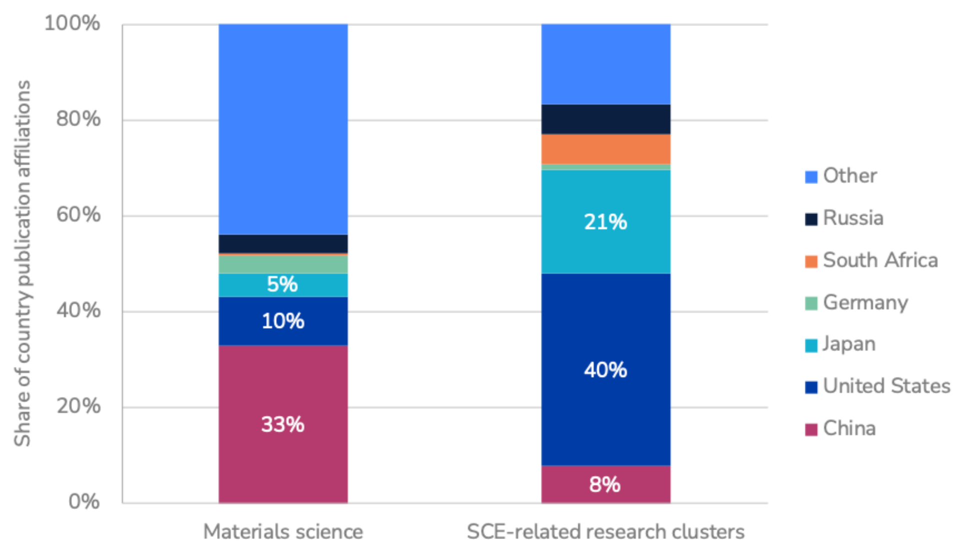
Figure 3. U.S. leadership is even more pronounced among highly cited SCE-related research



Source: CSET Map of Science. Results generated August 11, 2021.

The productivity of the United States and Japan in SCE-related research is particularly notable, given that they contribute a smaller relative share of research within the broader discipline of materials science, which contains a substantial amount of SCE-related research. In materials science, China produces more research than any other country, representing a much larger share of research in materials science overall than in SCE-related research. Similarly, although Germany's output in SCE-related research has been small in recent years, its contributions to materials science overall are more significant. By contrast, the United States and Japan make up significantly smaller shares of the total global materials science research than they do of SCE-related research. Russia also produces a slightly smaller share of materials science research than SCE-related research. Notably, South Africa, while producing only a sliver of materials science research, is a small but significant contributor to SCE-related research output.

Figure 4. China dominates in materials science, but is comparatively marginal in SCE-related research



Source: CSET Map of Science. Results generated August 11, 2021.

Note: Figure displays the share of country publication affiliations, not the share of publications. For example, a paper affiliated with U.S., Chinese, and German authors will count as one paper for each of those countries. The share is then the number of a country's affiliations over the total number of country publication affiliations.

Higher funding activity is associated with higher productivity in SCE-related research

Perhaps unsurprisingly, Japan and the United States are not only especially active in SCE-related research, they are also major funders of this research. In the clusters analyzed, CSET's database included funding information for 35 percent of publications.[13] Twenty-nine percent of all papers in SCE-related clusters—82 percent of all papers for which data is available—were funded by the funding organizations listed in Table 1 below.[14] Chinese agencies also show up as relatively active funders, which may be related to China's growing output of SCE-related research.

Table 1. Major funding organizations in SCE-related clusters

Rank	Organization	Country/Region	Funded paper count, 2000-2020*
1	Japan Society for the Promotion of Science	Japan	164
2	Office of the Director of National Intelligence	United States	105
3	United States Army Research Office	United States	66
4	National Institute of Advanced Industrial Science and Technology	Japan	59
5	Japan Science and Technology Agency	Japan	41
6	United States Office of Naval Research	United States	26
7	Chinese Academy of Sciences	China	22
8	National Natural Science Foundation of China	China	22
9	Ministry of Education, Culture, Sports, Science and Technology	Japan	18
10	European Commission	EU	17

Source: CSET Map of Science. Results generated August 11, 2021.

