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An Assessment of U.S.-Allied Nations' Industrial Bases in Quantum Technology



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About This Report

Quantum technology is an emerging area that the U.S. government has identified as important for future U.S. economic prosperity and national security. This report assesses the quantum industrial bases of several U.S.-allied nations that are major players in the development of this technology. It begins with a global look at the quantum technology ecosystem and then does deeper dives into the quantum industrial bases of Australia, the United Kingdom, Germany, and Japan. It concludes with recommendations for how the United States can promote strong ties with its allies in quantum technology research and development. A separate, online-only volume containing the appendixes is available at www.rand.org/t/RRA2055-1.

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Summary

Quantum technology is an emerging technology area that the U.S. government has identified as important for future U.S. economic prosperity and national security. Although many applications are still at early stages of maturity, quantum technology has the promise to deliver capabilities in information collection, processing, and communication that far exceed the theoretical capability of many existing systems.

In 2022, the RAND Corporation released a report that developed a set of metrics for assessing any nation's production capacity in quantum information science and technology and then applied the metrics to the United States and China.¹ This report uses a very similar methodology to assess the quantum industrial bases of several other nations, with the goals of better understanding any areas of comparative strength or weakness and identifying potential options for mutually beneficial cooperation between the United States and allied nations.

Approach

As in our previous research, we assessed nations along four main dimensions: open scientific research, government support, commercial industry activity, and technical achievement. Within each dimension, we applied several metrics to each nation to compare their strengths and weaknesses in an objective and repeatable way. Whenever possible, we separately applied our metrics across the three main quantum technology application domains—quantum computing, quantum communications, and quantum sensing—to get more granular information about each nation's capacity.

We began with a global look at the full quantum technology ecosystem, focusing mostly on easily scalable metrics, such as scientific publishing and patenting. Using the resulting findings, we selected four nations (based on a combination of high-impact scientific publishing, high patenting, and/or having strong official ties with the U.S. government)—Australia, the United Kingdom (UK), Germany, and Japan—and examined the quantum industrial base of each in more depth, focusing on any unique aspects of each. We then formulated recommendations to U.S. government policymakers for encouraging strong cooperation with U.S. allies in quantum technology research and development (R&D).

Key Findings

- Extensive international collaboration already exists between entities within the United States and entities within allied nations in quantum technology R&D. Specifically, those entities include both universities and private companies.
- Other than the United States and China, Germany and the UK are the two nations with the highest output of scientific research in each of the three application domains. Japan is one of the next two nations in each application domain.
- Germany and the UK are the U.S.-allied nations with the highest government investment in quantum technology R&D. (However, the Netherlands invests a higher proportion of its gross domestic product in government funding for quantum technology R&D than either Germany or the UK does.)

¹ Edward Parker, Daniel Gonzales, Ajay K. Kochhar, Sydney Litterer, Kathryn O'Connor, Jon Schmid, Keller Scholl, Richard Silbergliitt, Joan Chang, Christopher A. Eusebi, and Scott W. Harold, *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*, RAND Corporation, RR-A869-1, 2022.

- Japan has the highest level of patenting in each of the three application domains.
- The cutting edge of quantum technology is rapidly shifting from open research institutions to private industry, and it is becoming more difficult to determine the technical state of the art from nonproprietary sources.
- Many nations have announced ambitious plans to develop their own quantum computers domestically over the next few years. But as of April 2023, Austria is the only nation (other than the United States and China) to have developed a universal quantum computer prototype with more than six qubits and precisely documented technical specifications. Other nations may have produced similarly powerful prototypes whose performance has not been publicly documented in detail.
- The quantum industrial bases of Australia, the UK, Germany, and Japan each have distinct organizational structures and focuses. For example, the Australian and UK commercial quantum technology industries consist mostly of start-ups; the German industry has significant activity by both start-ups and large corporations; and the Japanese industry has very little start-up activity and conducts most of its R&D in large, established corporations. Moreover, each nation has a somewhat different pattern of government, industry, and academic collaboration. For example, German and Japanese quantum technology companies are more closely linked to government-funded R&D programs than Australian and UK companies are.
- Australia, Germany, Japan, and the UK each engage in significant scientific collaboration with, and receive significant research funding from, both U.S. and Chinese organizations.
- In one technical area—silicon-spin-qubit quantum computing—other nations are arguably ahead of both the United States and China.
- U.S.-allied nations provide various key components in the quantum technology supply chain.

Recommendations

- Focus quantum technology R&D collaboration with U.S.-allied nations in areas where the nations' technical strengths complement those of the United States.
- Leverage the complementary organizational aspects of the quantum industrial bases of the United States and its allies.
- Identify and monitor critical component and material suppliers based in U.S.-allied nations.
- Identify and monitor potential sources of technology leakage in allies' funding and collaboration networks.
- Organize a recurring multilateral meeting of quantum technology experts from leading U.S. and ally governments to facilitate information-sharing and planning.

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Introduction

In 2022, National Security Advisor Jake Sullivan identified quantum information systems as one of the families of technologies that will generate “leap-ahead breakthroughs and new industries that will drive our prosperity [and] shape our national security.”¹ These systems apply the principles of quantum physics—the counterintuitive laws of physics that apply at the atomic scale or at extremely low temperatures—to enable powerful new methods of collecting, processing, and transmitting information that (in principle) could far exceed the fundamental limits of our current technology. Most applications of quantum information science are still in the early stages but have rapidly matured over the past several years. Ten years ago, almost all quantum information science research and development (R&D) was conducted within academic laboratories, but a commercial industry is now growing rapidly all around the world. The process of commercializing these technologies has begun in earnest.

Moreover, strong technical talent and active quantum information science research exist all over the world. National Security Advisor Sullivan also identified “deepening and integrating our alliances and partnerships” as one of four pillars at the heart of the U.S. government’s industrial and innovation strategy for emerging technologies.² One example of such international cooperation is the 2021 establishment of the Trade and Technology Council to help coordinate policy between the United States and the European Union.³ Another example is the 2022 agreement between Australia, the United Kingdom (UK), and the United States (AUKUS), which contained an AUKUS Quantum Arrangement “to deliver generation-after-next quantum capabilities.”⁴

To retain its leading position in the globally interconnected field of quantum technology, the United States will need to cooperate with its many allied nations that are also technically strong in this area—particularly as the People’s Republic of China emerges as a strong technical competitor.⁵

In 2020, policymakers within the Office of the U.S. Under Secretary of Defense for Research and Engineering asked the RAND Corporation to develop a set of metrics for assessing a nation’s industrial base in quantum technology and to apply the metrics to the United States and to the People’s Republic of China.⁶ We

¹ Jake Sullivan, “Remarks by National Security Advisor Jake Sullivan at the Special Competitive Studies Project Global Emerging Technologies Summit,” White House, September 16, 2022.

² Sullivan, 2022.

³ White House, “U.S.-EU Summit Statement,” June 15, 2021.

⁴ White House, “Implementation of the Australia–United Kingdom–United States Partnership (AUKUS),” fact sheet, April 5, 2022.

⁵ For a short discussion of some of the major policy considerations surrounding international cooperation with allied nations regarding quantum technology R&D, see Edward Parker, *Promoting Strong International Collaboration in Quantum Technology Research and Development*, RAND Corporation, PE-A1874-1, 2023.

⁶ The results of that project are documented in Edward Parker, Daniel Gonzales, Ajay K. Kochhar, Sydney Litterer, Kathryn O’Connor, Jon Schmid, Keller Scholl, Richard Silberglitt, Joan Chang, Christopher A. Eusebi, and Scott W. Harold, *An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology*, RAND Corporation, RR-A869-1, 2022.

found that the United States and China are the two global leaders in quantum technology along many different metrics, but that many other nations are also very important global players, whether in terms of scientific research output, patenting, or providing critical components and materials to the U.S. commercial industry.⁷

In 2022, officials within the Office of the U.S. Under Secretary of Defense for Research and Engineering asked RAND to conduct another project, in which we would apply a similar methodology to assess the quantum industrial bases of several major U.S.-allied nations. They also asked us to make policy recommendations regarding R&D cooperation with U.S. allies. This report documents the findings of that project.

Brief Overview of Quantum Technology Applications

Quantum technology is usually broken down into three main (overlapping) classes of applications that we refer to as *application domains: quantum computing, quantum communications, and quantum sensing*.⁸ For a short technical overview of each application domain, we refer the reader to Chapter One of our previous report,⁹ and a longer and more detailed discussion can be found in Parker (2021). This section provides a brief summary.¹⁰

Quantum computing refers to a new (and still rudimentary) class of computers that operate on very different basic principles from today's digital computers. The eventual applications of quantum computers (like most quantum technologies) remain highly uncertain, but researchers have proposed potential applications for scientific simulation (e.g., materials science or drug design); for numerical optimization (e.g., for logistics); and, more speculatively, for machine learning. Another famous potential application of quantum computers is *Shor's algorithm*, which could allow a large quantum computer to efficiently break the encryption systems that are used to secure today's internet traffic. The latter application is still generally considered to be many years away. The timelines for the other applications are highly uncertain, but some companies believe that they could become technically feasible over the next few years on relatively small-scale quantum computers. Currently, many different basic architectures for quantum computers are being pursued in parallel and use different types of *qubits* (the basic building block of a quantum computer) that operate on completely different physical principles. Examples of qubits under investigation include *superconducting transmon* qubits, *trapped-ion* qubits, *neutral cold-atom* qubits, *photonic* qubits, *silicon-spin* qubits (SSQs), and *topological* qubits.¹¹

Quantum communications refers to the fast transmission of qubits (or other small quantum systems) over long distances. The earliest—and, so far, the only practical—application of quantum communications is *quantum key distribution* (QKD), which uses the counterintuitive properties of quantum physics to increase the cybersecurity of communication transmissions and help defend against message interception.¹² Further into

⁷ In this report, we use the terms *quantum information science* and *quantum technology* mostly interchangeably, although we use the former term more often in the context of scientific research and the latter term more often in the applied or commercial context. See Parker et al. (2022) for a discussion of the subtle distinctions that these two terms sometimes imply.

⁸ The U.S. Department of Defense breaks atomic clocks out as a fourth category of applications, but the U.S. National Quantum Initiative includes atomic clocks within quantum sensing. As in our 2022 report, we chose to use the National Quantum Initiative's taxonomy.

⁹ Parker et al., 2022. A longer and more detailed discussion can be found in Edward Parker, *Commercial and Military Applications and Timelines for Quantum Technology*, RAND Corporation, RR-A1482-4, 2021.

¹⁰ The information in the rest of this section is drawn from Parker et al. (2022).

¹¹ See Parker et al. (2022) for a brief summary of how each of these types of qubits physically operates.

¹² QKD is not, however, a high priority for the U.S. federal government, and the National Security Agency has publicly discouraged its use for national security systems (National Security Agency, "Quantum Key Distribution (QKD) and Quantum Cryptography (QC)," website, undated).

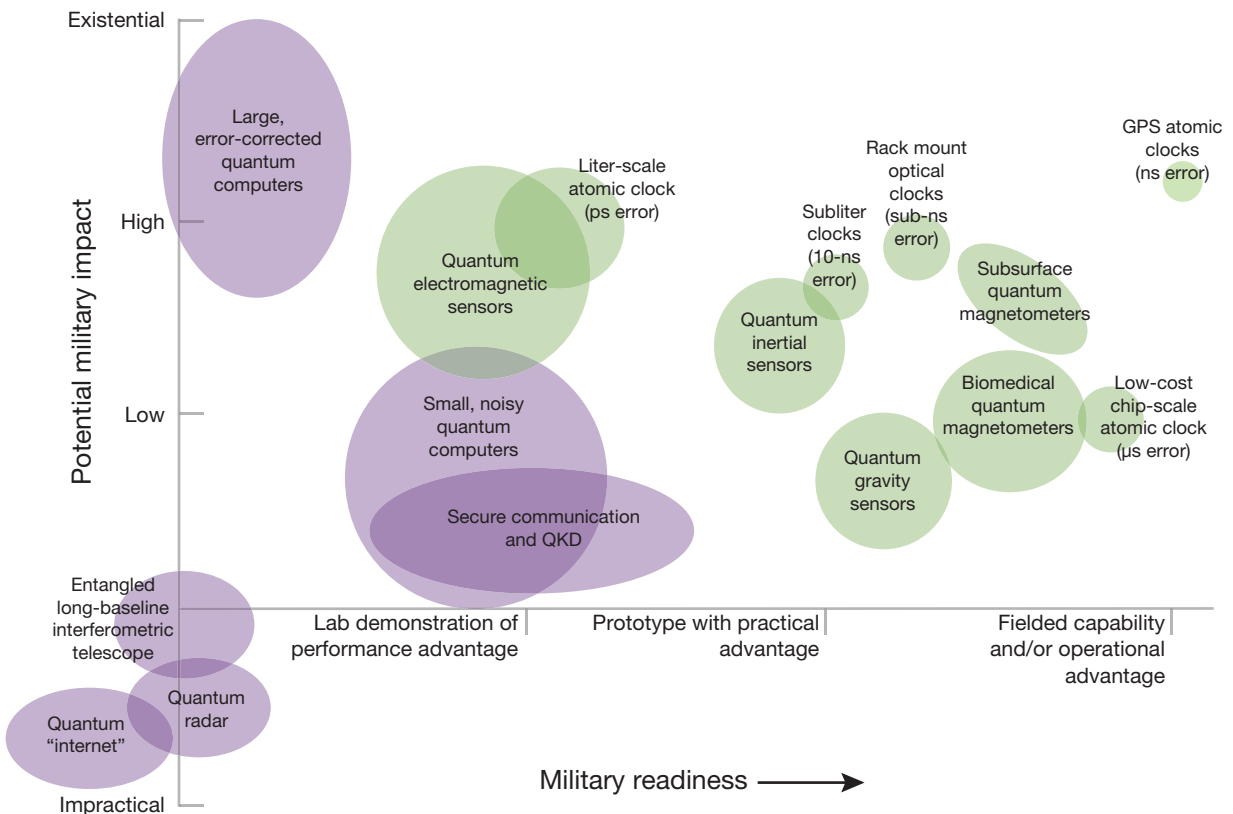
the future, more-advanced quantum communications systems that are capable of *entanglement distribution* may enable the networking together of quantum computers and/or quantum sensors, as well as more-secure forms of QKD (known as *device-independent* QKD).

Quantum sensing refers to the use of sensors that approach the fundamental limits of sensitivity set by the laws of quantum physics or that take advantage of quantum physics to achieve higher efficiency, higher stability, smaller form factors, etc. This category is very broad and includes many types of sensors, including electrometers and magnetometers for measuring static electric or magnetic fields, antennas for detecting electromagnetic radiation, accelerometers, gyroscopes, and gravimeters. Proposed applications include—among many others—positioning, navigation, and timing without the Global Positioning System; biomedical imaging; seismography; underground prospecting or tunnel detection; and sensitive antennas that can operate in congested electromagnetic environments.

Figure 1.1 shows the U.S. Department of Defense’s assessment of the current military readiness and the eventual military impact of various quantum technologies.

This summary should provide enough technical background for almost all of this report except for the sections that discuss technical metrics.

FIGURE 1.1
U.S. Department of Defense’s Assessment of the Military Readiness and Impact of Various Quantum Technologies



SOURCE: Provided to RAND by the Office of the Undersecretary of Defense for Research and Engineering.

NOTE: This is an updated version of a similar figure in Parker et al. (2022). Green denotes devices that must be integrated into (typically mobile) systems to realize advantage. The challenges are size reduction and ruggedization. Purple denotes systems that deliver a (typically stationary) independent advantage. The challenges are scaling up the capability and mitigating loss and errors. Ellipse size indicates the degree of uncertainty.

Summary of Our Methodology

Our 2022 report developed a large set of metrics that could be applied to any nation's quantum industrial base. They were organized into four categories:

1. The **scientific research metrics** assessed the nation's overall open scientific output. We constructed a comprehensive database of nearly all (English-language) scientific journal articles published on quantum technology over the previous ten years, then used that database to compare countries' performance along various dimensions.
2. The **government support metrics** assessed the level and structure of the nation's government investment in quantum technology R&D.
3. The **commercial activity metrics** assessed the overall state of the nation's industry by considering all the commercial companies headquartered within that nation.
4. The **technical achievement metrics** took a more granular look at specific technical achievements by individual organizations within the nation to identify technologies in which that nation was at the cutting edge.

The methodology for this project was similar. We used the same four categories of metrics and consistently applied a subset of the metrics from our previous report across multiple countries.¹³ In the previous report, the top level of organization was the country under consideration; in this report, the four categories of metrics just outlined constitute the top level of organization in each chapter. This facilitates comparison among the larger number of nations discussed here. Whenever possible, we have broken down our findings according to the three quantum application domains discussed earlier.

Assessed Nations and Organization of This Report

We began this project with a global look at the entire quantum ecosystem, which is presented in Chapter 2. We report some data for each of the four categories of metrics listed earlier but, given the broad scope of this chapter, focus mostly on the easily scalable metrics involving scientific publications and patenting. We include findings for the highest-activity nations, as measured by each metric. The set of highest-activity nations varied across metrics and technology application domains, so we were asked to choose a common baseline of countries to include across all metrics to ensure some degree of consistency in our reported data. In consultation with our sponsors, we chose Australia, Denmark, Finland, Germany, Japan, the Netherlands, South Korea, Sweden, and the UK.¹⁴

Based on our findings, we choose to do deeper dives into the quantum industrial bases of Australia, the UK, Germany, and Japan. We report the results of these deep dives in Chapter 3. Within each of the four categories of metrics, we consistently applied our metrics to these four countries as a second level of organization, and (whenever possible) applied them separately across the three application domains as a third level of organization. (However, in the "Technical Achievement" section in Chapter 3, we reverse the second and third levels of organization and discuss each application domain together instead of discussing each nation

¹³ Parker et al., 2022.

¹⁴ This selection should not be interpreted as implying that these nations are the most important or leading nations in quantum technology. We selected them based on a variety of criteria, including the diversity of their sizes, geographic locations, and technical specialties.

together. Given the more-technical nature of that section, it would make less sense to combine discussions of different application domains.)

In Chapter 4, we step back and give a short holistic summary assessment of each of the four nations' quantum industrial bases, focusing on any ways in which we found that nation's quantum industrial base to be notably distinct from those of the other three nations.

Chapter 5 summarizes our key findings and offers recommendations for how U.S. policymakers can best benefit from our close ties with allied and partner nations—particularly the four allied nations that we studied in detail.

A separate online annex (available at www.rand.org/t/RRA2055-1) offers supplementary material. In the annex, Appendix A provides additional findings and some relevant technical background. Appendix B provides methodological details for our scientific research publication analysis.

One member of our research team was located in Australia, which allowed him to conduct several in-person conversations with Australian government and industry stakeholders (which we did not have the resources to do for the UK, Germany, or Japan). This allowed us to gain additional details about the government and commercial industry sectors of the Australian quantum industrial base, which we summarize in Appendix C.

A Global Look at the Quantum Technology Ecosystem

This chapter presents a comparative overview of the leading nations in quantum technology along various dimensions in all four categories of metrics. It is (deliberately) less comprehensive than the deeper dives into four countries presented in the next chapter.

For the assessments reported in this chapter, we specifically focused on a common baseline set of nine U.S.-allied nations, which we chose in consultation with our sponsors: Australia, Denmark, Finland, Germany, Japan, the Netherlands, South Korea, Sweden, and the UK. This allowed us to conduct a medium-level dive on these nations and ensured some degree of consistency across the findings reported in this chapter. For most metrics reported in this chapter, we also include leading nations that are not part of the set but, for some metrics, we concentrate on the set of nine nations for clarity of presentation.

Scientific Research

To assess the magnitude and character of a nation’s scientific output in the three quantum information science application domains, we examined the scientific publications produced by its research organizations. Using a methodology similar to that in our previous report, which assessed the U.S. and Chinese quantum industrial bases,¹ we used Web of Science bibliographic data to build three publication datasets—one each for quantum computing, communications, and sensing—that span the 2012–2021 period. Each dataset was built based by querying the Web of Science for a series of domain-specific keywords.²

Total Publishing Activity

Across the three quantum information science application domains, we found a relatively consistent ordering of the baseline set of U.S.-allied nations by total research output over the 2012–2021 period of analysis. For all three quantum application domains, we found that Germany and the UK have significantly higher output than any other country assessed. Japan and Australia occupy the third and fourth spots, respectively, for the three quantum information science application domains. Table 2.1 provides the ranking of the countries assessed here based on publication output within the three quantum application domains.

Quantum Computing

Table 2.2 depicts the top ten global publishing countries and the nine allies in the common baseline for the quantum computing application domain. For each of the quantum application domains, we computed

¹ Parker et al., 2022.

² Appendix A in the annex describes the methodological details associated with the publication analysis in this report.