It is especially notable that funding from IARPA, which falls under the Office of the Director of National Intelligence, is correlated with the spike in U.S. SCE-related research activity over the last four years, which has made the United States the global leader in

* Numbers in this column include all papers funded at least partially by the corresponding organization; papers funded by multiple organizations are counted once for each.

SCE-related research. IARPA has had three major SCE-related programs in recent years: Cryogenic Computing Complexity (C3), SuperTools, and SuperCables. The C3 project, which ran from 2014 to 2019, coincided with the recent spike in publications from the United States. The SuperTools and SuperCables projects were follow-ups to C3, geared towards building out inputs of tooling and components for SCE. Appendix A provides more detail on the funding programs in the top six countries producing SCE-related research.

Conclusion

The field of superconductor electronics holds significant potential for greatly improving the energy-efficiency of computing, perhaps addressing one of the key bottlenecks to continued hardware progress over the next decade. This brief has shown that the United States and Japan are consistent leaders in SCE-related research, with authors from these two countries involved in 75 percent of SCE-related publications over the past two decades. The United States has been especially active in SCE research in the last few years, producing 49 percent of SCE-related publications between 2018 and 2020, compared to just 34 percent on average between 2000 and 2020. This jump in research productivity coincided with IARPA's Cryogenic Computing Complexity program, which focused on superconductor electronics research.

Meanwhile, China is a small but increasingly significant producer of SCE-related research, having recently invested at least $145 million in this area.[15] China could plausibly replicate in SCE its success in fields such as materials science, but for now is much less active in SCE-related research than are the United States and Japan.

Research leadership and presence of funding organizations seem to be intertwined at the country level—the countries with prominent funding organizations also produced the most research. Further growth in this field may depend on interest from government funding agencies. Indeed, even a single initiative such as IARPA's Cryogenic Computing Complexity program may give a country an advantage in SCE-related research. Thus, while the

United States and Japan are currently leaders in SCE-related research, this could change quickly if countries such as China decide to devote greater resources to this emerging hardware paradigm.

Authors

Karson Elmgren, CSET Research Assistant, focused on research and writing for this report.

Ashwin Acharya and Will Hunt, CSET Research Analysts, developed the methodology for the report and contributed to research and writing. All authors contributed equally.

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Appendix A: Funding Programs for SCE Research

The countries and regions producing the most SCE-related research have all funded substantial research and development programs in superconductor electronics.

United States: The history of superconductor electronics begins in the 1960s when IBM launched a decades-long project that aimed to develop superconductor computers. More recently, the Intelligence Advanced Research Projects Activity (IARPA) has supported SCE-related research through its Cryogenic Computing Complexity (C3), SuperTools and SuperCables programs. Although funding numbers for these projects are not public, they may represent tens of millions of dollars of investment.[16] Furthermore, well over half of the current fabrication processes for superconductor electronics were developed by U.S. groups. These include SUNY Polytechnic's Qubit Rev.0 process, which has achieved the largest wafers (300 mm) and smallest feature size (140 nm), as well as several from MIT's Lincoln Laboratory and Minnesota's SkyWater Technology.[17]

Japan: Japanese researchers have played an important role in the history of applied superconductivity. One of the two main SCE logic paradigms, adiabatic quantum flux parametron, was developed in Japan. Japan's National Institute of Advanced Industrial Science and Technology has developed three fabrication processes for manufacturing SCE. Japan also established the International Superconductivity Technology Center (ISTEC) in 1988, which was later subsumed by other research organizations in 2016. More recently, the Japan Science and Technology Agency invested in SCE-related technology through its Advanced Low Carbon Technology Research and Development Program (ALCA) launched in 2010. Various projects in this program are aimed at increasing energy efficiency to reduce the carbon footprint of computing, including several SCE-related projects receiving between about $280,000 USD (30 million yen) and $1.8 million USD (200 million yen) per year.[18]