TABLE 2.1
Ranking of Nine Allied Nations' Total Publication Output
Within Each Application Domain, 2012–2022

Country	Rank		
	Quantum Computing	Quantum Communications	Quantum Sensing
Germany	1	2	1
UK	2	1	2
Japan	3	3	3
Australia	4	4	4
Netherlands	5	7	6
South Korea	6	5	5
Denmark	7	7	7
Sweden	8	8	9
Finland	9	9	8

TABLE 2.2
Quantum Computing Publication Output and Collaboration Metrics,
by Country, 2012–2022

Country	Global Rank	Publications	Countries with at Least One Collaboration	Centrality	Publications per \$B of GDP	Share of Publications with International Collaboration (%)
United States	1	7,915	77	1.00	0.424	46.1
China	2	7,593	61	0.91	0.619	28.5
Germany	3	2,844	67	0.95	0.831	70.2
UK	4	2,355	71	0.98	0.789	70.4
Japan	5	2,212	63	0.93	0.498	46.3
India	6	1,685	57	0.87	0.739	26.0
Canada	7	1,638	60	0.91	1.029	68.3
France	8	1,414	65	0.95	0.571	70.3
Australia	9	1,197	52	0.82	0.856	74.2
Italy	10	1,184	66	0.96	0.639	63.7
Netherlands	14	747	53	0.85	0.945	75.2
South Korea	18	568	52	0.84	0.373	51.8
Denmark	22	370	43	0.77	1.177	78.9
Sweden	24	278	40	0.72	0.540	79.5
Finland	28	226	40	0.72	0.926	73.9

NOTE: This list merges the sets of the top ten global publishers for this application domain and the nine allies in the common baseline.

country-level eigenvector centrality, a standard metric from graph theory that indicates how important a country is within the global research network.³ The second through fifth columns are various levels of overall activity, which are strongly correlated with the overall size of the country. The last two columns report two different ways of measuring the country's scientific output normalized by its size: the number of scientific publications per unit of total gross domestic product (GDP), and the percentage of publications that have an international collaborator. The latter quantity is a simple and interpretable metric for how connected the nation is to the global scientific research community (adjusted for the nation's size). We believe that both the absolute and the size-normalized measures convey useful information about the nation's contribution to the global quantum information science ecosystem.

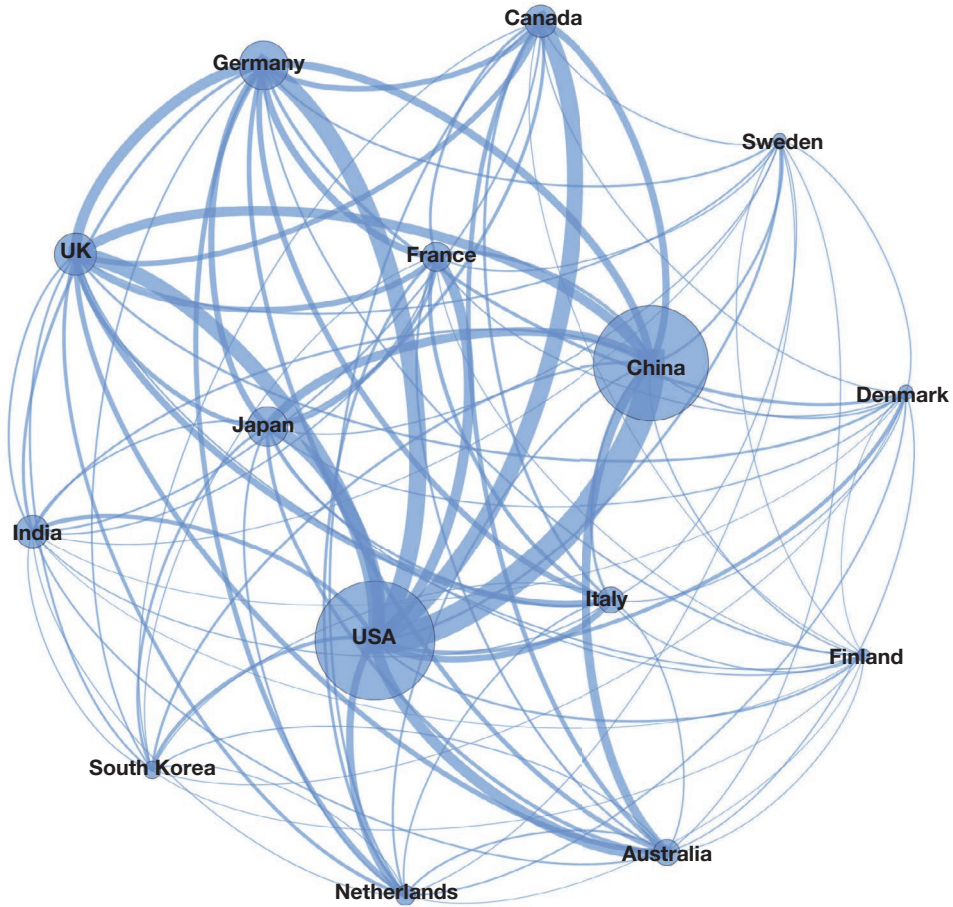
Table 2.2 indicates that the United States and China lead the world in quantum computing publishing by a significant margin. In the quantum computing domain, the United States has the highest centrality score. Denmark followed by Canada are the most productive quantum computing publishers on a per unit of GDP basis. In fact, Denmark ranks first in publication output in all three application domains on a per unit of GDP basis. Across all three application domains, the European nations and Australia had a significantly higher share of international collaboration than did the United States, China, Japan, and South Korea.

Figure 2.1 depicts the coauthorship network of the top quantum computing publishing countries. The network graph indicates that the most common international collaboration (observed in the thickness of the edge between the nodes) during the analysis period was between the United States and China. It is worth noting that, while China is highly productive in terms of quantum computing publication output, it is not particularly central in the network, given its high publication count. The UK, Italy, Germany, France, and Japan are more central than China, despite having lower total quantum computing publication output.⁴

³ Throughout this report we use eigenvector centrality to measure a node's centrality in the network. Appendix B contains additional details about this measure and how we computed it.

⁴ Only relative (and not absolute) eigenvector centralities are mathematically significant in a network; we chose to normalize the centralities so that the highest node's centrality equals 1. The fact that eight different countries have an eigenvector centrality above 0.9 indicates that many countries are approximately equally central in the network—or, put another way, no country is the single main hub of collaboration. For a random weighted network, eigenvector centrality would be positively correlated with the total number of collaborations, so we might have expected that China and the United States would be the most central by a significant margin, simply because they publish the most papers.

FIGURE 2.1
Quantum Computing Coauthorship Network



NOTE: The figure represents the countries listed in Table 2.2. Node size is determined by the number of publications a country has produced in the field during the 2012–2021 period of analysis. Edges reflect collaborations (i.e., coauthored publications) between countries, and the thickness of edges is determined by the number of collaborations between the countries. The graph layout uses the Fruchterman-Reingold force-directed approach.

Quantum Communications

Table 2.3 depicts the country-level publication totals for quantum communications. China is, by a healthy margin, the global leader in quantum communications research output.⁵ Despite China's large output, its research is relatively self-contained; it has a lower network centrality than four other nations (despite its high total output) and the lowest percentage of international collaborations.

Figure 2.2 depicts the coauthorship network of the top quantum communications publishing countries. While the United States trails China in terms of quantum communications publication output, it ranks first in centrality, indicating its important role in the international quantum communications collaboration network.

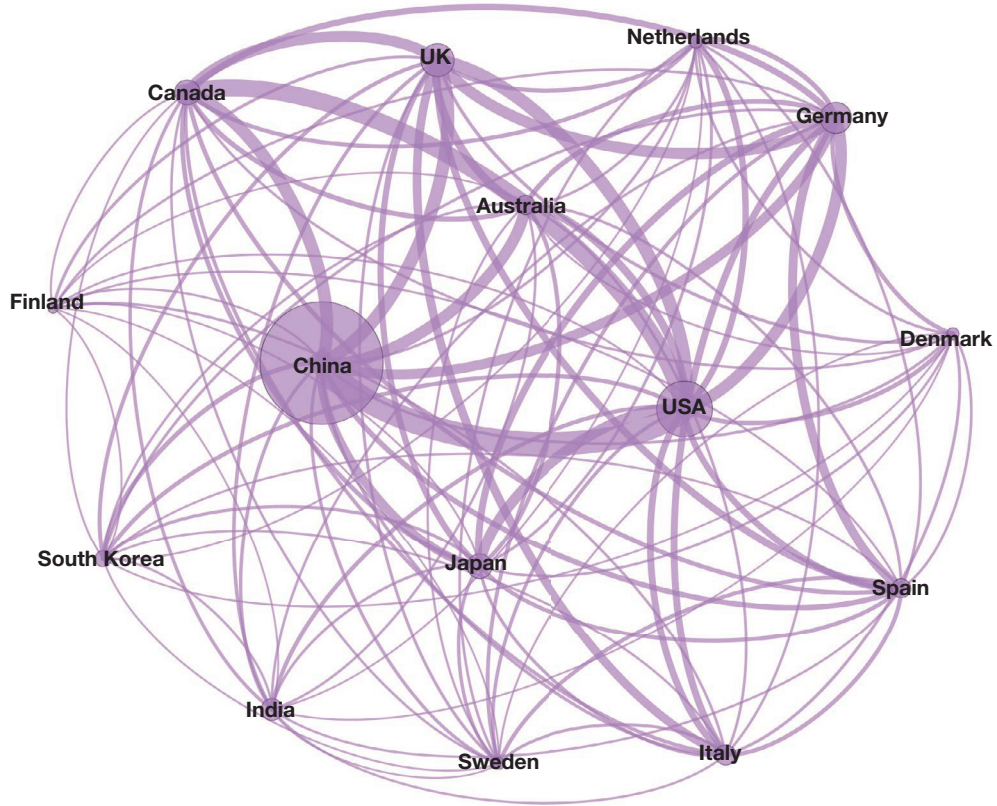
TABLE 2.3
Quantum Communication Publication Output and Collaboration Metrics,
by Country, 2012–2022

Country	Global Rank	Publications	Countries with at Least One Collaboration	Centrality	Publications per \$B of GDP	Share of Publications with an International Collaboration (%)
China	1	6,992	62	0.92	0.570	19.3
United States	2	2,906	70	1.00	0.156	51.0
UK	3	1,518	62	0.95	0.509	71.7
Germany	4	1,394	62	0.95	0.407	68.0
Canada	5	1,034	57	0.90	0.650	76.0
Japan	6	1,013	51	0.87	0.228	49.3
India	7	830	43	0.76	0.364	28.1
Italy	8	730	59	0.93	0.394	66.6
Spain	9	646	49	0.83	0.530	75.9
Australia	10	639	41	0.76	0.457	75.1
South Korea	15	499	40	0.75	0.328	37.1
Netherlands	20	315	38	0.71	0.398	72.5
Denmark	22	232	33	0.68	0.738	74.8
Sweden	24	207	38	0.75	0.402	78.7
Finland	38	82	28	0.59	0.336	79.0

NOTE: This list merges the sets of the top ten global publishers for this application domain and the nine allies in the common baseline.

⁵ This is consistent with the findings of Parker et al. (2022).

FIGURE 2.2
Quantum Communications Coauthorship Network



NOTE: The figure represents the countries listed in Table 2.3. Node size is determined by the number of publications a country has produced in the field during the 2012–2021 period of analysis. Edges reflect collaborations (i.e., coauthored publications) between countries, and the thickness of edges is determined by the number of collaborations between the countries. The graph layout uses the Fruchterman-Reingold force-directed approach.

Quantum Sensing

Table 2.4 depicts country-level analysis of quantum sensing publication output. The field of quantum sensing is small relative to the other two application domains; the nine countries considered here published just 2,416 quantum sensing publications, compared with 5,883 quantum communication and 10,734 quantum computing publications. Over the 2012–2021 period of analysis, China was the top producer of quantum sensing publications—but as we discuss later, China’s output had a very different topical focus from those of other nations.

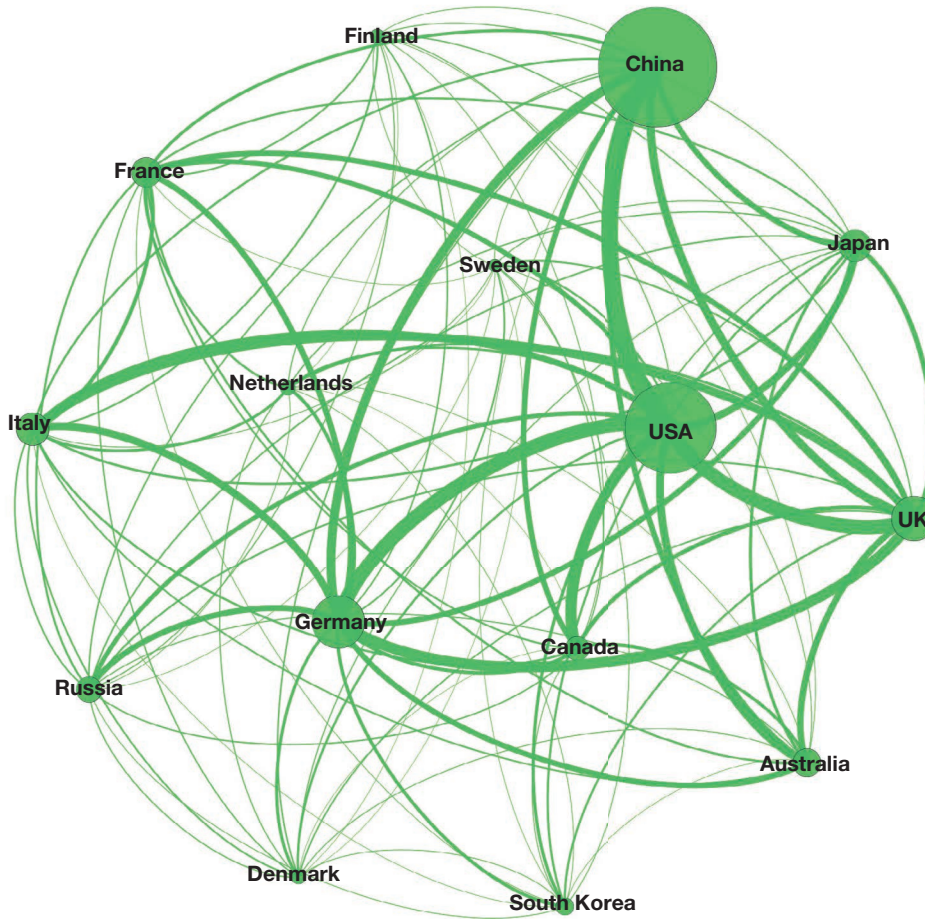
Figure 2.3 depicts the coauthorship network of the top quantum sensing publishing countries. Germany is the most central country in the quantum sensing coauthorship network, despite producing fewer publications than the United States and China.

TABLE 2.4
Quantum Sensing Publication Output and Collaboration Metrics, by Country, 2012–2022

Country	Global Rank	Publications	Countries with at Least One Collaboration	Centrality	Publications per \$B of GDP	Share of Publications with an International Collaboration (%)
China	1	1,853	41	0.92	0.151	19.3
United States	2	1,367	50	0.98	0.073	51.0
Germany	3	725	52	1.00	0.212	68.0
UK	4	589	44	0.94	0.197	71.7
Italy	5	387	43	0.89	0.209	66.6
Japan	6	378	42	0.92	0.085	49.3
France	7	342	44	0.94	0.138	72.6
Australia	8	307	39	0.88	0.220	75.1
Russia	9	271	33	0.79	0.193	28.6
Canada	10	245	31	0.78	0.154	76.0
South Korea	14	136	28	0.74	0.089	37.1
Netherlands	19	93	28	0.73	0.118	72.5
Denmark	21	77	29	0.77	0.245	74.8
Finland	22	69	26	0.67	0.283	79.0
Sweden	26	46	27	0.73	0.089	78.7

NOTE: This list merges the sets of the top ten global publishers for this application domain and the nine allies in the common baseline.

FIGURE 2.3
Quantum Sensing Coauthorship Network



NOTE: The figure represents the countries listed in Table 2.4. Node size is determined by the number of publications a country has produced in the field during the 2012–2021 period of analysis. Edges reflect collaborations (i.e., coauthored publications) between countries, and the thickness of edges is determined by the number of collaborations between the countries. The graph layout uses the Fruchterman-Reingold force-directed approach.

High-Impact Research Activity

Scientific publications are not all of equal importance. Certain publications have profound and lasting impact on a field, while others have trivial impact. One way to account for heterogeneity in publication impact is to consider a publication's citation count. Publications that accrue many citations from subsequent research can be said to have greater impact. To account for heterogeneity in publication quality, we computed the number of publications for each country that fell into the top decile of the citation distribution.⁶

The national rankings within the nine common baseline countries based on high-impact publications were very similar to those based on total publication counts. In fact, the only country that fell in the rankings was South Korea. Given its total publications, South Korea ranked fifth in quantum communication and quantum sensing and sixth in computing. However, using the high-impact metric (i.e., publications in the

⁶ Jon Schmid, *An Open-Source Method for Assessing National Scientific and Technological Standing: With Applications to Artificial Intelligence and Machine Learning*, RAND Corporation, RR-A1482-3, 2021.

top decile of the citation distribution), South Korea ranked eighth in all three domains. The ratios of high-impact publications between countries were also closely proportional to the ratios of total publications.

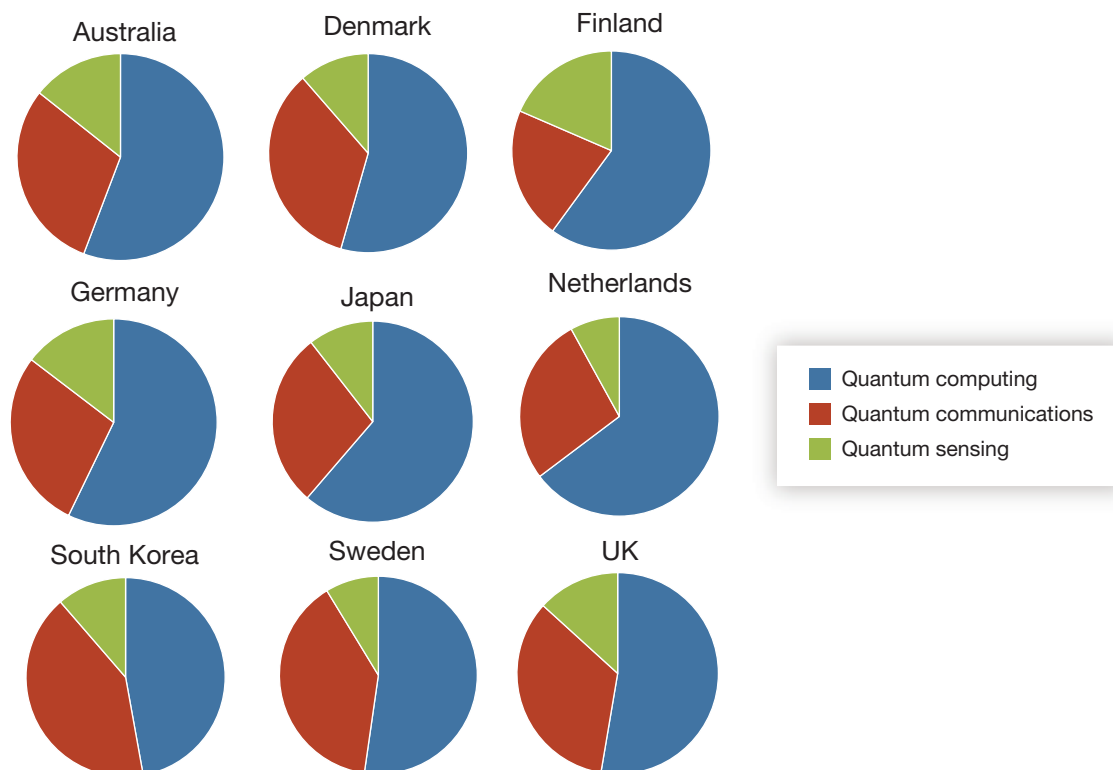
Topical Focus

Figure 2.4 shows the comparative proportions of scientific publishing across the three application domains for each of the nine common baseline nations. For the most part, they are fairly similar: Every nation has the most publications about quantum computing and the least on quantum sensing. Notably, South Korea is the only nation within the common baseline set that had (slightly) more publications on quantum communications or sensing than on quantum computing.

The three quantum application domains considered here are complex technical fields with many subdomains. For example, within the quantum computing application domain, distinct communities of researchers work on particular hardware (e.g., optical computer development) and software (e.g., quantum machine learning) approaches. To assess country-level activity at a level of detail greater than the application domain, we defined a set of subdomains of interest for each application domain.

For quantum computing, we considered four subdomains: algorithms and end-user applications; basic computational paradigms; hardware approaches; and critical enablers, characterization, and benchmarking. For quantum communications, we considered three subdomains: quantum-secured communication; entanglement-based protocols; and critical enablers, characterization, and benchmarking. For quantum

FIGURE 2.4
Proportional Scientific Publishing Across Quantum Information Science Application Domains, by Nation



NOTE: Publications that were categorized within multiple application domains are counted multiply within each domain in this figure.

sensing, we considered four subdomains: technical approaches and enablers, imaging applications, nonimaging applications, and quantum metrology.

The following subsections depict the results of this topic analysis. Each row in a table corresponds with a small set of closely related author-provided keywords related to that topic, and the table reports the number of publications with an author from each country that provides one of that row's words as an author-provided keyword. Darker-shaded cells indicate higher values. Appendix B gives further details on methodology and lists the exact set of keywords corresponding to each row.

Quantum Computing

Tables 2.5 and 2.6 depict the country-level scientific publishing activity for select subdomains. Table 2.5 contains the country-level subdomain output measured in publication counts, and Table 2.6 depicts the same data as a proportion of the that country's total number of publications within the application domain (e.g., 10 percent of U.S. quantum computing publications dealt with the topic of quantum simulation).

Broadly speaking, the distribution of publication activity between different subtopics is very similar among countries, particularly for the larger countries. For example, quantum simulation and quantum optimization were the two main applications for every country, with quantum machine learning far behind and almost no research on Shor's algorithm. There are very slight differences in relative focus between various qubit types. Japan is somewhat more focused than other countries on non-gate-based approaches to quantum computing, such as quantum annealing and cluster-state computing. Generally speaking, no country invests a large proportion of its research in any one subtopic. There is more variation among the smaller countries—for example, Denmark and Finland have unusually large proportions of publishing on quantum dots and superconducting qubits, respectively—but this largely reflects the fact that the total number of publications is smaller for these countries, so a relatively small absolute number of publications can significantly change the proportions.

TABLE 2.5
Quantum Computing Subdomains, by Country, Absolute Counts, 2012–2021

	USA	China	Germany	UK	Japan	India	Canada	France	Australia	Italy	Russia	Netherlands	Iran	South Korea	Denmark	Sweden	Finland
Algorithms and end-user applications																	
Quantum simulation	757	445	362	226	136	60	102	180	85	149	50	57	44	38	29	17	14
Quantum machine learning	125	140	24	56	32	39	29	12	19	26	18	15	8	18	3	1	2
Optimization	719	536	154	140	152	178	148	74	49	71	46	46	71	34	14	13	11
Computational complexity	126	110	18	37	30	14	30	15	20	10	17	19	8	9	4	3	0
Grover’s algorithm	127	136	20	49	23	31	15	14	9	16	18	13	6	10	3	3	1
Shor’s algorithm	46	30	7	10	6	14	1	3	5	1	2	3	2	4	0	4	1
Variational quantum eigensolver	86	10	12	22	17	2	23	2	3	4	5	7	0	2	2	0	1
QAOA	84	7	14	4	3	0	9	3	4	3	7	6	0	7	1	2	0
Basic computational paradigms																	
Quantum annealing	285	43	40	45	134	10	72	14	2	40	6	14	5	5	6	5	3
Cluster state	188	380	110	76	160	54	44	51	53	40	45	9	19	13	13	7	8
Adiabatic quantum computing	100	32	20	17	21	3	20	3	4	13	5	1	4	1	0	1	0
Boson sampling	53	41	30	41	17	0	26	10	23	23	2	9	2	13	4	0	0
Noisy intermediate-scale quantum	165	48	26	44	18	7	20	5	12	5	8	9	1	9	2	2	3
Fault tolerant	52	27	10	18	8	19	11	7	6	2	3	0	6	0	3	2	0
Hardware approaches																	
Optical computing	278	326	52	73	41	162	44	39	47	30	32	13	38	22	8	6	5
Single photon	333	462	196	163	102	22	75	74	81	65	54	37	9	50	34	26	10

Table 2.5—Continued

	USA	China	Germany	UK	Japan	India	Canada	France	Australia	Italy	Russia	Netherlands	Iran	South Korea	Denmark	Sweden	Finland
Quantum dot	362	300	175	123	113	82	63	92	89	44	53	82	24	33	44	18	13
Spin qubits	192	83	77	50	67	6	33	42	78	23	13	53	4	6	7	8	4
Superconducting qubit	566	374	202	94	156	27	94	82	49	50	116	44	8	26	38	33	38
Trapped ion	243	114	122	83	27	11	25	37	35	20	8	12	8	10	7	7	3
Rydberg atom	130	155	122	80	23	8	10	63	11	36	28	16	5	13	15	5	0
Nitrogen-vacancy center	74	167	56	16	31	4	3	7	13	5	7	8	0	4	5	2	1
Majorana fermions	181	142	63	28	42	10	20	20	13	18	16	26	3	9	10	6	1
Critical enablers, characterization, and benchmarking																	
Quantum error correction	424	116	120	118	94	43	105	47	92	18	18	55	9	18	23	8	5
Quantum control	157	169	43	30	23	9	37	29	39	18	9	12	12	7	5	2	6
Fidelity	709	749	213	185	145	65	134	73	141	50	57	65	19	38	41	19	16
Quantum memory	103	90	35	31	35	7	24	17	20	5	24	11	7	7	8	5	1
Total publications	7,890	7,591	2,836	2,351	2,209	1,684	1,631	1,410	1,195	1,183	1,020	746	566	568	369	278	226

NOTE: QAOA = quantum approximate optimization algorithm. Darker-shaded cells indicate higher values.

TABLE 2.6

Quantum Computing Subdomains, by Country, Proportional Counts, 2012–2021

	USA (%)	China (%)	Germany (%)	UK (%)	Japan (%)	India (%)	Canada (%)	France (%)	Australia (%)	Italy (%)	Russia (%)	Netherlands (%)	Iran (%)	South Korea (%)	Denmark (%)	Sweden (%)	Finland (%)
Algorithms and end-user applications																	
Quantum simulation	10	6	13	10	6	4	6	13	7	13	5	8	8	7	8	6	6
Quantum machine learning	2	2	1	2	1	2	2	1	2	2	2	2	1	3	1	0	1
Optimization	9	7	5	6	7	11	9	5	4	6	5	6	13	6	4	5	5
Computational complexity	2	1	1	2	1	1	2	1	2	1	2	3	1	2	1	1	0
Grover’s algorithm	2	2	1	2	1	2	1	1	1	1	2	2	1	2	1	1	0
Shor’s algorithm	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0
Variational quantum eigensolver	1	0	0	1	1	0	1	0	0	0	0	1	0	0	1	0	0
QAOA	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	1	0
Basic computational paradigms																	
Quantum annealing	4	1	1	2	6	1	4	1	0	3	1	2	1	1	2	2	1
Cluster state	2	5	4	3	7	3	3	4	4	3	4	1	3	2	4	3	4
Adiabatic quantum computing	1	0	1	1	1	0	1	0	0	1	0	0	1	0	0	0	0
Boson sampling	1	1	1	2	1	0	2	1	2	2	0	1	0	2	1	0	0
Noisy intermediate-scale quantum	2	1	1	2	1	0	1	0	1	0	1	1	0	2	1	1	1
Fault tolerant	1	0	0	1	0	1	1	0	1	0	0	0	1	0	1	1	0

Table 2.6—Continued

	USA (%)	China (%)	Germany (%)	UK (%)	Japan (%)	India (%)	Canada (%)	France (%)	Australia (%)	Italy (%)	Russia (%)	Netherlands (%)	Iran (%)	South Korea (%)	Denmark (%)	Sweden (%)	Finland (%)
Hardware approaches																	
Optical computing	4	4	2	3	2	10	3	3	4	3	3	2	7	4	2	2	2
Single photon	4	6	7	7	5	1	5	5	7	5	5	5	2	9	9	9	4
Quantum dot	5	4	6	5	5	5	4	7	7	4	5	11	4	6	12	6	6
Spin qubits	2	1	3	2	3	0	2	3	7	2	1	7	1	1	2	3	2
Superconducting qubit	7	5	7	4	7	2	6	6	4	4	11	6	1	5	10	12	17
Trapped ion	3	2	4	4	1	1	2	3	3	2	1	2	1	2	2	3	1
Rydberg atom	2	2	4	3	1	0	1	4	1	3	3	2	1	2	4	2	0
Nitrogen-vacancy center	1	2	2	1	1	0	0	0	1	0	1	1	0	1	1	1	0
Majorana fermions	2	2	2	1	2	1	1	1	1	2	2	3	1	2	3	2	0
Critical enablers, characterization, and benchmarking																	
Quantum error correction	5	2	4	5	4	3	6	3	8	2	2	7	2	3	6	3	2
Quantum control	2	2	2	1	1	1	2	2	3	2	1	2	2	1	1	1	3
Fidelity	9	10	8	8	7	4	8	5	12	4	6	9	3	7	11	7	7
Quantum memory	1	1	1	1	2	0	1	1	2	0	2	1	1	1	2	2	0
Total publications	7,890	7,591	2,836	2,351	2,209	1,684	1,631	1,410	1,195	1,183	1,020	746	566	568	369	278	226

NOTE: Darker-shaded cells indicate higher values.

Quantum Communications

Tables 2.7 and 2.8 depict the country-level scientific publishing activity in counts and proportion, respectively, for the quantum communication subdomains. China's primacy in quantum communication publishing is worth noting; China is the top global publisher in every subdomain with the exception of quantum error correction, in which the United States is the global leader.⁷ China and Russia are modestly more focused on QKD than U.S.-allied nations are, but the difference is not huge.

Quantum Sensing

Tables 2.9 and 2.10 provide the publishing counts and proportional counts, respectively, for the quantum sensing subdomains. Here the results are more mixed; in some cases, the United States leads China (e.g., most of the technical approaches and enablers) and in others (e.g., the imaging and quantum metrology subdomains) China is the global leader.

One notable result is the very high proportion of Chinese quantum sensing publications that focus on ghost imaging; remarkably, Chinese researchers published more than 700 papers on that topic within the decade, nearly an order of magnitude more than the United States. Other, more modest differences are Germany's and Japan's focus on nitrogen-vacancy centers and magnetometry and France's focus on atom interferometry and gravimetry. (France is the only listed country with a higher share of publications on gravimetry than on magnetometry.)

⁷ Quantum error correction spans both quantum computing and quantum communications (e.g., within quantum repeaters), but these counts include only publications that we separately classified as being focused on quantum communications. The quantum computing database includes much larger numbers of publications about quantum error correction.

TABLE 2.7
Quantum Communications Subdomains, by Country, Absolute Counts, 2012–2021

	China	USA	UK	Germany	Canada	Japan	India	Italy	Spain	Australia	Russia	South Korea	Iran	Netherlands	Denmark	Sweden	Finland
Quantum-secured communication																	
Quantum cryptography	774	407	176	146	154	151	175	68	53	56	150	94	34	69	26	18	9
Quantum key distribution	1,857	545	371	190	257	221	153	111	141	116	175	105	41	45	48	34	8
Entanglement-based protocols																	
Entanglement	2,462	917	510	472	328	292	376	268	220	219	120	171	191	105	71	65	27
Quantum teleportation	431	108	68	53	35	74	93	39	21	20	19	26	37	13	11	6	2
Quantum secret sharing	264	20	10	7	11	12	18	1	4	12	1	10	14	1	6	2	0
entanglement swapping	231	53	28	27	17	21	18	19	9	11	1	20	31	3	7	2	0
Entanglement concentration	168	20	12	6	6	12	11	7	3	3	3	5	2	1	1	4	0
measurement device independent	295	26	39	8	38	19	14	3	24	9	1	13	0	2	5	4	0
Critical enablers, characterization, and benchmarking																	
Fidelity	606	235	109	125	74	78	76	54	27	44	18	29	45	31	23	20	3
quantum memory	155	93	39	41	37	29	15	7	17	22	12	6	7	14	11	2	0
quantum repeater	141	121	60	92	53	64	2	15	16	32	7	12	8	28	17	8	0
quantum error correction	22	59	16	13	22	17	7	1	6	7	6	4	4	7	0	1	1
Total publications	6,991	2,897	1,517	1,391	1,029	1,010	830	730	644	639	616	499	379	313	230	207	81

NOTE: Darker-shaded cells indicate higher values

TABLE 2.8

Quantum Communications Subdomains, by Country, Proportional Counts, 2012–2021

	China (%)	USA (%)	UK (%)	Germany (%)	Canada (%)	Japan (%)	India (%)	Italy (%)	Spain (%)	Australia (%)	Russia (%)	South Korea (%)	Iran (%)	Netherlands (%)	Denmark (%)	Sweden (%)	Finland (%)
Quantum-secured communication																	
Quantum cryptography	11.1	14.0	11.6	10.5	15.0	15.0	21.1	9.3	8.2	8.8	24.4	18.8	9.0	22.0	11.3	8.7	11.1
Quantum key distribution	26.6	18.8	24.5	13.7	25.0	21.9	18.4	15.2	21.9	18.2	28.4	21.0	10.8	14.4	20.9	16.4	9.9
Entanglement-based protocols																	
Entanglement	35.2	31.7	33.6	33.9	31.9	28.9	45.3	36.7	34.2	34.3	19.5	34.3	50.4	33.5	30.9	31.4	33.3
Quantum teleportation	6.2	3.7	4.5	3.8	3.4	7.3	11.2	5.3	3.3	3.1	3.1	5.2	9.8	4.2	4.8	2.9	2.5
Quantum secret sharing	3.8	0.7	0.7	0.5	1.1	1.2	2.2	0.1	0.6	1.9	0.2	2.0	3.7	0.3	2.6	1.0	0.0
Entanglement swapping	3.3	1.8	1.8	1.9	1.7	2.1	2.2	2.6	1.4	1.7	0.2	4.0	8.2	1.0	3.0	1.0	0.0
Entanglement concentration	2.4	0.7	0.8	0.4	0.6	1.2	1.3	1.0	0.5	0.5	0.5	1.0	0.5	0.3	0.4	1.9	0.0
Measurement device independent	4.2	0.9	2.6	0.6	3.7	1.9	1.7	0.4	3.7	1.4	0.2	2.6	0.0	0.6	2.2	1.9	0.0
Critical enablers, characterization, and benchmarking																	
Fidelity	8.7	8.1	7.2	9.0	7.2	7.7	9.2	7.4	4.2	6.9	2.9	5.8	11.9	9.9	10.0	9.7	3.7
Quantum memory	2.2	3.2	2.6	2.9	3.6	2.9	1.8	1.0	2.6	3.4	1.9	1.2	1.8	4.5	4.8	1.0	0.0
Quantum repeater	2.0	4.2	4.0	6.6	5.2	6.3	0.2	2.1	2.5	5.0	1.1	2.4	2.1	8.9	7.4	3.9	0.0
Quantum error correction	0.3	2.0	1.1	0.9	2.1	1.7	0.8	0.1	0.9	1.1	1.0	0.8	1.1	2.2	0.0	0.5	1.2
Total publications	6,991	2,897	1,517	1,391	1,029	1,010	830	730	644	639	616	499	379	313	230	207	81

NOTE: Darker-shaded cells indicate higher values.

TABLE 2.9
Quantum Sensing Subdomains, by Country, Absolute Counts, 2012–2021

	China	USA	Germany	UK	Italy	Japan	France	Australia	Russia	Canada	South Korea	Netherlands	Denmark	Finland	Iran	Sweden
Technical approaches and enablers																
Atom interferometer	153	164	93	71	50	15	109	27	6	7	7	22	9	2	0	2
Nitrogen-vacancy center	123	133	133	32	20	73	22	52	13	5	11	17	5	1	0	0
Single photon	102	122	62	60	54	33	7	21	15	23	11	10	8	1	5	12
Cold atom	66	54	45	27	19	4	42	9	6	1	7	8	6	1	1	0
Bose-Einstein condensate	23	40	46	14	12	3	12	10	4	3	4	4	1	0	2	0
Quantum dot	12	29	36	12	5	12	9	4	2	2	4	3	1	2	1	2
Rydberg atom	6	18	5	3	2	2	6	0	2	2	0	0	1	0	1	0
Imaging applications																
Ghost imaging	705	83	31	47	17	43	27	26	17	17	6	5	0	21	13	2
Quantum radar	44	40	5	3	5	4	0	1	0	21	0	1	0	1	1	2
Quantum imaging	203	100	22	50	34	6	14	14	10	18	6	6	0	1	1	2
Quantum illumination	6	14	3	7	5	3	0	1	0	6	1	1	0	3	1	0
Nonimaging applications																
Magnetometry	117	114	81	34	16	48	15	33	45	12	7	10	5	2	1	2
Gyroscope	24	32	3	6	2	0	13	3	5	1	0	1	0	0	0	0
Atomic clocks	18	35	21	23	10	4	5	7	7	5	2	3	10	0	0	1
Dark matter	2	29	10	6	4	4	5	4	2	1	1	1	1	0	0	1
Gravimeter	39	18	19	8	8	0	23	3	1	2	1	7	1	0	0	2
Quantum radiometry	0	1	4	1	3	0	0	0	0	0	1	0	0	0	0	0

Table 2.9—Continued

	China	USA	Germany	UK	Italy	Japan	France	Australia	Russia	Canada	South Korea	Netherlands	Denmark	Finland	Iran	Sweden
Quantum metrology																
Quantum metrology	357	221	143	183	131	73	60	59	42	60	31	13	21	14	18	12
Spin squeezing	126	90	40	32	23	21	15	23	7	25	5	0	15	2	4	1
Total publications	1,853	1,363	724	589	387	377	341	307	271	245	136	92	77	69	51	46

NOTE: Darker-shaded cells indicate higher values

TABLE 2.10
Quantum Sensing Subdomains, by Country, Proportional Counts, 2012–2021

	China (%)	USA (%)	Germany (%)	UK (%)	Italy (%)	Japan (%)	France (%)	Australia (%)	Russia (%)	Canada (%)	South Korea (%)	Netherlands (%)	Denmark (%)	Finland (%)	Iran (%)	Sweden (%)
Technical approaches and enablers																
Atom interferometer	8	12	13	12	13	4	32	9	2	3	5	24	12	3	0	4
Nitrogen-vacancy center	7	10	18	5	5	19	6	17	5	2	8	18	6	1	0	0
Single photon	6	9	9	10	14	9	2	7	6	9	8	11	10	1	10	26
Cold atom	4	4	6	5	5	1	12	3	2	0	5	9	8	1	2	0
Bose-einstein condensate	1	3	6	2	3	1	4	3	1	1	3	4	1	0	4	0
Quantum dot	1	2	5	2	1	3	3	1	1	1	3	3	1	3	2	4
Rydberg atom	0	1	1	1	1	1	2	0	1	1	0	0	1	0	2	0

Table 2.10—Continued

	China (%)	USA (%)	Germany (%)	UK (%)	Italy (%)	Japan (%)	France (%)	Australia (%)	Russia (%)	Canada (%)	South Korea (%)	Netherlands (%)	Denmark (%)	Finland (%)	Iran (%)	Sweden (%)
Imaging applications																
Ghost imaging	38	6	4	8	4	11	8	8	6	7	4	5	0	30	25	4
Quantum radar	2	3	1	1	1	1	0	0	0	9	0	1	0	1	2	4
Quantum imaging	11	7	3	8	9	2	4	5	4	7	4	7	0	1	2	4
Quantum illumination	0	1	0	1	1	1	0	0	0	2	1	1	0	4	2	0
Nonimaging applications																
Magnetometry	6	8	11	6	4	13	4	11	17	5	5	11	6	3	2	4
Gyroscope	1	2	0	1	1	0	4	1	2	0	0	1	0	0	0	0
Atomic clocks	1	3	3	4	3	1	1	2	3	2	1	3	13	0	0	2
Dark matter	0	2	1	1	1	1	1	1	1	0	1	1	1	0	0	2
Gravimeter	2	1	3	1	2	0	7	1	0	1	1	8	1	0	0	4
Quantum radiometry	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	0
Quantum metrology																
Quantum metrology	19	16	20	31	34	19	18	19	15	24	23	14	27	20	35	26
Spin squeezing	7	7	6	5	6	6	4	7	3	10	4	0	19	3	8	2
Total publications	1,853	1,363	724	589	387	377	341	307	271	245	136	92	77	69	51	46

NOTE: Darker-shaded cells indicate higher values.

Government Support

Data Sources

We started from *A Quantum Revolution: Report on Global Policies for Quantum Technology*, which provided extensive information on government-funded quantum technology programs and projects in different countries.⁸ We supplemented these data with additional information for each of the nine U.S.-allied countries in our common baseline set, drawing from websites belonging to a various entities, including research councils; research centers; ministries of education, research, and energy; and academic institutions. These sources are listed below Figure 2.5. Some nations' governments had funded research councils that provided annual reports on actual quantum technology investments. In other cases, we drew on press releases reporting funding information, in which case we distinguished between planned and actualized funding. Unless otherwise indicated, all currencies have been converted to U.S. dollars using the exchange rates at the time of data collection in late 2022, which may have changed somewhat from the exchange rates at the time of spending.

Total and Annualized Spending

Figures 2.5 and 2.6 respectively summarize total and approximate annualized spent or planned government spending on quantum technology activities. This includes R&D, training, education, building facilities, and other non-research-specific activities, at both the national and state levels.

The total funding amounts include active quantum programs as of 2023. These programs began (and have documented government funding) as early as 2012 and project as far out as 2034. Because different countries' government programs extend over very different periods that only partially overlap, it is difficult to compare them directly. To make these investments more directly comparable, we estimated annualized spending amounts by dividing each country's spending for each quantum program over the lifetime of that program.⁹

The UK leads in funding, mostly because of a planned \$3 billion in government funding between 2024 and 2034 announced in the UK's National Quantum Strategy.¹⁰ The UK is followed by Germany, then by significantly lower levels of government funding from Japan and the Netherlands, with Australia rounding out the top five countries out of nine that were included in common baseline set of allied nations. Figure 2.6 also shows the (approximate) annualized spending as a percentage of GDP to give a measure that is normalized by country size.

Most of Germany's government funding for quantum technology comes from a coronavirus 2019 (COVID-19) relief stimulus package that allocates a considerable amount of funding to "future technologies." €2 billion of this €50 billion future technology package will go to quantum technology, but it remains to be seen whether this level of funding will be sustained as COVID-19 emergency measures end.¹¹ As noted in Figure 2.5, without this COVID-19-specific funding, Germany's total government funding for quantum technology is brought down to about \$0.9 billion—comparable to that of the Netherlands.