Germany: SCE-related research in Germany is often funded by EU bodies such as the European Commission, and frequently involves collaboration with other EU member states, especially France. The European Commission has funded a variety of SCE projects over the years, dating back to the SCENET Network of Excellence for superconductivity established in 1994. The commission also created the FLUXONICS network of university laboratories, national research centers and private companies, which provides research groups with foundry services for fabricating superconductor devices. However, more recent funding efforts are more difficult to identify. Germany's Leibniz-IPHT and PTB have each developed SCE fabrication processes; at 250 nm, PTB's voltage standard process currently has the second smallest feature size.

Russia: In 1985, Soviet researchers at Moscow State University published a seminal paper proposing a new paradigm of SCE logic—rapid single-flux-quantum. However, by the early 1990s, all three coauthors of the paper had emigrated to the United States.[19] More recently, Russia's Foundation for Promising Innovations, founded in 2012 and modeled on the United States' Defense Advanced Research Projects Agency, funded a project on superconducting qubit technology, and organized a seminar on cryogenic computing in October 2020.

China: Although not a traditional leader in this space, the Chinese government may be increasing its attention to the area, having funded a $145 million research effort into cryogenic computing in 2017. Chinese Academy of Sciences President Bai Chunli has opined that SCE will "help China cut corners and overtake [other countries] in integrated circuit technology."[20] Shanghai Institute of Microsystem and Information Technology also recently developed a superconductor electronics fabrication process, which has achieved only 100 mm wafers and 1400 nm feature sizes.

South Africa: Research and development activities related to SCE in South Africa have been primarily associated with Stellenbosch University, which joined the EU's FLUXONICS Society in 2009. The university's Superconductivity, Advanced materials and Nano Devices (SAND) group has given rise to two SCE electronic design automation software projects: NioCAD (now defunct) and InductEx. NioCAD was supported by a grant from the South

African National Research Foundation's Innovation Fund and was in business from 2010 to around 2013. InductEx, launched in 2015, counts IBM and NIST among its customers. InductEx's technology is based on work funded by the South African National Research Foundation, as well as IARPA.