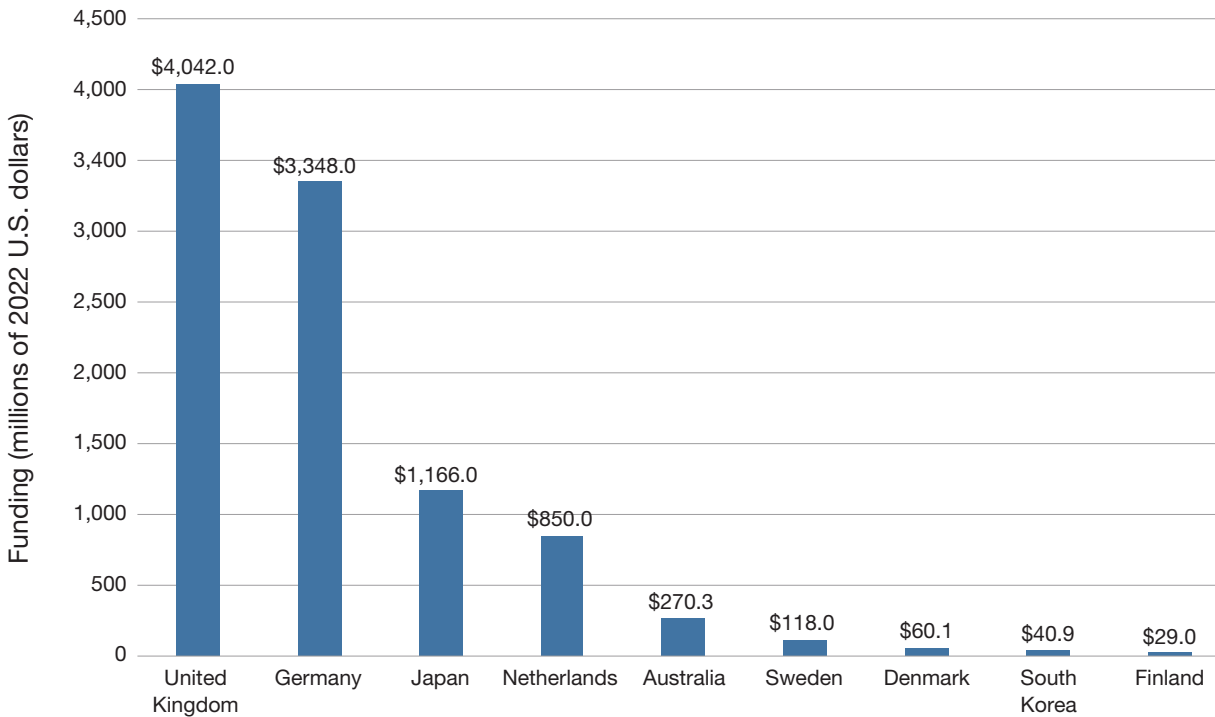
⁸ Kung and Fancy, 2021.

⁹ An important caveat is that this yields only the annual spending averaged over the program lifetime, not the spending for any particular year, so these numbers are still not directly comparable. For example, if two national government programs spend the same increasing amount every year, a program that extends further into the future will report a higher average annual spending than one that extends further into the past, even if both governments are spending the same total amount each year.

¹⁰ Department for Science Innovation & Technology, *National Quantum Strategy*, 2023.

¹¹ Éanna Kelly, "Germany Unveils €50B Stimulus for 'Future-Focused' Technologies," *Science Business*, June 4, 2020.

FIGURE 2.5
Total Government Funding for Quantum Technology Between 2012 and 2034



SOURCES: Government of the Netherlands, "Government Allocates €646 Million to Projects Designed to Boost Economic Growth," press release, April 21, 2021; Japan Science and Technology Agency, "Japanese Ongoing Projects in the Field of Quantum Science (FY2021)," webpage, 2021; Johnny Kung and Muriam Fancy, *A Quantum Revolution: Report on Global Policies for Quantum Technology*, CIFAR, 2021; ML4Q, "EIN Quantum NRW: North Rhine-Westphalia Joins Forces to Establish a Hub for Quantum Science and Technologies," webpage, undated; Niels Bohr Institute, "FIRE-Q: Field-Ready Single-Photon Quantum Technology," webpage, undated; Quantum Technology Finland, "About: Key Numbers," webpage, undated; Annette Stettien and Wiebke Rögner, *Facts and Figures*, Forschungszentrum Jülich, 2021; Swinburne University of Technology, "ColdQuanta-Swinburne Centre to Turbocharge Quantum Tech," press release, October 28, 2022; Department for Science Innovation & Technology, *National Quantum Strategy*, United Kingdom, 2023; University of Sydney, "Universities Welcome NSW Government Backing for Sydney Quantum Academy," press release, March 9, 2019.

NOTE: Germany's COVID-19 recovery fund includes a \$2.4 billion investment in quantum technologies, which may or may not be realized in the coming years. Excluding this investment, German government funding for quantum research is about \$0.9 billion, which would place Germany in between Japan and the Netherlands in terms of government investment.

Industry Activity

Table 2.11 summarizes the start-up ecosystem aspect of the commercial quantum technology industries of U.S.-allied countries. Start-ups represent only one part of the commercial industry, but this table focuses on start-ups because of the clarity and availability of data on them and because they have defined goals and typically publicly report funding.¹² We included the nine common baseline allied nations, as well as Canada and France, because of their notably large quantum technology start-up industries. The last column identifies the total publicly announced funding raised by all start-ups headquartered in each country.¹³

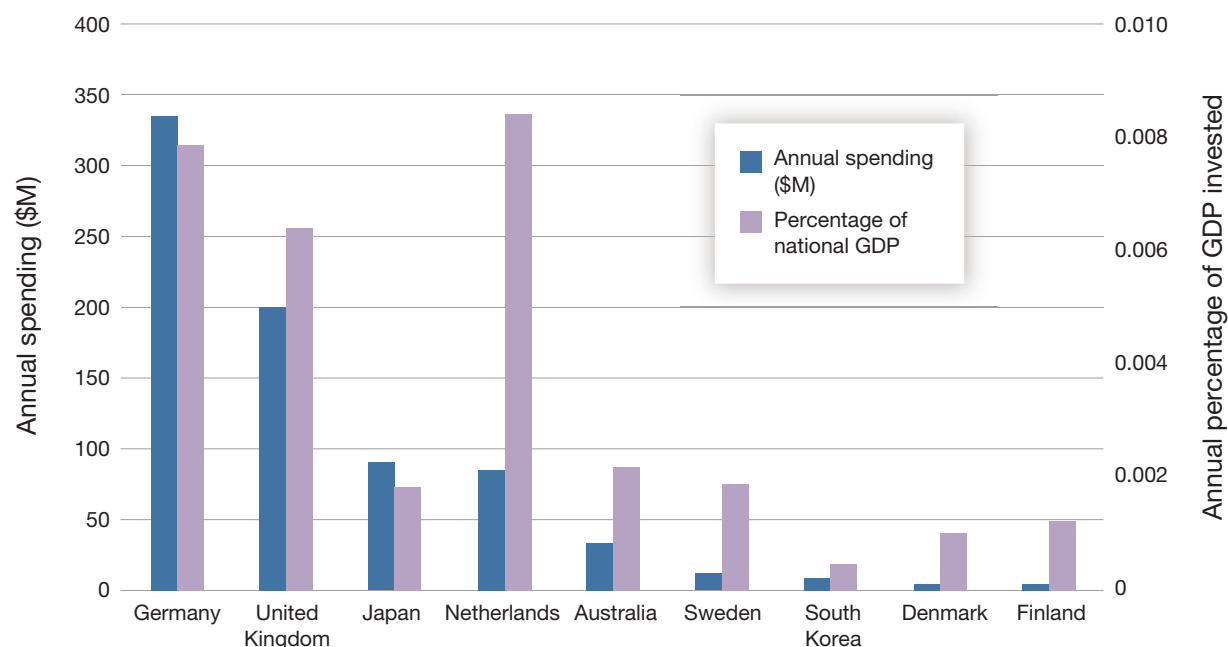
Of the selected countries, the UK has the largest number of start-ups with the most funding, although Australia's relatively few start-ups are better funded on average. While this table reports data on start-ups, the

¹² It can be much difficult to tell the extent of the quantum R&D efforts of larger and more-established companies, and we did not have the resources to do so for the entire global ecosystem.

¹³ As we discuss in Chapter 3, different countries have different legal requirements and industry cultures regarding reporting start-up funding, so these figures may have different levels of completeness.

FIGURE 2.6

Approximate Annual Government Funding for Quantum Technology Research and Development



NOTE: By comparison, the U.S. federal government spent \$918 million on quantum technology R&D in fiscal year 2022, or about 0.0036 percent of GDP (National Science & Technology Council, *National Quantum Initiative Supplement to the President's FY 2023 Budget*, Subcommittee on Quantum Information Science, January 2023). No reliable public-source information is available on China's annual government quantum technology spending (Parker et al., 2022).

TABLE 2.11
Number of Quantum Technology Start-Ups of U.S.-Allied Nations

Country	Number of Start-Ups	Total Start-Up Funding (\$M)
Canada	31	709.00
UK	29	561.80
Australia	7	429.60
Finland	5	237.80
France	13	216.64
Germany	24	144.60
Netherlands	9	29.30
Japan	10	24.20
Denmark	3	2.27
South Korea	3	0.90
Sweden	3	0.05

SOURCES: Companies identified from Quantum Computing Report, homepage, undated; Quantum Insider, homepage, undated; and Quantum Zeitgeist, homepage, undated. Financial information derived from Crunchbase, homepage, undated; Bloomberg, homepage, undated; and supplemental press releases and news coverage.

state of the quantum technology industrial base does not solely depend on start-up companies and the funding they raise. Public and established private firms are also working on developing quantum technologies or enabling materiel. Different countries vary in their approaches to scientific and technological development, with some countries' industrial bases focused more on investments from large publicly owned conglomerates (as in Japan) or mid-sized private firms (as in Germany) rather than start-ups. We will discuss these structural differences in greater detail in the following chapters.

Technical Achievement

This section summarizes two different aspects of global technical achievement. The first subsection describes global patenting activity by nation. The second subsection captures one particular aspect of national achievement: which nations (outside the United States or China) have achieved or announced a concrete timeline to build or acquire a working quantum computer prototype.

Patenting Activity

Inventors submit patent applications to national and international patent-granting organizations with the expectation of legal protection for the invention described in the application, should the patent be granted, for 20 years in the country or countries in which the application is filed. The resources invested in developing the (invention and) patent application are akin to a bet that the application will result in a patent grant that protects a market innovation providing a greater return than that investment. Moreover, patent applications are customarily filed first in the country in which the invention is made.¹⁴ Accordingly, the volume of patent applications and/or patents issued in a technical area provides a measure of the potential innovations in that technical area in the country in which they are initially filed.¹⁵ We used the same keywords as for the publication counts to count the total number of patent application first filed in each of the allied countries in each of the areas of quantum information science and technology.

The patent data that we used were derived from the IFI's CLAIMS Direct Data Collection platform, which includes full-text patent data from 38 countries, together with metadata, such as filing date, patent classes, assignees, and drawings.¹⁶ Patent text is machine translated to English, and the format is standardized to facilitate analysis.¹⁷ For each technical sector, we counted all patent applications that have any of the keywords associated with that sector anywhere in the text. For quantum computing, which has a specific technology subclassification under the Cooperative Patent Classification Scheme, which many national and international patent-granting organizations use, we included patent applications assigned to this subclassification that were not captured by the keywords. We recorded the year in which each patent application was filed, as well as the priority year of a family of patent applications when multiple applications were filed on a single invention. For issued patents, we recorded the year of the patent grant.

¹⁴ In the United States, a Foreign Filing License is required from the Department of Commerce to file a patent application overseas. This practice is common among national patent-granting organizations.

¹⁵ Excluding innovations stemming from inventions for which a patent application is not filed, e.g., those kept as trade secrets.

¹⁶ IFI, "CLAIMS Direct Data Collection," database, undated.

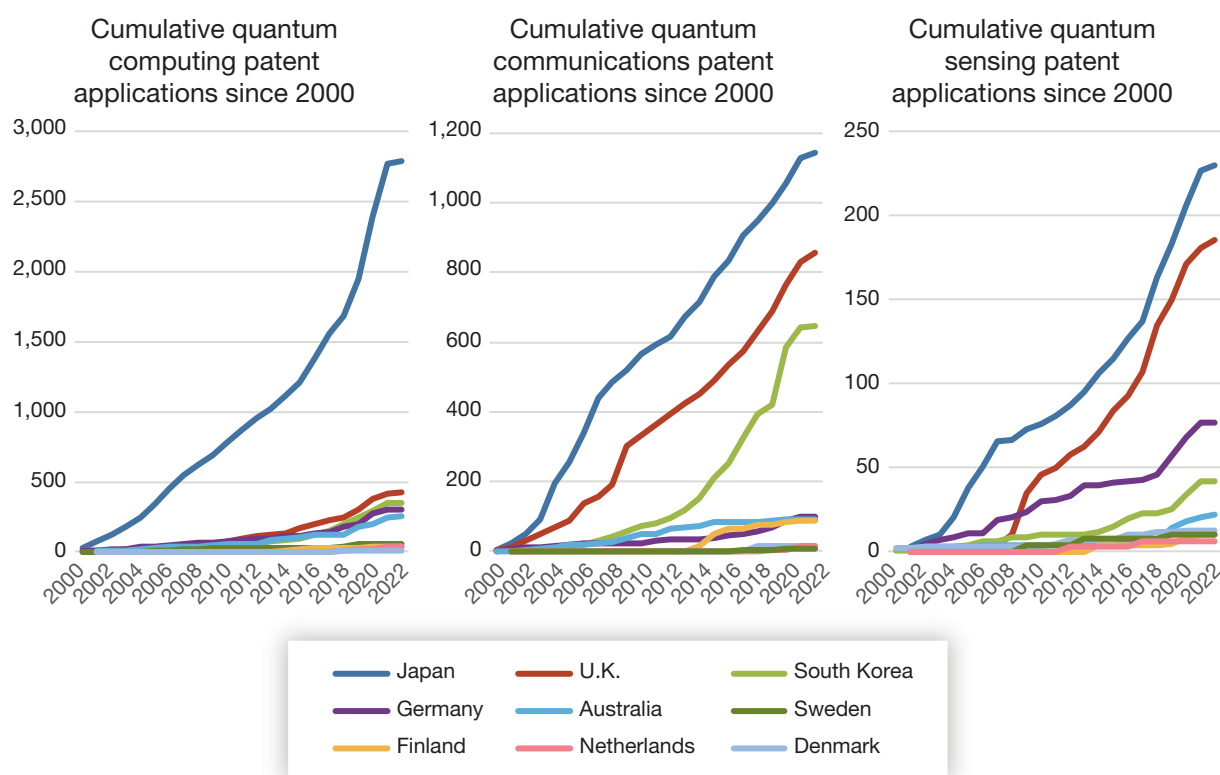
¹⁷ This dataset includes more than 100 sources and 125 million records. It is generally considered to be the most comprehensive patent dataset, containing the large majority of all patents filed anywhere in the world (patent data from IFI, undated).

Figure 2.7 shows the total patent applications for quantum computing, communications, and sensing from the nine common baseline U.S.-allied countries.¹⁸ We are reporting cumulative rather than annual totals to smooth out the high levels of year-to-year noise. More patent applications were first filed in Japan than in any of the other allied countries in all three areas of quantum information science and technology. However, it is important to note that the total patent application filings in allied countries are much smaller than those of the United States and China, which are shown for comparison in the notes to each figure.

Areas of Patenting Activity

In addition to the cumulative patent counts for each application domain, we investigated the technical areas in which patent applications have been filed in different countries in quantum computing, quantum communications and quantum sensing, using the same technical subareas that we used for publications and displayed in Tables 2.5 through 2.10. In this case, we included all countries filing patent applications. Appendix A supplies the resulting tables.

FIGURE 2.7
Cumulative Quantum Technology Patent Applications from U.S.-Allied Countries



SOURCE: RAND analysis of patent data from IFI, undated.

NOTE: Over the same period, the totals were 18,844 in the United States and 9,677 in China for quantum computing; 4,612 in the United States and 11,454 in China for quantum communications; and 1,569 in the United States and 1,332 in China for quantum sensing.

¹⁸ See Parker et al., 2022.

Quantum Computer Prototypes in U.S.-Allied Nations

A global assessment of demonstrated leadership in specific deployments of quantum technology applications was out of scope for this project. But we did collect data on one specific and concrete facet of technology leadership: which nations have built, or announced specific timelines to build, a functioning quantum computer prototype with specified technical metrics of any type.

Previous RAND research found that, as of 2021, the United States was the only nation to deploy quantum computers of a meaningful scale that used trapped-ion and neutral-atom qubit technologies, and the United States and China were the only two nations to deploy quantum computers using superconducting transmon qubit technology (with the two nations' prototypes having similar technical performance).¹⁹ Since then, countries in Europe and Japan and South Korea have begun actively developing quantum computers using multiple qubit technologies.

Table 2.12 summarizes the quantum computing development or acquisition activities that have been publicly disclosed in the nine common-baseline U.S.-allied countries, as well as one especially notable achievement from Austria. The only specific target for technical metrics that we were able to find was the number of qubits. The number of qubits by itself (without any metrics for qubit or logic-operation quality, such as one- or two-gate fidelities or qubit coherence times) gives very little information about the capabilities of a quantum computer—so, while the number of qubits in a quantum computer is a rough proxy for the difficulty of its construction, it should not necessarily be interpreted as a proxy for the computational abilities of the resulting prototype.

Research groups in Germany, Japan, and the UK have purchased quantum computers from the U.S. companies IBM and Rigetti for experimentation and software development. Private companies in these countries are experimenting with quantum computers to see if they can develop new materials, chemicals, battery technologies, and pharmaceuticals.

Research groups in Europe and Asia are also building quantum computers of their own design, and (as we discuss further in Chapter 3) Germany is also trying to develop its own indigenous quantum computing supply chains. Table 2.12 shows that Japan, South Korea, Australia, and Finland have set national or company goals for their indigenous quantum computing programs. The most ambitious allied country is Japan, which has stated it will develop a 1,000-qubit quantum computer by 2026, with development led by Fujitsu and RIKEN. In March 2023, Fujitsu and RIKEN announced the availability to outside users of their first indigenous quantum computer, although they have not yet released technical specifications.²⁰

As of March 2023, research groups in Austria, the Netherlands, Finland, Australia, and Japan have produced prototype quantum processors that can execute both (a) two-qubit logic gate operations and (b) high-fidelity single-qubit gate operations with an error rate of less than 1 percent. These groups are shown in bold in Table 2.18.

AQT, headquartered in Innsbruck, Austria, is especially notable in Table 2.12. AQT has developed a trapped-ion quantum computer with 20 qubits that can execute high-fidelity gate operations.²¹ This is by far the largest quantum computer prototype (as measured by qubit count) that we found outside the United States or China. The AQT computer has approximately the same number of qubits as the trapped-ion quan-

¹⁹ Parker et al., 2022.

²⁰ Nippon Communications Foundation, "Japan to Put 1st Domestic Quantum Computer into Service," webpage, March 24, 2023.

²¹ Pogorelov et al., 2021.

TABLE 2.12
Quantum Computer Programs in U.S.-Allied Countries

Country	Qubit Type	Year	No. of Qubits	Company or Consortium	Notes
Austria	Trapped ion	2022	20	Alpine Quantum Technologies (AQT)	Demonstrated gate operations
Netherlands	Spin	2018	2	TU Delft and QuTech	Demonstrated gate operations
Netherlands	Spin	2022	6	TU Delft and QuTech	Demonstrated gate operations
Finland	Superconducting transmon	2021	5	VTT IQM Quantum Computers	Demonstrated gate operations
Finland	Superconducting transmon	2024	54	VTT IQM Quantum Computers	Planned
Australia	Spin	2023	4	Diraq	Demonstrated gate operations
Australia	Spin	2023	10	Silicon Quantum Computing	Planned
Australia	Spin	2030	100	Silicon Quantum Computing	Planned
Australia	Spin	2033	256	Diraq	Planned
Japan	Superconducting transmon	2021	27	IBM	Imported from the United States
Japan	Spin	2022	2	RIKEN TU Delft and QuTech	Demonstrated gate operations
Japan	Superconducting transmon	2023	64	Fujitsu RIKEN	Planned
Japan	Superconducting transmon	2026	1,000	Fujitsu RIKEN	Planned
Germany	Superconducting transmon	2021	27	IBM	Imported from the United States
Germany	Superconducting transmon	2024	—	Consortium	Planned
Germany	Trapped ion	2026	—	Universal Quantum UK	Planned single-chip computer, built in UK but funded and installed in Germany
Germany	Trapped ion	2026	100	Universal Quantum UK	Planned multichip computer, built in UK but funded and installed in Germany
Sweden	Superconducting transmon	2022	25	Chalmers University of Technology	Sweden designed and built; no public benchmarks for gate operations

Table 2.12—Continued

Country	Qubit Type	Year	No. of Qubits	Company or Consortium	Notes
Sweden	Superconducting transmon	2029	100	Chalmers University of Technology	Planned
South Korea	Superconducting transmon	2023	27	IBM	Imported from the United States
South Korea	Superconducting transmon	2024	20	Consortium (TBD)	Planned
South Korea	Superconducting transmon	2026	50	Consortium	Planned
UK	Superconducting transmon	2022	32	Rigetti	Imported from the United States
UK	Photonic	—	—	Orca	Delivered to the UK Ministry of Defence
Denmark	Photonic	—	—	Denmark Technical University	Planned room temperature quantum computer

SOURCES: RAND analysis of information from John Russell, "IBM and University of Tokyo Roll Out Quantum System One in Japan," HPCwire, July 27, 2021; Paul Smith-Goodson, "IBM and Fraunhofer Announce German Quantum Computing Partnership," *Forbes*, June 15, 2021; IBM, "IBM and Yonsei University Unveil Collaboration to Bring IBM Quantum System One to Korea," press release, November 16, 2021; Akira Oikawa and Ami Yamada, "Fujitsu, Riken to Offer First Japan-Made Quantum Computer," *Nikkei Asia*, August 22, 2022; Oxford Instruments, "Rigetti Computing Expands Global Presence with UK Quantum Computer Launch," press release, June 21, 2022; ORCA Computing, "Quantum Machines Selects ORCA Computing for Quantum Computing Center," press release, July 20, 2022; Leo Laikola "Finnish Researchers Say Their First Quantum Computer Is Up and Running," Bloomberg, November 30, 2021; IQM, "Multiverse Computing and IQM Quantum Computers Announce Partnership to Develop Application-Specific Processors," webpage, August 18, 2022; T. F. Watson, S. G. J. Phillips, E. Kawakami, D. R. Ward, P. Scarlino, M. Veldhorst, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, et al., "A Programmable Two-Qubit Quantum Processor in Silicon," *Nature*, Vol. 555, March 29, 2018; Stephan G. J. Phillips, Mateusz T. Madzik, Sergey V. Amitonov, Sander L. de Snoo, Maximilian Russ, Nima Kalhor, Christian Volk, William I. L. Lawrie, Delphine Brousse, Larysa Tryputen, et al., "Universal Control of a Six-Qubit Quantum Processor in Silicon," *Nature*, Vol. 609, September 2022; QSolid, "QSolid—Paving the Way for the First German Quantum Computer," press release, September 3, 2022; Universal Quantum, "Universal Quantum wins €67m Contract to Build the Fully Scalable Trapped-Ion Quantum Computer," press release, November 2, 2022; Lim Chang-won, "Government-Initiated Task Force Launched to Develop 50-Qubit Quantum Computer by 2026," *Aju Business Daily*, June 9, 2022; I. Pogorelov, T. Feldker, Ch. D. Marciniak, L. Postler, G. Jacob, O. Kriegelsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, et al., "Compact Ion-Trap Quantum Computing Demonstrator," *PRX Quantum*, Vol. 2, June 17, 2021; Silicon Quantum Computing, "About—Silicon Quantum Computing," webpage, undated; Will Gilbert, Tuomo Tantt, Wee Han Lim, MengKe Feng, Jonathan Y. Huang, Jesus D. Cifuentes, Santiago Serrano, Philip Y. Mai, Ross C. C. Leon, Christopher C. Escott, et al., "On-Demand Electrical Control of Spin Qubits," *Nature Nanotechnology*, Vol. 18, No. 2, January 2023; "Archer Materials Validates & Demonstrates Qubit Coherence at Room Temperature, in Non-Vacuum Environment," webpage, Qubit Report, October 13, 2021; Ingela Roos, "New Swedish Quantum Computer to Be Made Available to Industry," press release, Chalmers, January 23, 2023; Denmark Technical University, "DTU Researchers Tighten Grip on Quantum Computer," press release, July 10, 2021.

NOTES: Bolded entries indicate an indigenously developed quantum computer that has demonstrated high-quality qubit gate operations. Date refers to actual or planned initial operating capability, depending on the date shown. Rows are ordered by nation (in descending order of qubits demonstrated and then qubits planned) and then chronologically. QuTech is joint research institute governed by the Delft University of Technology (TU Delft) and the Netherlands Organisation for Applied Scientific Research.

tum computers offered by IonQ and Quantinuum in the United States,²² making it a world-class system. It is worth noting that AQT claims its computer runs at room temperature.²³ The AQT prototype quantum processor was developed with assistance from researchers from Germany and Russia.

There is also a multinational European effort to develop a trapped-ion quantum computer. The UK company Universal Quantum, through its German subsidiary, has been funded by the German Quantum Initiative to build and install two trapped-ion quantum computers for the German Aerospace Center in Germany. The first computer will be a single-chip device whose number of qubits has not been disclosed. The second one will be a multichip computer with up to 100 qubits.²⁴ This multichip trapped-ion quantum computer will use a matter link to shuttle ions between chips that preserves the phase coherence of the ion qubits.²⁵

A notable superconducting transmon demonstration in Europe is Finland's IQM's quantum processor prototype, which has five qubits and has demonstrated high-fidelity gate operations. IQM plans to introduce a 54-qubit computer in 2024.

Several other prototypes listed in Table 2.12 that have demonstrated high-fidelity gate operations use SSQs.²⁶ The largest device of this kind as of January 2023 was demonstrated by academic researchers at TU Delft and QuTech in the Netherlands and has six qubits.²⁷ As we will discuss in Chapter 3, Intel has manufactured quantum processors in the United States based on the QuTech design.

The UK company ORCA Computing claims to have developed a photonic quantum computer and delivered a prototype to the UK Ministry of Defense.²⁸ ORCA Computing is scheduled to deliver a second prototype computer to a research organization in Israel in 2023. Technical performance parameters for this computer have not been disclosed to the public.

Discussion

A general theme of this chapter is that, while the United States and China are the two most important nations in quantum technology R&D by many metrics, there are many other important national players. These other players are quite similar to one another in level of importance. Even excluding the United States and China, the next-leading nation depends strongly on the choice of metric. Germany and the UK lead in scientific publishing and total government funding; the Netherlands' national government invests the highest percentage of national GDP on quantum technology R&D; Japan leads in patenting; and Canada has the most and best-funded quantum technology start-ups. Demonstrated technical achievement is difficult to summarize, but all the nations mentioned earlier—as well as others, such as Austria—have demonstrated impressive achieve-

²² Quantinuum's latest-generation trapped-ion quantum computer has 20 qubits, while IonQ's latest-generation system has 21 qubits. Quantinuum is dual-headquartered in the United States and the UK. See "Quantinuum, "Quantinuum Completes Hardware Upgrade; Achieves 20 Fully Connected Qubits," press release, June 14, 2022; IonQ, "IonQ Aria: Practical Performance," webpage, March 1, 2023.

²³ Alpine Quantum Technologies, "AQT | The World's Leading 19" Rack-Mounted Quantum Computer," webpage, undated.

²⁴ Universal Quantum, 2022.

²⁵ M. Akhtar, F. Bonus, F. R. Lebrun-Gallagher, N. I. Johnson, M. Siegele-Brown, S. Hong, S. J. Hile, S. A. Kulmiya, S. Weidt, and W. K. Hensinger, "A High-Fidelity Quantum Matter-Link Between Ion-Trap Microchip Modules," *Nature Communications*, Vol. 14, No. 531, February 8, 2023.

²⁶ We will discuss SSQs in more detail in Chapter 3.

²⁷ Mateusz T. Madzik, Serwan Asaad, Akram Youssry, Benjamin Joecker, Kenneth M. Rudinger, Erik Nielsen, Kevin C. Young, Timothy J. Proctor, Andrew D. Baczewski, Arne Laucht, et al., "Precision Tomography of a Three-Qubit Donor Quantum Processor in Silicon," *Nature*, Vol. 601, January 2022.

²⁸ ORCA Computing, 2022.

ments. Moreover, all these countries are frequent scientific collaborators in quantum science, and many are of similar importance within the network of global scientific research. Most of these nations have a broadly similar, and quite diverse, research portfolio.

The overall picture shows that the field of research is quite geographically decentralized, with impressive achievements and capabilities across many different countries and a relatively low degree of national specialization. Many leading countries appear to have broadly similar priorities for scientific research (although with a few slight differences); the differences in the level and nature of industry activity among these countries are more notable.

The Australian, United Kingdom, German, and Japanese Quantum Ecosystems

The global look detailed in Chapter 2 revealed that, within each of the three quantum technology application domains, the UK and Germany were the next two countries after the United States and China with the highest total scientific research output and with the highest output of frequently cited scientific papers. Japan was one of the following two countries in each of the three domains. Moreover, in each of the three application domains, more patents were filed in Japan than in any other country (other than the United States or China). While Australia was not quite as active for these metrics, its membership in the AUKUS arrangement and its geographic separation from the other three countries discussed earlier made it another natural candidate for further study.

We therefore chose to do deeper dives into the quantum industrial bases of Australia, the UK, Germany, and Japan. These four nations are geographically diverse and have different industry structures and funding sources, as we will discuss. In this chapter, we compare our findings for these four countries across each of our categories of metrics.

Scientific Research

In Chapter 2, we presented country-level metrics on scientific publishing output for the three quantum information science application domains and subdomains. In this chapter, we take a closer look at the character of this output, considering the particular organizations responsible for driving output and the roles that firms play in the domestic research ecosystems of the focal countries. We separately address foreign institutions based in the United States and in China, given the leading role that these two nations play in the global quantum technology ecosystem.¹ Additional details regarding the publication output for these countries can be found in Appendix A.

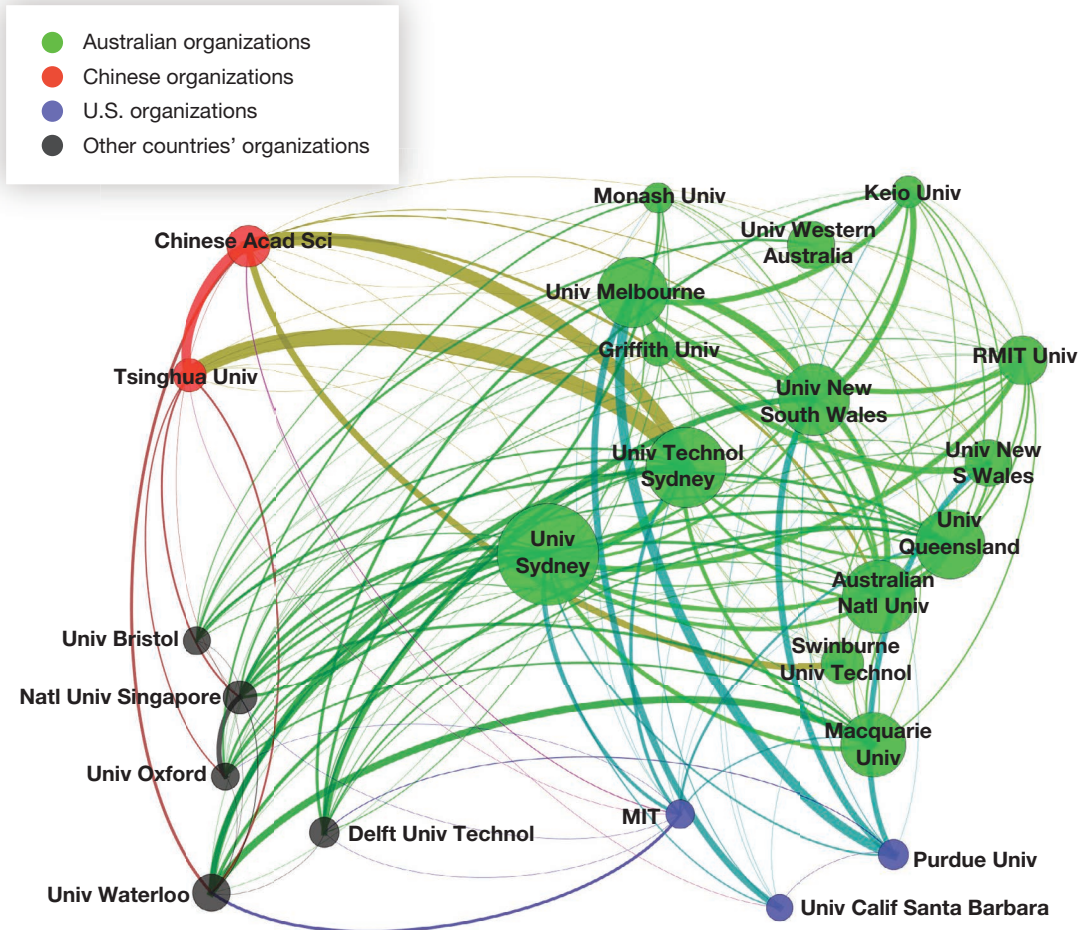
Australia

Figures 3.1, 3.2, and 3.3 depict the organizational collaboration networks for the quantum computing, quantum communications, and quantum sensing fields, respectively, within the Australian publication dataset (i.e., the subset of publications with at least one author from an organization based in Australia).² The graphs depict the key organizations, and the collaborations among them, that are driving publishing in the field in Australia. Each edge's color is an equal mixture of the colors of the nodes that it connects.

¹ Parker et al., 2022.

² In Figure 3.1, the cutoff point for inclusion is 20 publications. In the tables and figures to follow, distinct cutoff points are used to ensure the presentation of an adequate sample of publishing organizations.

FIGURE 3.1
Institutional Coauthorship Network for Quantum Computing Research with Australian Authors

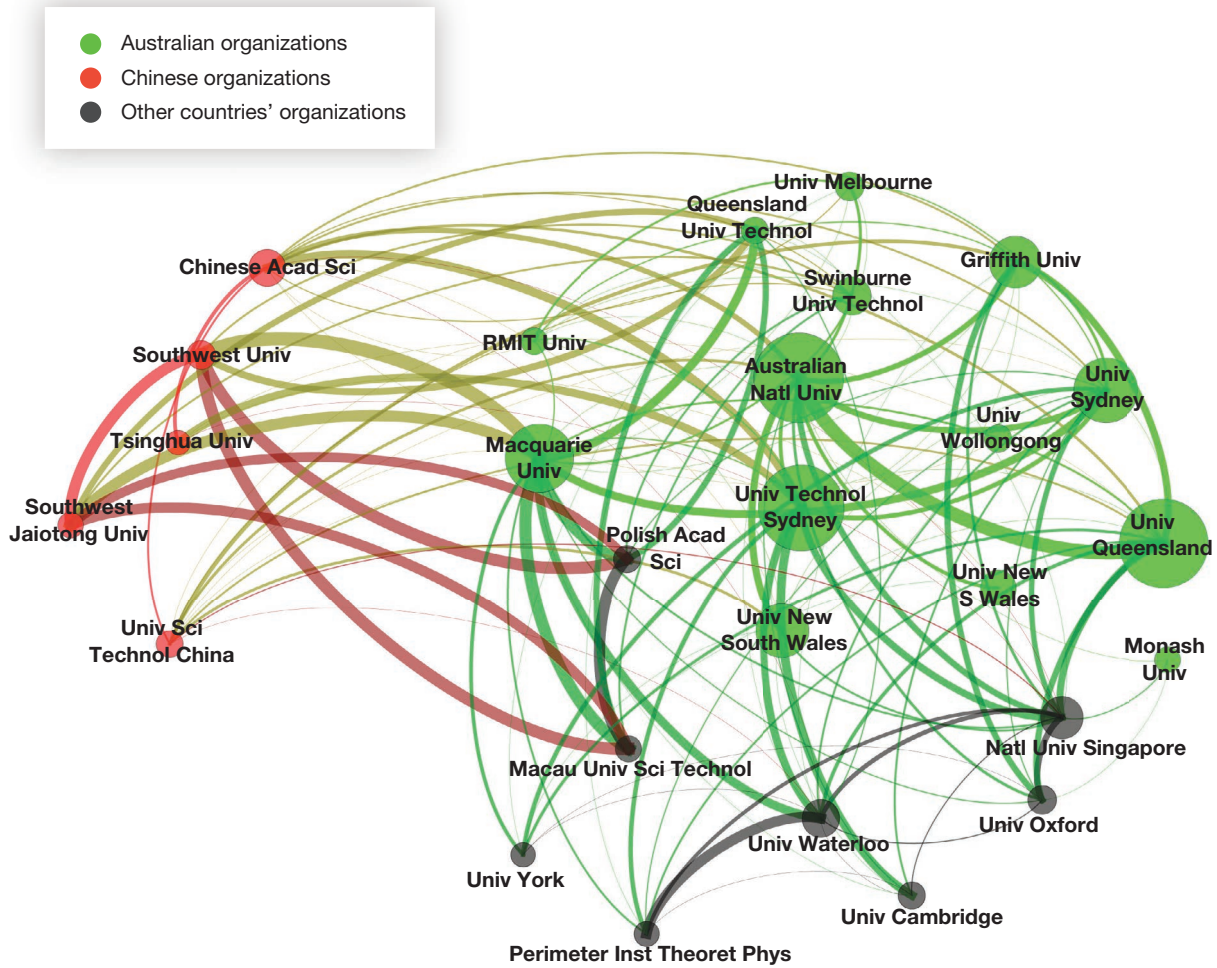


NOTE: RMIT = Royal Melbourne Institute of Technology.

In the quantum computing network, the University of Sydney, which hosts a Microsoft-supported quantum computing institute and the Quantum Science Group, is the most important player in the Australian quantum computing ecosystem, ranking first in total publications and centrality. In this network, there are two significant ties with Chinese organizations: the Chinese Academy of Sciences and Tsinghua University. Coauthorship ties to these Chinese organizations are particularly strong (depicted by the edge weight) with the University of Technology of Sydney.

In the quantum communication network (Figure 3.2), Australian National University is the most productive Australian publisher of quantum communications and quantum sensing articles (Figure 3.3). Although it is only listed on six quantum communications with Australian coauthors, the University of Glasgow is the most central organization within the Australian scientific publishing network for quantum communications. Five Chinese organization play a significant role in the Australian quantum communication coauthor-

FIGURE 3.2
Institutional Coauthorship Network for Quantum Communications Research with Australian Authors

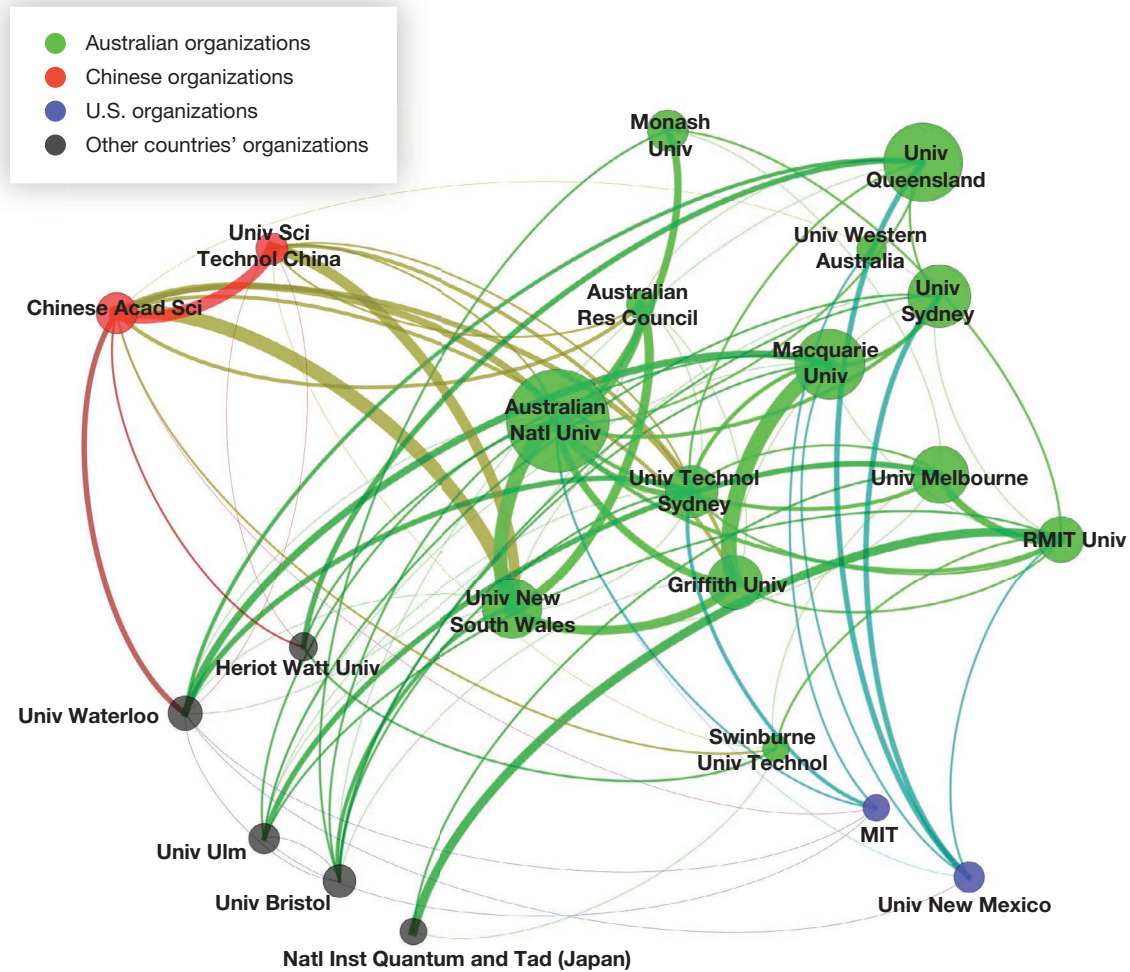


ship network, which is perhaps not surprising, given China's demonstrated commitment to quantum communications research.³

Table 3.1 lists the top publishing firms within the Australian publication dataset across the three application domains. For quantum computing, large U.S. technology firms, such as Google, IBM, Microsoft, and Amazon, are common collaborators with Australian organizations in the field of quantum computing. For example, Macquarie University and Google had 11 joint publications during the 2012–2021 analysis period. It is noteworthy that only three Australian companies published two or more publications with Australian organizations in the field of quantum computing. In quantum communications, University of New South Wales (UNSW) and U.S. defense contractor Northrop Grumman jointly published 12 publications. In quantum sensing, an Australian firm specializing in image processing hardware and software, Instruments & Data Tools, was the top ranking corporate publisher, publishing five publications with Australian National University over the analysis period.