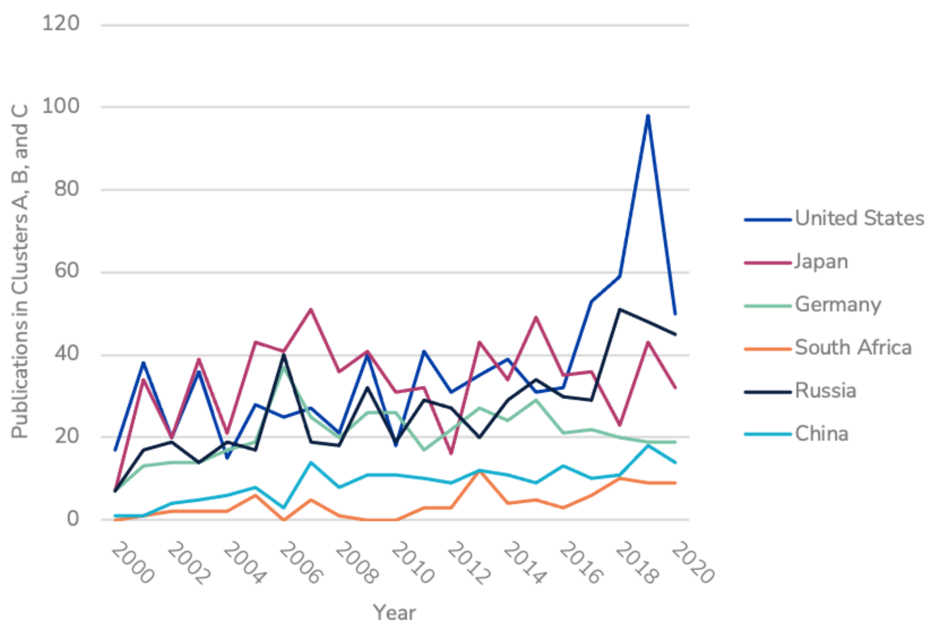
Appendix B: Including Cluster 3374

Besides Clusters A and B, one other cluster contains a high number of SCE-related papers cited in IRDS—Cluster 3374 (Cluster C).[21] This cluster contains 35 IRDS papers (14 percent of IRDS-cited papers in CSET's Map of Science), including 20 cited in the Memory subsection. The 20 IRDS papers were reviewed by an expert who described them as relating to "materials and device physics with potential applications to SCE," but the vast majority of papers in the cluster appear to be much less relevant to SCE. In aggregate, Clusters A, B, and C together contain 154 IRDS-cited papers, or about 64 percent of the 242 IRDS papers identified in the Map of Science. However, while IRDS-cited papers made up roughly 8 percent of papers published between 2000 and 2020 in both Cluster A and Cluster B, IRDS-cited papers made up only 2 percent of papers in Cluster C from 2000-2020. Qualitatively, Cluster C appears to consist largely of physics research not explicitly targeted at SCE. This appendix presents an analysis of publications including Cluster 3374 as a more comprehensive, if less precise, view of SCE-related research trends.

When including Cluster C, the United States and Japan remain prominent in terms of total research productivity (Figure 1B). However, within this larger body of research, Germany and especially Russia are much more prominent, with Russia overtaking Japan in the last three years. Growth in Russian publications may be related to funding from the Russian Foundation for Basic Research, as well as Russia's DARPA-like Foundation for Promising Innovations.

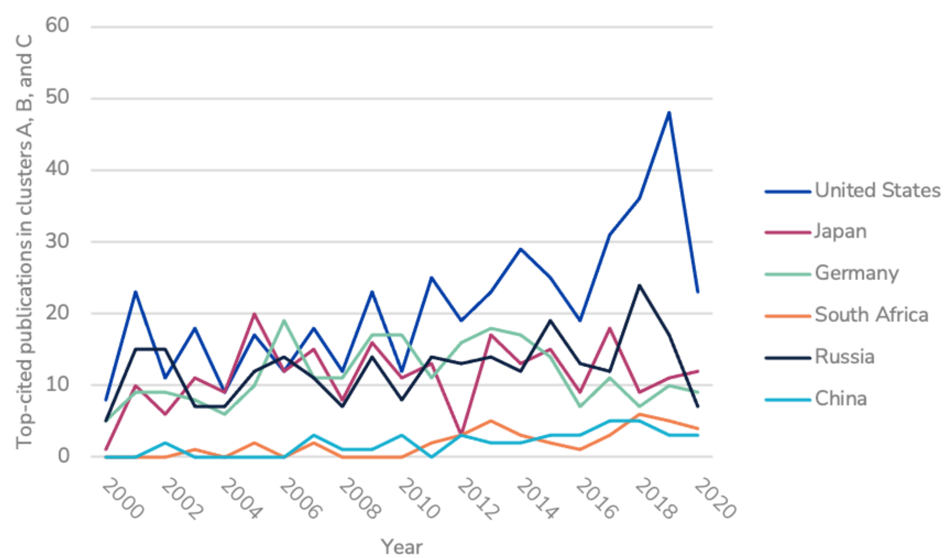
The United States is even more strongly represented in the top 25 percent of most-cited research within these three clusters, while Japan, Germany and Russia are represented somewhat less (Figure 2B). Overall, the picture is similar to that seen in the body of this paper: the United States and its allies produce the majority of all SCE-related research.

Figure 1B. Russia and Germany are much more prominent when including Cluster C



Source: CSET Map of Science. Results generated August 11, 2021.

Figure 2B. The United States clearly leads among highly cited publications including Cluster C



Source: CSET Map of Science. Results generated August 11, 2021.