³ Parker et al., 2022.

FIGURE 3.3
Institutional Coauthorship Network for Quantum Sensing Research with Australian Authors



United Kingdom

Figures 3.4, 3.5, and 3.6 depict the coauthorship network graphs for the quantum computing, quantum communications, and quantum sensing, respectively, within the UK publication dataset (i.e., the subset of publications with at least one author from an organization based in the UK, including research laboratories of foreign-owned companies). Oxford University, which hosts 38 quantum information science–focused research teams, is the most important research organization within the UK quantum computing and quantum communications publishing ecosystems, ranking first in both publication output and network centrality in both domains.⁴

The UK quantum sensing network includes a Chinese organization among the top collaborators: The University of Science and Technology of China has collaborations with Imperial College London and Oxford University. No U.S.-based organization appears in the UK networks of top collaborators.

⁴ Oxford Quantum, “Oxford Quantum: A Core for Quantum Science and Technology,” webpage, undated.

TABLE 3.1
Highest-Publishing Companies with Australian Coauthors, 2012–2021

Domain	Organization	Publications
Quantum computing	Google	15
	Q CTRL	13
	IBM	12
	Microsoft	12
	Baidu	7
	HRL Laboratories	7
	Nippon Telegraph and Telephone (NTT)	7
	Element Six	4
	Turing	4
	Several organizations tied at	3
Quantum communications	Northrop Grumman	12
	Baidu	4
	QuintessenceLabs	4
	Element Six	3
	Magellan Aerospace	3
	Thales	3
	A*QUANTUM	2
	Collinstar Capital	2
	Nokia Research Center	2
	Xanadu	2
	Many organizations tied at	1
Quantum sensing	Instruments & Data Tools	5
	Microsoft	3
	Element Six	2
	Magellan Aerospace	2
	Adamas Nanotechnology	1

Table 3.2 lists the top publishing firms within the UK publication dataset across the three application domains. For quantum computing, there is evidence of an emerging quantum computing cluster in Cambridge, centered around the University of Cambridge. Japanese firms Hitachi and Toshiba published 17 and 14 joint publications with University of Cambridge, respectively. Cambridge Quantum Computing, a Cambridge-based firm focused on quantum software and quantum cybersecurity, is the top corporate UK publisher of quantum computing publications.

In quantum communications, Toshiba, by a significant margin, is the firm with the most publications coauthored with UK based authors. Over the analysis period, Toshiba coauthored 48 quantum communications publications with Cambridge University and 11 with University of Sheffield. In quantum sensing, TopGaN, a Polish firm specializing in laser technology, published five quantum sensing publications with UK-based firm Compound Semiconductor Technologies Global and four with the University of Glasgow.

FIGURE 3.4
Institutional Coauthorship Network for Quantum Computing Research with UK Authors

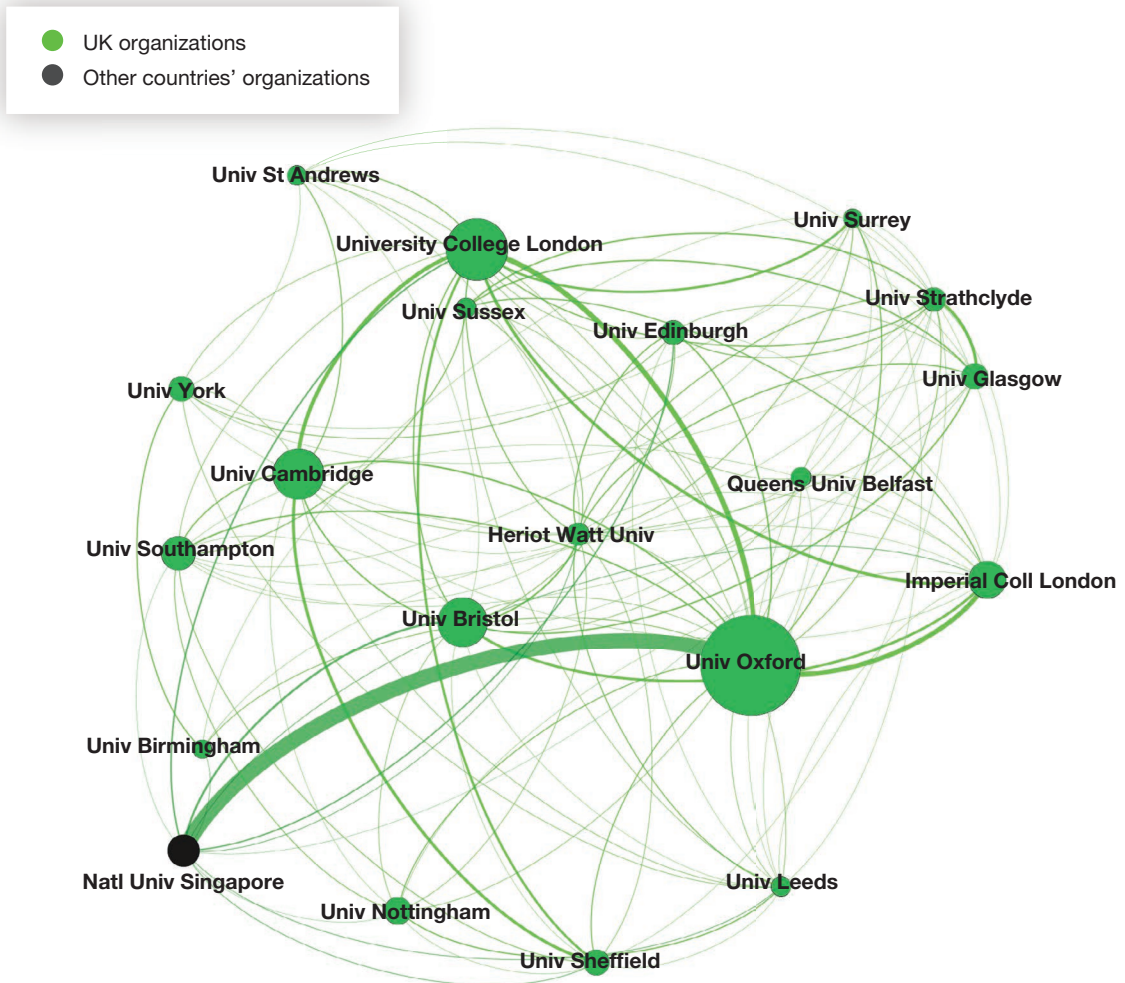


FIGURE 3.5
Institutional Coauthorship Network for Quantum Communications Research with UK Authors

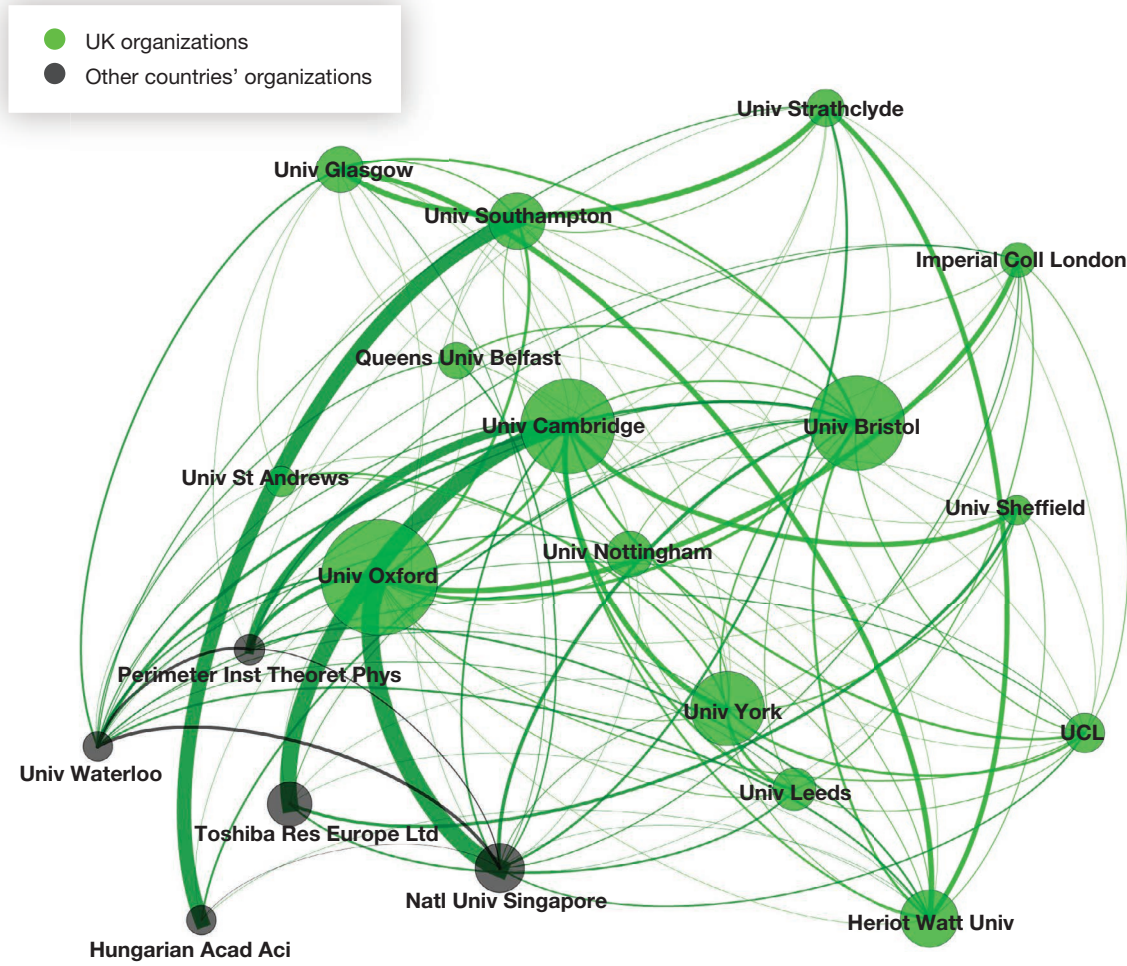


FIGURE 3.6
Institutional Coauthorship Network for Quantum Sensing Research with UK Authors

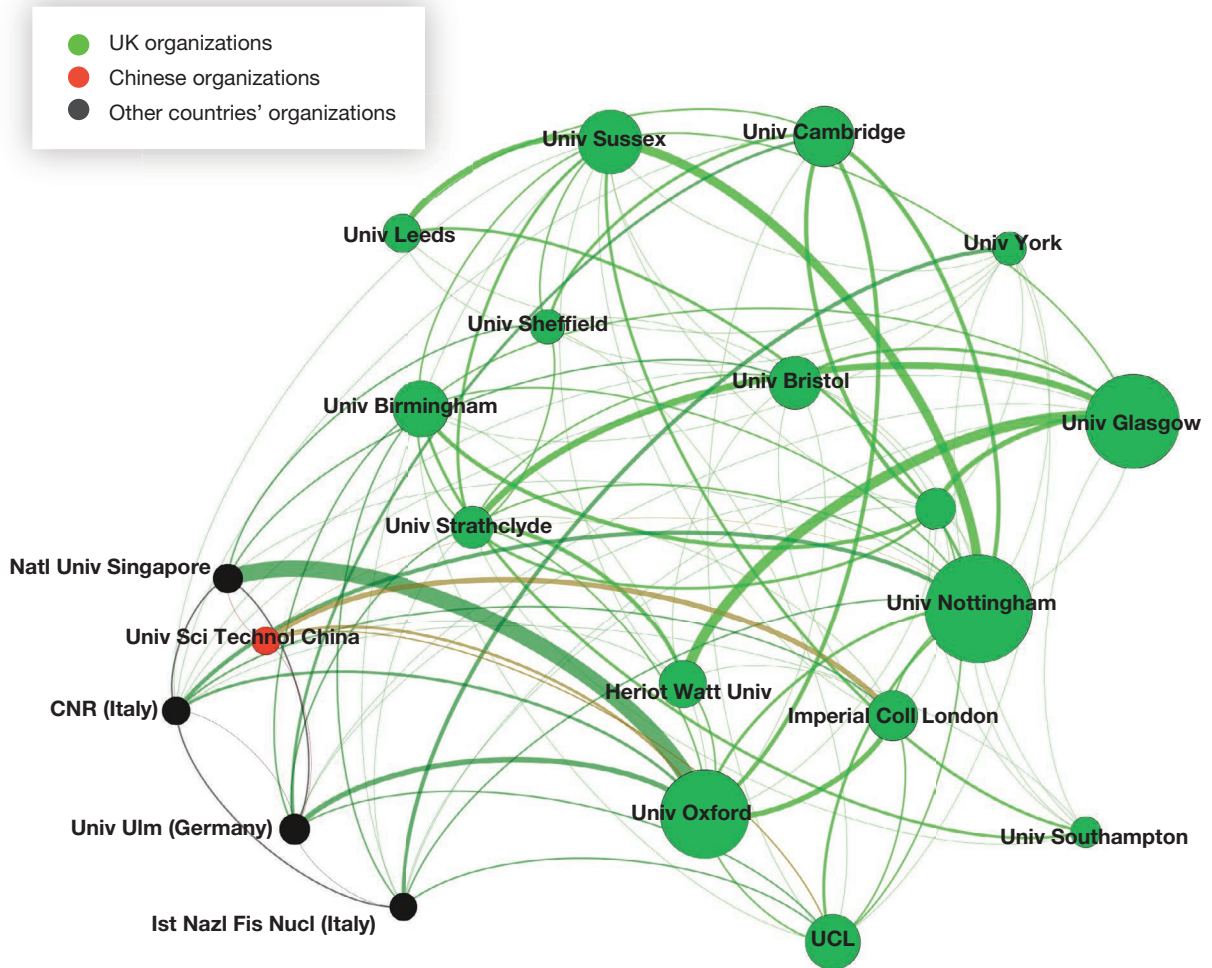


TABLE 3.2
Highest-Publishing Companies with UK Coauthors, 2012–2021

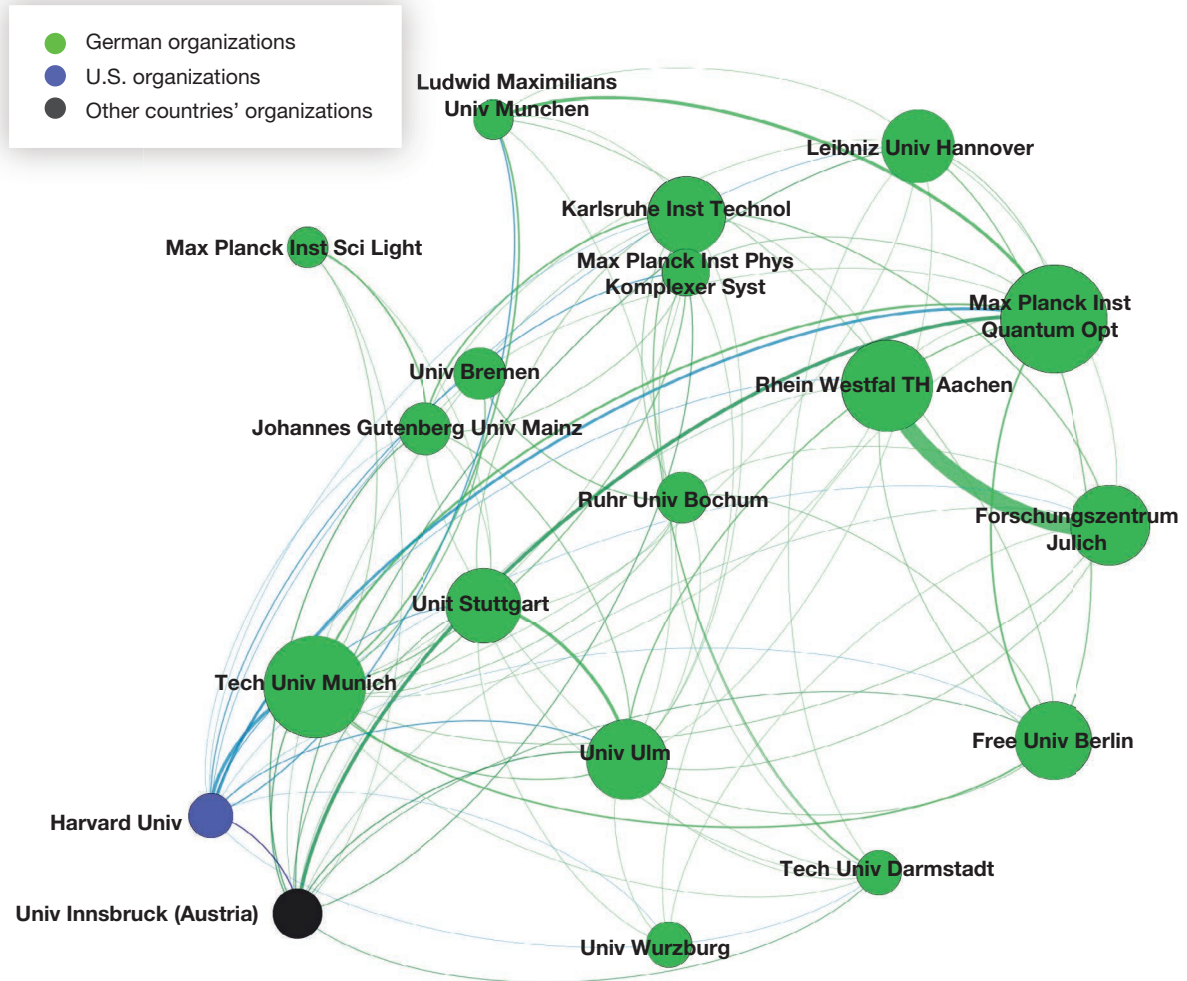
Domain	Organization	Publications
Quantum computing	Cambridge Quantum Computing	24
	Hitachi Cambridge Laboratory	24
	Toshiba	17
	NTT	16
	Element Six	15
	IBM	15
	Rahko	11
	Microsoft	10
	Telecom Paris	10
	Google	8
	Several organizations tied at	7
Quantum communications	Toshiba	81
	Element Six	13
	Microsoft	9
	NTT	9
	PQShield	5
	Xanadu	5
	Baidu Research	4
	ID Quant	4
	Nokia Research Center	4
	QKD	3
		Several organizations tied at
Quantum sensing	TopGaN	11
	Element Six	9
	NTT	7
	Compound Semiconductor Technologies Global	5
	Helia Photon	5
	Toshiba	4
		Several organizations tied at

Germany

Figures 3.7, 3.8, and 3.9 depict the German collaboration networks for quantum computing, communications, and sensing, respectively. The Max Planck Institute of Quantum Optics, based in Garching, Germany, is the most prolific publisher of quantum computing publications in Germany. It is also the second most central organization to the Germany quantum computing research ecosystem, behind Oxford University.

As for the UK, the German networks have little Chinese participation. The University of Science and Technology of China, which has coauthorship relationships with six German organizations in the field of quan-

FIGURE 3.7
Institutional Coauthorship Network for Quantum Computing Research with German Authors



tum sensing, is the only Chinese organization depicted in the networks of top publishers from the German quantum publication datasets (i.e., all quantum publications with at least one Germany-based author).

Table 3.3 lists the top corporate publishers in the German computing dataset across the three quantum domains. The top corporate collaborator with German organizations on the topic of quantum communications during the period of analysis was Chinese telecommunications firm Huawei. In quantum sensing, Sumitomo, a highly diversified Japanese firm, coauthored three quantum computing publications with the University Stuttgart. And Airbus coauthored two quantum computing publications with the Max Planck Institute for the Science of Light and Leibniz University.

FIGURE 3.8
Institutional Coauthorship Network for Quantum Communications Research with German Authors

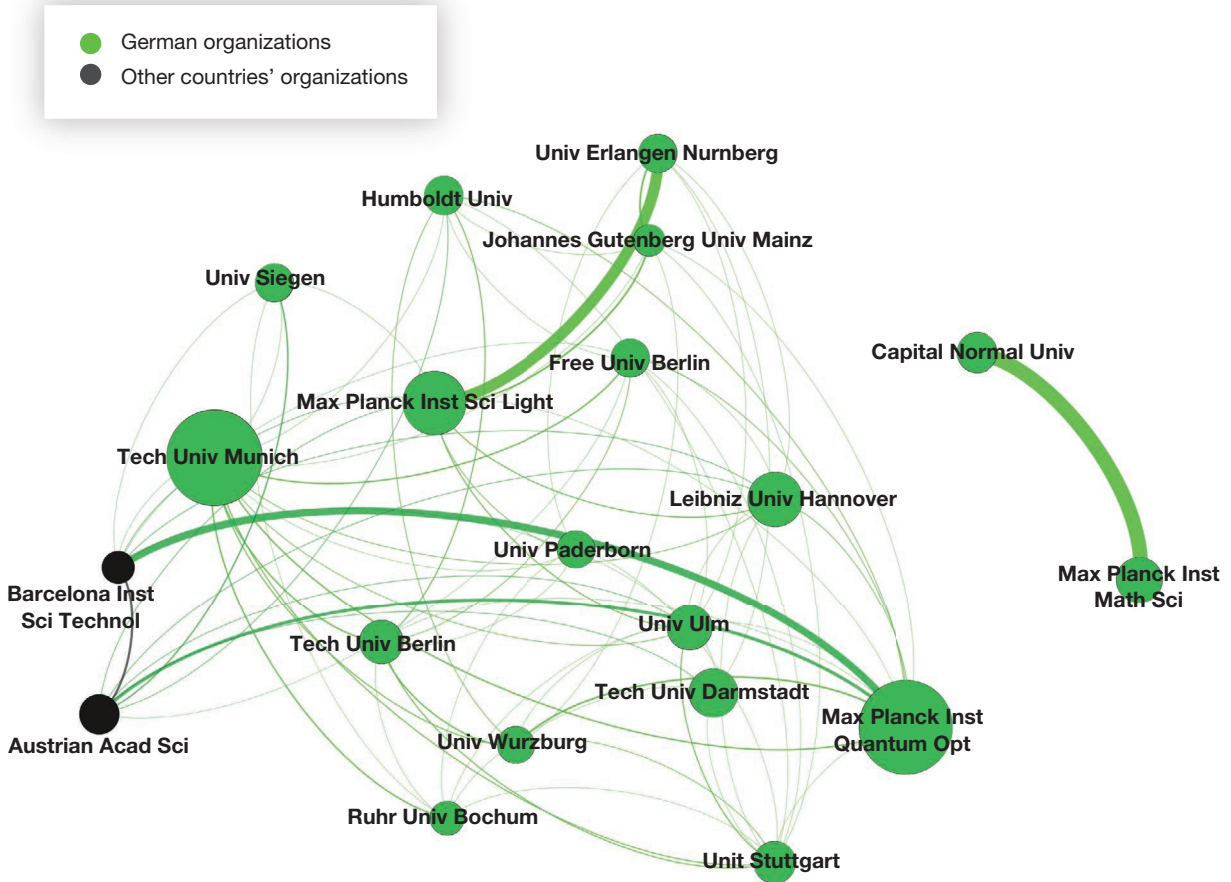


FIGURE 3.9
Institutional Coauthorship Network for Quantum Sensing Research with German Authors

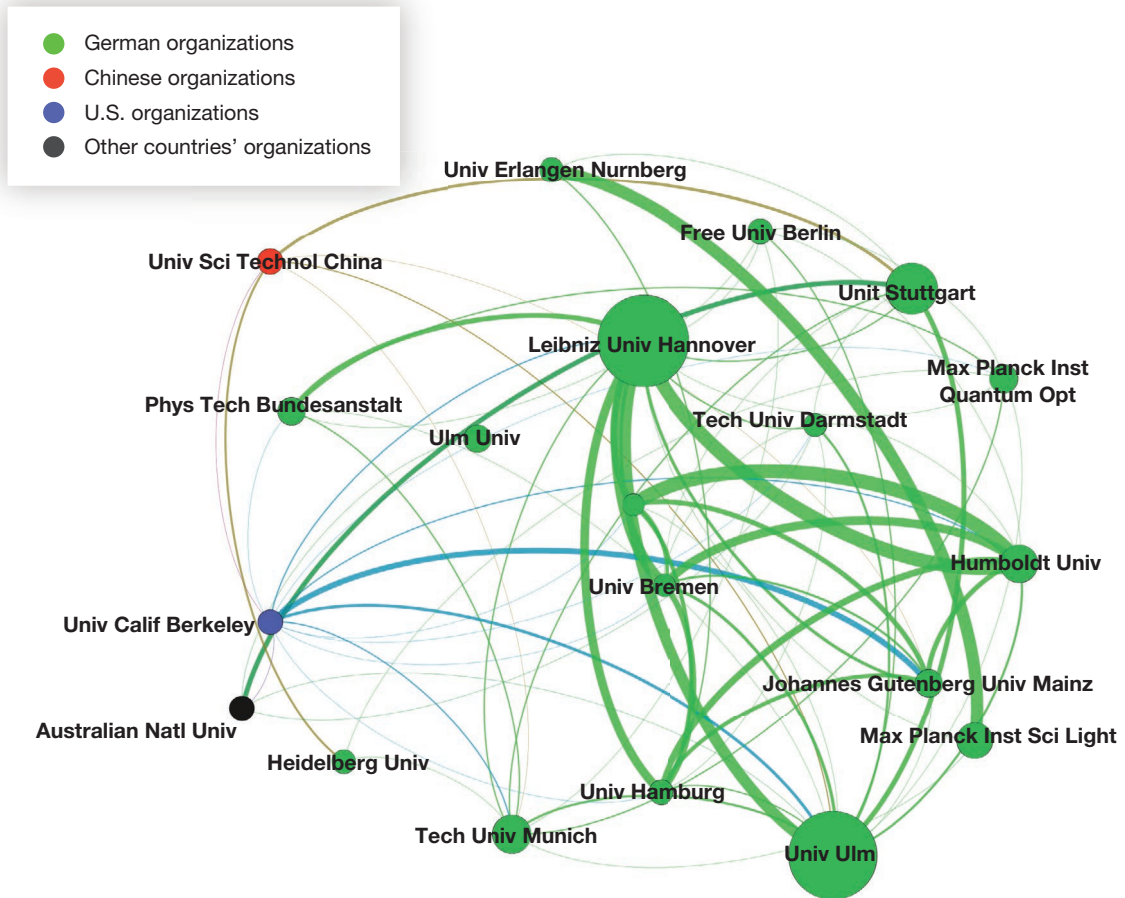


TABLE 3.3
Highest-Publishing Companies with German Coauthors, 2012–2021

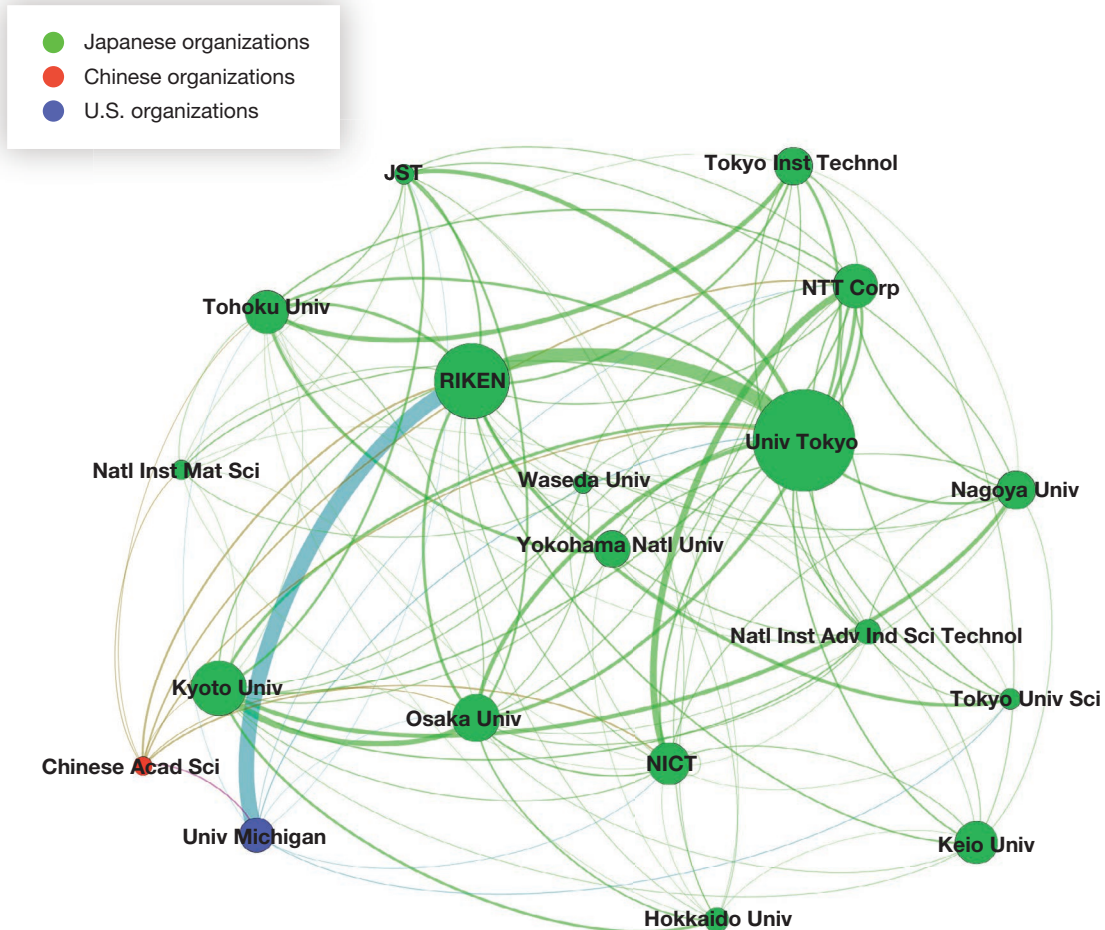
Domain	Organization	Publications
Quantum computing	Deutsches Forschungszentrum für Künstliche Intelligenz	48
	IBM	23
	GSI Helmholtzzentrum Schwerionenforsch	8
	Infineon Technologies	8
	Google	7
	Airbus	6
	VITCON Projectconsult	6
	Element Six	5
	NTT	5
	Several organizations tied at	4
Quantum communications	Huawei Technologies Düsseldorf	19
	Austrian Institute of Technology	6
	PicoQuant	6
	Qutools	6
	Toshiba	6
	Airbus	5
	Robert Bosch	5
	OHB System	4
	Attocube Systems	3
	IBM	3
	Several organizations tied at	2
Quantum sensing	Sumitomo Electric Industries	6
	Airbus	4
	Huawei Technologies Düsseldorf	3
	Tokyo Gas	3
	Several organizations tied at	2

Japan

Figures 3.10, 3.11, and 3.12 depict the network graphs for the quantum computing, quantum communications, and quantum sensing fields, respectively, within the Japan publication dataset (i.e., all relevant publications with at least one author based at a Japanese organization). The University of Tokyo, which hosts a joint research lab with IBM, as well as several domestic initiatives, is the most important player in Japan’s overall quantum science research ecosystem, ranking first or second in total publications and network centrality in all three domains.⁵ The Chinese Academy of Science has significant collaboration relationships with Japanese

⁵ The University of Tokyo, “Quantum Initiative Projects,” webpage, undated; IBM-UTokyo lab, “QII: Quantum Innovation Initiative Council (Japanese),” webpage, undated.

FIGURE 3.10
Institutional Coauthorship Network for Quantum Computing Research with Japanese Authors



universities in the quantum computing and quantum sensing domains. Notably, the top Japanese publishing organizations include two that are not universities: the national laboratory RIKEN and the commercial NTT.

Table 3.4 lists the top corporate publishers within the Japan for the three application domains. Across all three domains, the most prolific Japanese firm by far is NTT, a large telecommunications company. In the field of quantum computing, NTT published 18 papers with Osaka University, 11 with Riken, and eight with Kyoto University. In the quantum communication domain, NTT coauthored 24 publications with National Institute of Information and Communications Technology, 18 with Osaka University, and ten with the University of Tokyo. In quantum sensing, NTT coauthored eight publications with the National Institute of Information and Communications Technology and four with the National Institute of Advanced Industrial Science and Technology, both of which are large national government research agencies.

FIGURE 3.11
Institutional Coauthorship Network for Quantum Communications Research with Japanese Authors

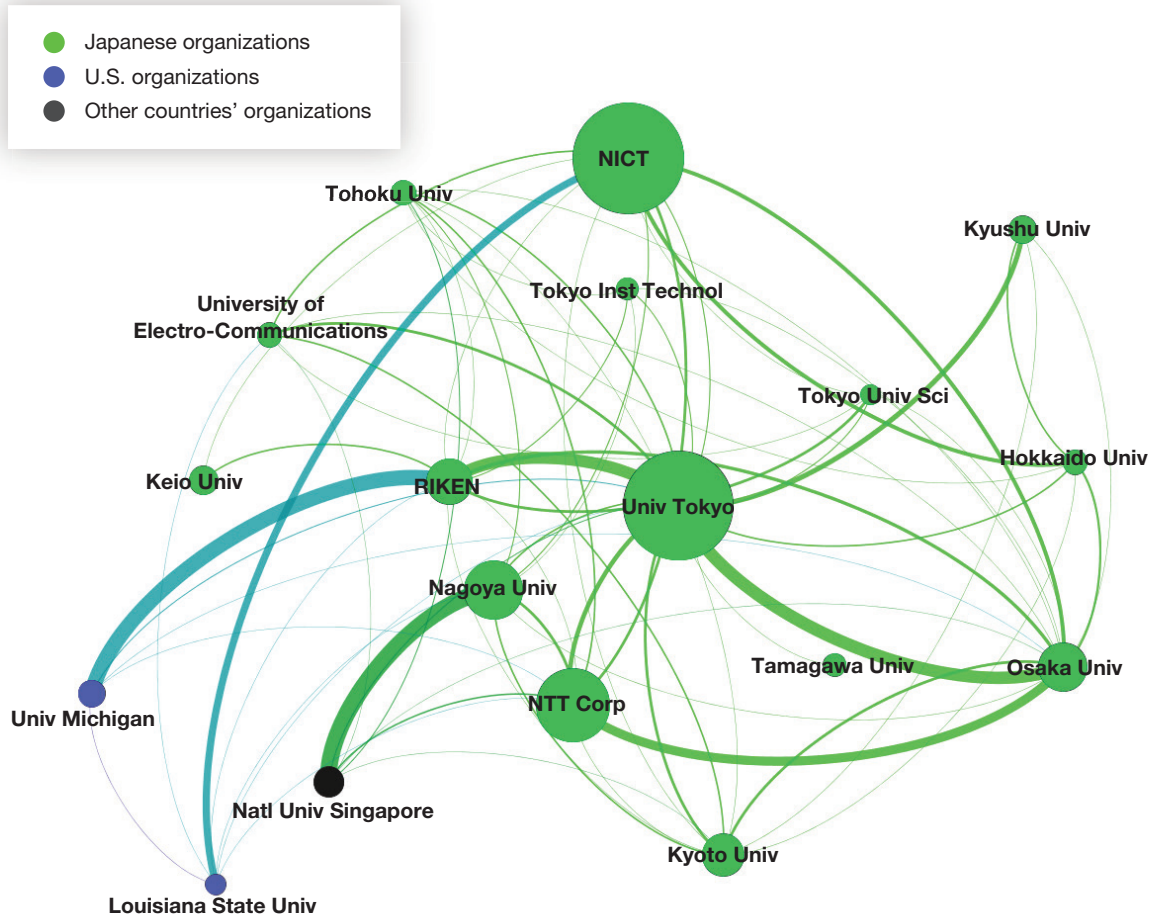


FIGURE 3.12
Institutional Coauthorship Network for Quantum Sensing Research with Japanese Authors

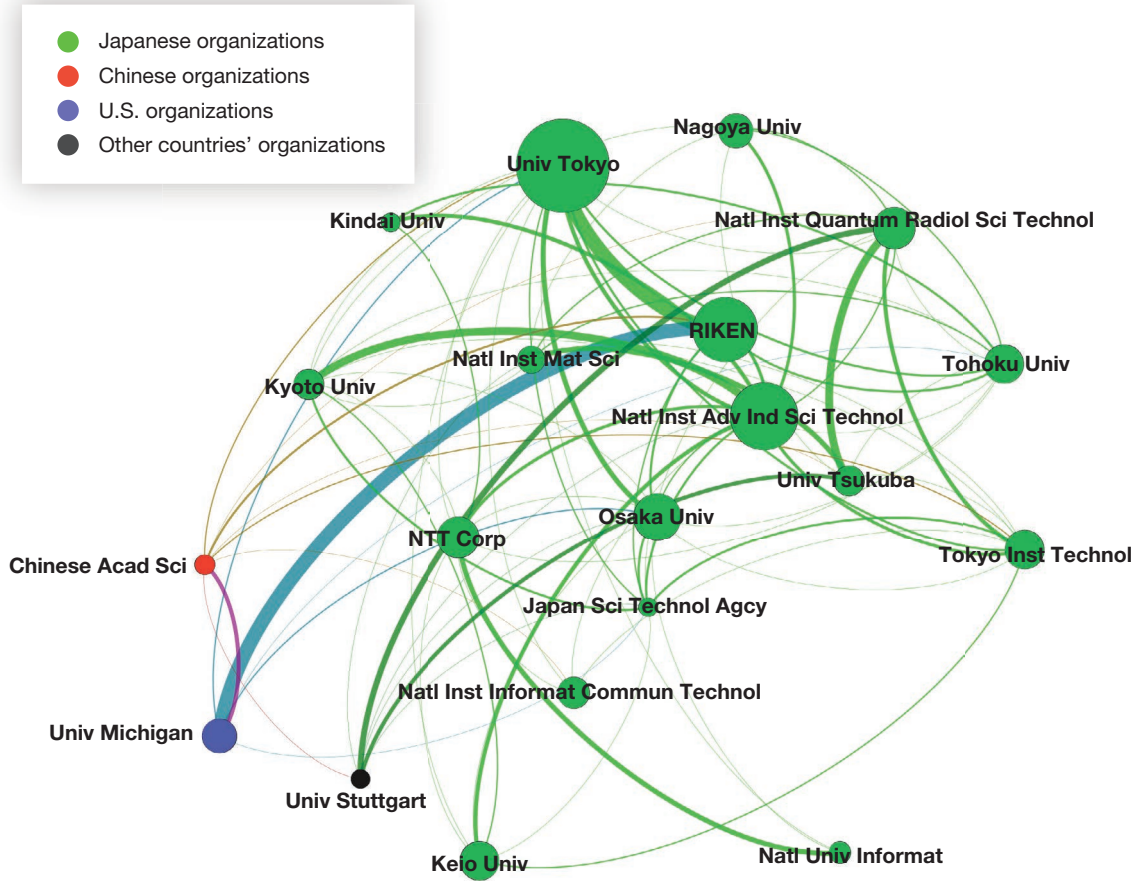


TABLE 3.4
Highest-Publishing Companies with Japanese Coauthors, 2012–2021

Domain	Organization	Publications
Quantum computing	NTT	162
	IBM	28
	Toshiba	27
	NEC	24
	QunaSys	14
	DENSO	12
	Hitachi	8
	NIT	8
	Sigma I	7
	Mitsubishi UFJ Financial Group	7
	Fujitsu	5
Quantum communications	NTT	130
	NEC Corp	18
	Toshiba	18
	Mitsubishi	15
	KDDI Research	7
	Fujitsu	4
	Oki Electric Industry	4
	Raytheon	4
	Hitachi	3
	Several organizations tied at	2
Quantum sensing	NTT	30
	Sumitomo Electric Industries	7
	Hitachi	3
	NEC	3
	Tokyo Gas	3
	Several organizations tied at	2

Government Support

This section summarizes government support for quantum activities (such as research, creation of hubs or centers, and academic opportunities or training for students and the quantum workforce for each country) and lists the organizations (mostly, but not entirely, governmental) that have funded the most scientific publications with an author from that country. This is one metric for the most important funders of quantum information science research within each country, those who may have access to or influence over the major research talent within that country.

Australia

The Australian federal government provides most of its research funding via the Australian Research Council (ARC). Since 2003 and through 2025, ARC has funded seven centers of excellence (CoEs) for quantum research, for a total of \$189 million.⁶ However, between 2017 and 2024 alone, the ARC has invested about \$99 million in two quantum-focused and two quantum-related CoEs.⁷ The quantum-focused centers are the Centre for Engineered Quantum Systems (EQUS) and the Centre for Quantum Computation and Communications Technology (CQC2T). These are funded in part by the Australian Department of Defence's Defence Science and Technology Group, although it is unclear how much funding comes from this group.

The governments of Victoria and New South Wales are also investing in research efforts. The first is a collaboration between the University of Swinburne and the U.S.-based company Inflection to build a Quantum Technology Centre at the university.⁸ The Victorian government is investing about \$19 million in the creation of the center, workforce development, and developing manufacturing capabilities for glass cells and photonics.⁹ The government of New South Wales invested \$10 million invested to help create the Sydney Quantum Academy (SQA).¹⁰ The SQA is headquartered at the University of Sydney and is a collaboration with three other local universities intended to provide educational opportunities to students of quantum information science through scholarships, cross-institutional collaboration, and other academic resources.¹¹ The NSW government's investment came from its Quantum Computing Commercialisation Fund (\$19.6 million), which also supported the launch of the Australian company Silicon Quantum Computing in 2017 with a \$6.8 million investment.¹² This company also received about \$18.8 million from the federal government.¹³ QuintessenceLabs, another Australian company focused on quantum-enhanced cybersecurity applications, saw a \$7 million investment from the Australian Department of Defence in 2017.¹⁴ All these investments, plus the Quantum Commercialization Hub and the Pawsey Supercomputing Research Centre, bring total government support for quantum to approximately \$270 million between 2017 and projected into 2024.

⁶ Cathy Foley, "Growing Australia's STEM Industries: Lessons from Quantum," Australia's Office of the Chief Scientist, 2022. All dollar figures reported in this section are in U.S. dollars.

⁷ Kung and Fancy, 2021.

⁸ Swinburne University of Technology, 2022.

⁹ Swinburne University of Technology, 2022.

¹⁰ University of Sydney, 2019.

¹¹ Sydney Quantum Academy, "Undergraduate Programs," webpage, undated.

¹² Kung and Fancy, 2021.

¹³ Kung and Fancy, 2021.

¹⁴ Kung and Fancy, 2021.