Major funders of research also matched the sources of research output when Cluster 3374 is included in the analysis. Both Japanese and U.S. funders were similarly prominent. The Russian Foundation for Basic Research was also common within this set, as might be expected based on the higher proportion of Russian publications. The prominence of the UK's Engineering and Physical Sciences Research Council and the Research Council of Norway is surprising, given that neither country was particularly prominent in research in these three clusters.

Table 1B. Major funding organizations in Clusters A, B, and C

Rank	Organization	Country/Region	Funded paper count, 2000-2020[†]
1	Japan Society for the Promotion of Science	Japan	230
2	Russian Foundation for Basic Research	Russia	185
3	Office of the Director of National Intelligence	United States	126
4	German Research Foundation	Germany	114
5	European Commission	EU	105
6	Engineering and Physical Sciences Research Council	United Kingdom	82
7	United States Army Research Office	United States	78
8	National Natural Science Foundation of China	China	67
9	Japan Science and Technology Agency	Japan	64
10	The Research Council of Norway	Norway	62

Source: CSET Map of Science. Results generated August 11, 2021.

[†] Numbers in this column include all papers funded at least partially by the corresponding organization; papers funded by multiple organizations are counted once for each.

Endnotes

[1] The 2020 IRDS CEQIP report, discussed later, defines superconductor electronics as "[using] circuits and components at least some of which are in the superconducting state."

[2] Office of the Director of National Intelligence, "IARPA Launches Program to Develop a Superconducting Computer," December 3, 2014, https://www.dni.gov/index.php/newsroom/news-articles/news-articles-2014/item/1146-iarpa-launches-program-to-develop-a-superconducting-computer.

[3] Alex Rubin et al., "The Huawei Moment" (Center for Security and Emerging Technology, July 2021), https://cset.georgetown.edu/publication/the-huawei-moment/.

[4] For example, EUV photolithography equipment—critical for manufacturing the most advanced logic chips, and supplied only by the Dutch firm ASML—is currently not required for fabricating the most advanced superconductor chips (though whether it will be needed for commercially-viable superconductor chips remains uncertain). Changes in equipment and other inputs required for making the highest-performing chips could generate opportunities for firms in China and other strategic rivals of the United States to enter the market.

[5] Autumn Toney, "Creating a Map of Science and Measuring the Role of AI in it" (Center for Security and Emerging Technology, June 16, 2021), https://cset.georgetown.edu/publication/creating-a-map-of-science-and-measuring-the-role-of-ai-in-it/.

[6] Citations in the IRDS may be biased by the authors of the report. The SCE section of the IRDS report was written by a panel of authors working at institutions in the United States (10), Japan (1), Russia (1), South Africa (1), and France (1). Based on our own findings, the United States appears to be overrepresented among IRDS SCE authors, while Japan, China, and Germany are underrepresented. Because the methodology in this brief takes IRDS citations only as a starting point for identifying SCE-relevant research clusters, the risk of bias should be considerably, but perhaps not entirely, mitigated.

[7] The section used is Section 2.3 in the 2020 IRDS report on Cryogenic Electronics and Quantum Information Processing. See the report here: "International Roadmap for Devices and Systems, 2020 Edition: Cryogenic Electronics and Quantum Information Processing" (IEEE, 2020), https://irds.ieee.org/images/files/pdf/2020/2020IRDS_CEQIP.pdf.

[8] These clusters were identified using an earlier version of CSET's Map of Science. They are most closely associated with clusters 8576 (Cluster A) and

25883 (Cluster B) in the updated Map of Science generated in August 2021. Cluster A from the earlier version of the Map closely resembles Cluster 8576 in the updated version: more than 90 percent of publications in Cluster A are also in Cluster 8576, and vice versa. However, cluster 25883 in the updated version of the Map contains many publications that were not included in Cluster B from the earlier version.

[9] More precisely, these clusters include research with high citation linkages to papers that IRDS cites as contributions to SCE.

[10] For example, two of the most central papers within Cluster A are titled "Superconductor digital electronics: Scalability and energy efficiency issues" and "Digital Superconducting Electronics Design Tools—Status and Roadmap." Meanwhile, two of the most central papers within Cluster B had the titles "NbTiN/AlN/NbTiN SIS Junctions Realized by Reactive Bias Target Ion Beam Deposition" and "Growth and Characterization of NbTiN Films Synthesized by Reactive Bias Target Ion Beam Deposition" — both of which are concerned with fabricating a common type of junction used in superconductor electronics.

[11] Publications in CSET's Map of Science were attributed to countries based on authors' affiliations. For publications with authors from multiple institutions and authors with multiple affiliations, credit for the publication was attributed to each contributing country, such that a paper with at least one U.S.-affiliated author and at least one Japanese-affiliated author would count as a paper for the United States and as a paper for Japan.

[12] Ideally, it would be desirable to show the top decile or centile of most-cited SCE-related papers. However, given the number of total papers in the sample, subsetting to the top decile or centile would have resulted in much noisier data.

[13] Given that some funder data is missing, only tentative inferences can be drawn about the importance of different funding organizations. However, the most common funding organizations in the available data align well with both publicly-available information about important funding organizations in different countries (Table 1), as well as the results on country-by-country research productivity from the previous section. We have no reason to believe our data on funding organizations is biased toward or against particular funders or countries.

[14] Note that many authors of papers lacking funding data were also affiliated with private organizations such as Hypres, Conductus, IBM, and Bell Labs, among others, suggesting that the data may underestimate the importance of these private organizations. On the other hand, these organizations also receive substantial government funding; for example, Hypres's work on superconductor electronics has received considerable funding from IARPA's C3 program.

[15] Michael Feldman, “China Aims to Be Global Leader in Superconducting Computers,” Top500, August 28, 2018, https://www.top500.org/news/china-aims-to-be-global-leader-in-superconducting-computers/.

[16] A similar but larger set of programs from DARPA known as the Electronics Resurgence Initiative has included programs ranging from $24 million to $71 million. Samuel K. Moore, “DARPA Picks Its First Set of Winners in Electronics Resurgence Initiative,” *IEEE Spectrum*, July 24, 2018, https://spectrum.ieee.org/darpa-picks-its-first-set-of-winners-in-electronics-resurgence-initiative. DARPA likely has a larger budget than IARPA — IARPA’s budget is not public — but this budget is spread across three to four times as many DARPA program managers, so the budget for a single program within each ARPA may be comparable. William B. Bonvillian, “DARPA and its ARPA-E and IARPA clones: a unique innovation organization model,” *Industrial and Corporate Change* 27, no. 5 (October 2018): 897-914, https://academic.oup.com/icc/article/27/5/897/5096003.

[17] Precision electronics manufacturing at nanoscale requires highly complicated, multi-stage fabrication processes which form a key and challenging technical input for making chips of any kind. Larger wafer sizes allow higher-throughput and thus more efficient manufacturing. Smaller feature sizes allow packing more computing power into a given surface area, which in CMOS devices has been accompanied by energy efficiency gains per Dennard scaling, as discussed above. See page 14 of the 2020 IRDS Cryogenic Electronics and Quantum Information Processing report for a full list of fabrication processes for SCE with technical details.

[18] “ALCA Outline,” ALCA, https://www.jst.go.jp/alca/en/outline.html.

[19] Two of the co-authors, Konstantin Likharev and Vasili Semenov, became important leaders of SCE-related research at SUNY Stony Brook. The third, Oleg Mukhanov, was a senior executive at key SCE firm Hypres, also in New York, for many years and recently co-founded Seeqc, a quantum computing firm spun out from Hypres.

[20] Feldman, “China Aims to Be Global Leader in Superconducting Computers.”

[21] In CSET’s updated Science Map, Cluster C corresponds to new cluster 9142.