In May 2023, Australia released its National Quantum Strategy after a yearlong consultation process with quantum experts, governments, and leaders from the broader community. The strategy is based on five themes: R&D, access to infrastructure and materials, building the workforce, supporting national interests, and ensuring an inclusive and ethical quantum ecosystem.¹⁵ An investment of AUS \$1 billion (U.S. \$670 million) will go toward growing “critical technologies,” including quantum computing.¹⁶ The strategy does not specify how much will be allocated for quantum specifically (artificial intelligence, robotics, and software developments are also a part of this budget).¹⁷ See Appendix C for more information about the National Quantum Strategy.

Table 3.5 shows the organizations that have funded the most Australian quantum information science publications.¹⁸ The ARC is the single biggest funder, but other countries’ governments fund a notable amount of research, including the governments of China and the United States (including a significant amount of funding from the U.S. Department of Defense).

TABLE 3.5
Top Funders of Australian Quantum Information Science Research

Funding Organization	Publications Funded
Australian Research Council	1,049
National Natural Science Foundation of China	282
U.S. Army Research Office	229
National Science Foundation (U.S.)	118
Engineering and Physical Sciences Research Council (UK)	116
Natural Sciences and Engineering Research Council of Canada	84
U.S. Air Force Office of Scientific Research	66
German Research Foundation	55
Canadian Institute for Advanced Research	52
European Research Council	49
Australian Government Research Training Program Scholarship	47
Japan Society for the Promotion of Science	42
National Key R&D Program of China	41
Australian government (not otherwise specified)	38
Fundamental research funds for the central universities (China)	38

¹⁵ Department of Industry, Science and Resources, *National Quantum Strategy: Building a Thriving Future with Australia’s Quantum Advantage*, Australian Government, May 2023.

¹⁶ Department of Industry Science and Resources, 2023, p. 22.

¹⁷ Department of Industry Science and Resources, 2023.

¹⁸ In this section, we define an *Australian quantum information science publication* to be any quantum information science publication in a scientific journal from our database that has at least one author affiliated with an institution based in Australia. The definition is similar for the other countries we discuss in this section. This does not imply that the Australian researchers themselves were directly funded by these agencies; the publications did not provide enough information for us to match the funding flows at the level of individual researchers.

United Kingdom

The UK's government support for quantum research takes a more centralized approach through the National Quantum Technologies Programme (NQTP)—the national strategy for quantum technologies. The NQTP consists of various research efforts and is funded in part by the government via UK Research and Innovation (UKRI). It began as a \$1 billion effort over ten years beginning in 2014. A renewed ten-year investment of \$3 billion was announced in March 2023 and will go into effect in 2024.¹⁹

The overarching program consists of four research hubs (each based at a different university and with a different research focus), the National Quantum Computing Centre, and the Quantum Metrology Institute based at the National Physical Laboratory.²⁰ The new investment will continue to grow the UK's network of research hubs; increase investment in the National Quantum Computing Centre; create accelerator programs for quantum commercialization; and continue to fund efforts under the previous investment, such as education and fundamental research.²¹

Specialized research is also being funded; one such project, called Speqtre, includes building a satellite QKD test bed and is a collaboration between the UK and Singapore. Another specialized project, Quantum Technologies for Fundamental Physics, aims to use quantum for understanding fundamental physics.²²

The NQTP contains the Industry Strategy Challenge Fund, through which companies bid for public funding to participate in collaborative research with other companies or research organizations. The objectives are to spur collaborative research on pressing societal challenges, to encourage other companies to invest in the UK, and to match public funding with private-sector funding. The fund is a means of driving commercialization and industrialization in quantum technology and has provided £153 million in funding for participating companies; UKRI expects private-sector support to reach £715 million by 2025.²³

Finally, there are three training and skill hubs for quantum systems engineering, centers for doctoral training, and fellowships, which all receive government funding under the NQTP.²⁴

Table 3.6 shows the organizations that have funded the most UK quantum information science research. Governments or private organizations within the European Union, the United States, China, Germany, Australia, Canada, and Singapore have funded a notable number of publications.

Germany

Public funding for Germany's quantum research comes from the federal government; the Federal Ministry of Education and Research (BMBF); the North Rhine–Westphalia state government; the Baden-Württemberg state government and Ministry of Science, Research, and Arts; and the Bavarian state government.

The federal government largely supports Germany's Quantum Alliance, a consortium of seven research programs (or CoEs), via the German Research Foundation.²⁵ Each program is a collaboration between universities and research organizations on either a specific quantum topic (such as quantum computing) or general quantum science and technology research. Funding information for these centers was not available on their websites.

¹⁹ Department for Science Innovation & Technology, 2023.

²⁰ UKRI, "Our Programme," webpage, undated.

²¹ Department for Science Innovation & Technology, 2023.

²² UKRI, undated.

²³ UKRI, undated.

²⁴ UKRI, undated.

²⁵ Kung and Fancy, 2021.

TABLE 3.6
Top Funders of UK Quantum Information Science Research

Funding Organization	Publications Funded
Engineering and Physical Sciences Research Council (UK)	1,961
European Union	316
European Research Council	311
National Natural Science Foundation of China	301
Royal Society	285
National Science Foundation (U.S.)	181
German Research Foundation	151
John Templeton Foundation (U.S.)	130
Australian Research Council	115
U.S. Army Research Office	111
Leverhulme Trust (UK)	104
Ministry of Education, Singapore	103
Natural Sciences and Engineering Research Council of Canada	87
U.S. Air Force Office of Scientific Research	86
Science and Technology Facilities Council (UK)	83

Other programs that the German federal government supports include the German Quantum Technologies Framework, which, among its other goals, is meant to spur the quantum research landscape and create applications for quantum technology.²⁶ State or federal governments also support the following four programs in some capacity:

- QuNet, led by Fraunhofer-Gesellschaft, is a quantum communications research initiative supported by the BMBF (\$30 million).²⁷
- The Education Innovation Network Quantum North Rhine–Westphalia is an academia-industry-research partnership supported by the state of North Rhine–Westphalia (\$12.5 million).²⁸
- QSolid is a quantum computing consortium (comprising 25 partners) supported by the BMBF (\$84 million).²⁹
- The IBM-Fraunhofer quantum computing collaboration is supported by the Baden-Württemberg and Bavaria state governments (\$48 million).³⁰

Combined with the Quantum Technologies Framework, a total of \$960 million has been allocated for quantum research, excluding COVID-19 relief funding for quantum research and CoEs.

²⁶ Kung and Fancy, 2021.

²⁷ Kung and Fancy, 2021.

²⁸ ML4Q, “EIN Quantum NRW: North Rhine-Westphalia Joins Forces to Establish a Hub for Quantum Science and Technologies,” webpage, undated.

²⁹ QSolid, 2022.

³⁰ Kung and Fancy, 2021.

Two major collaborators in government-funded research are Forschungszentrum Jülich and Fraunhofer. Both are large German research organizations (although Fraunhofer is about four times the size of Jülich) and play a major role in quantum technology development through various partnerships.

Table 3.7 lists the top funders of German quantum information science research. As with the UK, European Union funding sources are more important funders of German research than U.S. and Chinese sources are.

Japan

Two organizations provide most of the Japanese government's spending on quantum technology. One is RIKEN, Japan's largest research institute, which delivers a comprehensive array of scientific research, and the other is the Japan Science and Technology Agency. Although RIKEN is not officially a government agency, more than one-half of its budget comes from the Japanese government. RIKEN's annual budget is approximately \$746 million, and the Japan Science and Technology Agency's is approximately \$1.3 billion.

Other agencies involved in funding or allocating funding include the Japanese Ministry of Education Culture, Sports, Science, and Technology; the Cabinet Office; the New Energy and Industrial Technology Development Organization; and the Council for Science, Technology, and Innovation. These agencies house 11 research programs with a quantum focus, and an additional New Energy and Industrial Technology Development Organization–sponsored program has two quantum-related projects.

Each of these 12 programs contains various individual projects; one has as many as 30 projects—ten beginning each year in 2019, 2020, and 2021.³¹ Up to ten projects are typically initiated each year within these

TABLE 3.7
Top Funders of German Quantum Information Science Research

Funding Organization	Publications Funded
German Research Foundation	1,374
European Union	426
Alexander von Humboldt Foundation	370
European Research Council	295
National Natural Science Foundation of China	248
National Science Foundation (U.S.)	237
Engineering and Physical Sciences Research Council (UK)	210
German Federal Ministry of Education and Research	192
U.S. Army Research Office	115
Japan Society for the Promotion of Science	111
Australian Research Council	105
Natural Sciences and Engineering Research Council of Canada	93
Austrian Science Fund	77
Max Planck Society	77
Ministry of Economy and Competitiveness (Spain)	75

³¹ Japan Science and Technology Agency, “[Quantum Software] Technological Foundation of Advanced Quantum Computing and Information Processing,” webpage, PRESTO, undated.

programs, and their funding varies greatly—from \$0.2 million to \$9 million per project. Together, these 12 government-sponsored research programs have at least \$1.3 billion in total funding across the lifetimes of their projects (assuming the lowest projected funding).

RIKEN also oversees ten quantum technology innovation hubs, which are located across different universities and national institutes. It also hosts 15 quantum research projects within its Center for Quantum Computing.³² Funding for these projects is not detailed on RIKEN’s website.

Another important source of research funding that is unique to Japan is the Japan Society for the Promotion of Science. This organization was founded in a 1932 as a nonprofit foundation and became a quasi-governmental organization in 1967. In 2003, it officially separated from the Government of Japan and became an independent administrative institution that is associated with, but independent of, the Japanese government and is designed to exercise considerable autonomy to improve efficiency.

Table 3.8 lists the organizations that have funded the most quantum information science publications. As was the case for the other countries studied in this chapter, one domestic organization dominates the publication funding but to a lesser degree than for the other countries.

TABLE 3.8
Top Funders of Japanese Quantum Information Science Research

Funding Organization	Publications Funded
Japan Society for the Promotion of Science	1,313
Ministry of Education, Culture, Sports, Science and Technology	580
Japan Science and Technology Agency	482
Grants-in-aid for scientific research	368
National Natural Science Foundation of China	220
U.S. Army Research Office	131
National Science Foundation (U.S.)	127
U.S. Air Force Office of Scientific Research	119
RIKEN	107
Engineering and Physical Sciences Research Council (UK)	102
ImPACT Program of Council for Science, Technology and Innovation	98
German Research Foundation	86
John Templeton Foundation (U.S.)	74
Australian Research Council	73
Funding Program for World-Leading Innovative R&D on Science and Technology	46

³² RIKEN, “RIKEN Center for Quantum Computing (RQC),” webpage, undated.

Private Industry

In this section, for each of our four deep-dive countries, we first provide and discuss overall statistics for the nations' commercial quantum technology start-ups and other specialized firms, then provide a schematic diagram showing the research collaborations and flows of funding to the major domestic quantum technology R&D companies. We included only start-ups in the industry summary statistics because of a lack of available quantitative information from the large established companies, but our collaboration network diagrams do include large, established companies and are based on news reporting on the companies' R&D efforts.

For all charts in this section, we identified the quantum start-up companies using the Quantum Computing Report, Quantum Insider, and Quantum Zeitgeist websites and derived financial information from the Crunchbase, Tracxn, and Bloomberg websites and supplemental press releases and news coverage.

Appendix A contains the same research collaboration and funding diagrams for each country with a more granular color coding.

Australia

The Australian commercial quantum industry is small but diverse and well-funded. It centers on start-ups with robust backing from venture capital firms and Australian federal and state governments. As shown in Figure 3.13, which counts these firms by technology area, Australian firms are developing quantum computing hardware and software, quantum sensing, and enabling technologies.³³ Figure 3.14 shows a wave of start-up foundings in beginning in 2017 and continuing through the present, as well as several firms developing quantum and enabling technologies founded in preceding years (similar to what we found for the United States and China in our previous research).³⁴ Australia's sector varies in the size and capitalization of its companies, shown organized by number of employees and capital raised in Figure 3.15. The firms for which information was available were about evenly distributed between small, medium, and large firms, but slightly more than a quarter of the sector lacks data on funding or consisted of more established firms that do not rely on external investment (such as Archer Materials or MOG Laboratories). Most firms are midsized, with between ten and 50 employees, with a significant fraction of the sector consisting of small companies with fewer than ten employees, and only two firms with more than 50.

At the firm level, Australian quantum companies enjoy ample funding. Figure 3.16 shows that total funding for start-ups in Australia's quantum industry is spread across multiple firms, mostly concentrated in computing. Silicon Quantum Computing, which seeks to build a quantum computer embedded in a silicon chip, has raised \$213 million, about one-half of all funds raised by Australian companies. Other firms, which are pursuing alternative or spinoff technologies in computing and sensing, such as Q-CTRL and Diraq, follow Silicon Quantum Computing as the quantum technology start-ups with the most funding. Diraq, a spin-off of Silicon Quantum Computing, aims to develop full-stack quantum computers on silicon chips

³³ *Enabling technologies* includes basic components (e.g., lasers; optical components, such as lenses and mirrors; cabling) and other subsystems that can be used across all three application domains.

³⁴ Parker et al., 2022. Figures 3.14, 3.19, 3.24, and 3.29 in the present report show a wave of quantum start-ups being founded starting around 2017 (although slightly earlier in the UK), with relatively few start-ups founded before then and surviving to 2023. The few companies founded before 2017 mostly supply components (e.g., MOG Laboratories and M Squared Lasers) or quantum cryptography systems (e.g., Quantum Base, QuintessenceLabs). A few of them (e.g., Archer Materials) focused on other areas when they were founded but have since significantly pivoted to an emphasis on quantum technology. We suspect that the wave of new start-ups beginning around 2017 was mostly due to quantum computing technology becoming mature enough that prototype quantum computers started to achieve significant technical capabilities, culminating in Google's quantum supremacy demonstration in 2019.

FIGURE 3.13
Numbers of Australian Quantum Technology Start-Ups, by Technology Area

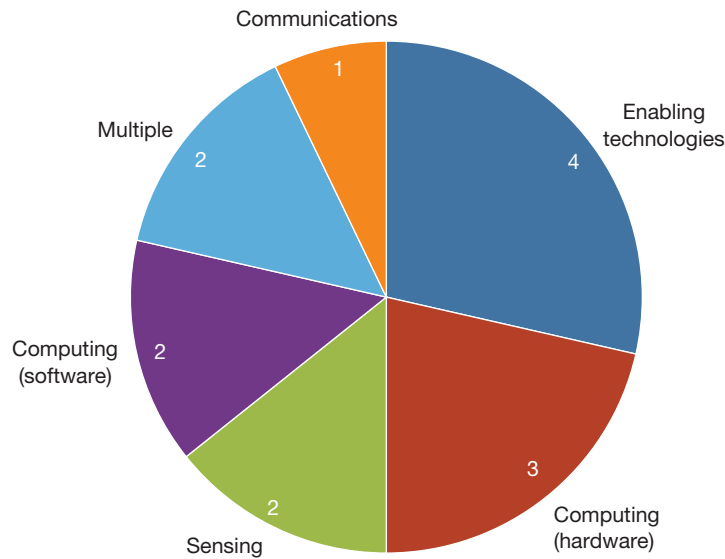
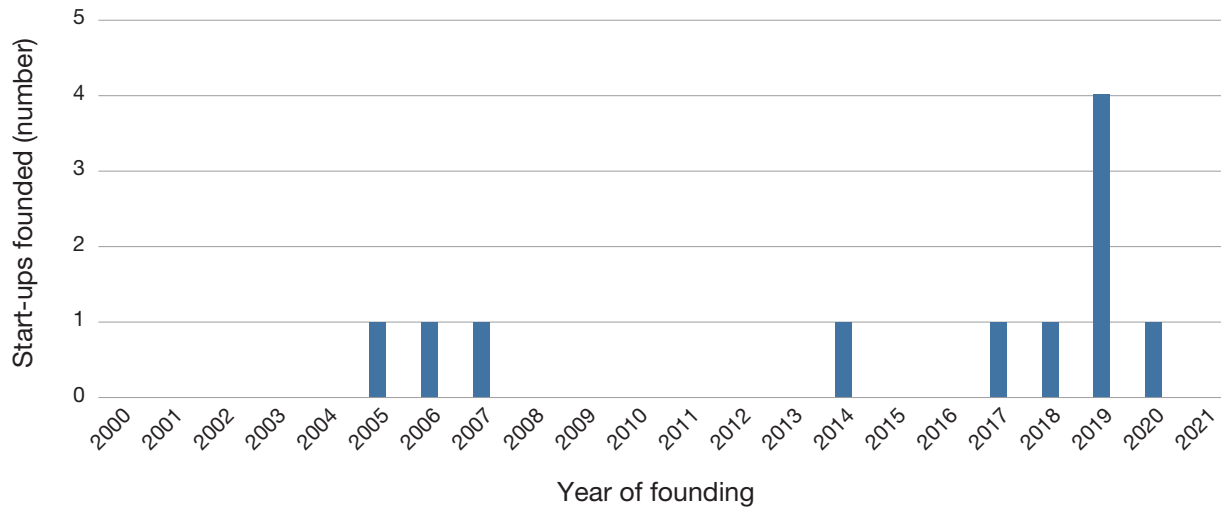


FIGURE 3.14
Australian Quantum Technology Start-Ups Founded, by Year



using silicon quantum dots. Q-CTRL is developing hardware-agnostic control technologies for quantum computers and sensors.

Australia’s quantum technology industry is represented by a consortium called the Australian Quantum Alliance, organized by the Tech Council of Australia. It consists of six Australian companies (Diraq, Nomad Atomics, Q-CRTL, Quantum Brilliance, QuintessenceLabs, and Silicon Quantum Computing) and, notably, three U.S. companies (Google, Microsoft, and Rigetti). Australian Quantum Alliance and the broader tech council advocate for the interests of their member companies by coordinating between firms, developing, and advocating for public policy to expand the role of the technology industry and quantum technology in the Australian economy.

FIGURE 3.15
Australian Quantum Technology Start-Ups, by Number of Employees and Amount of External Funding

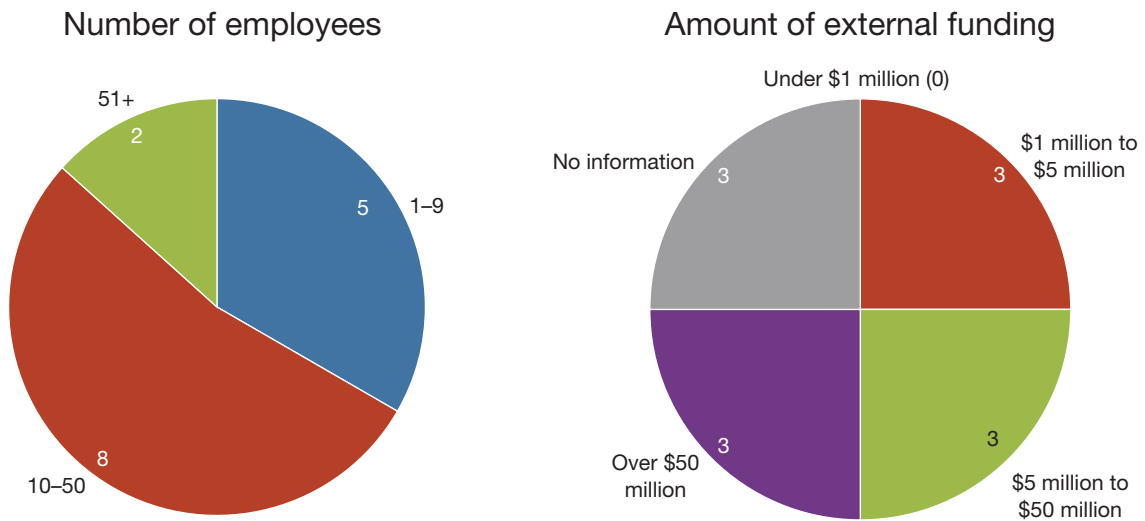
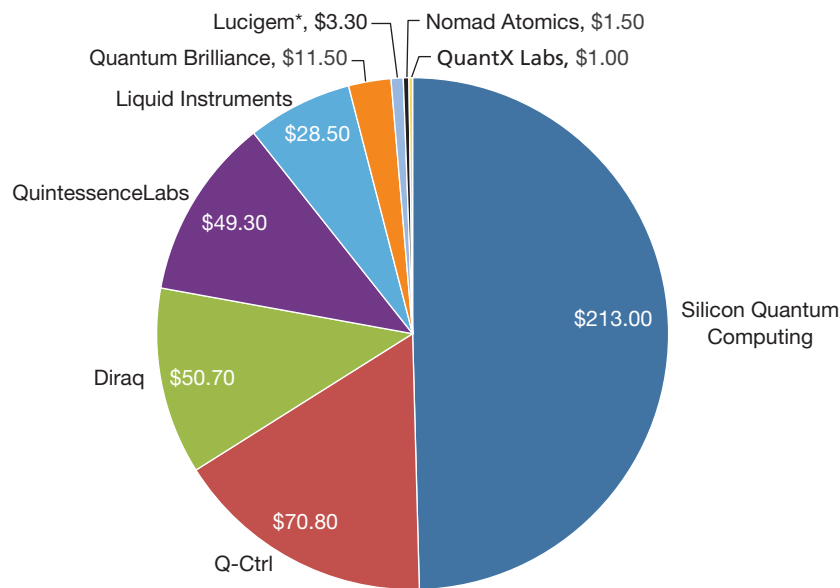
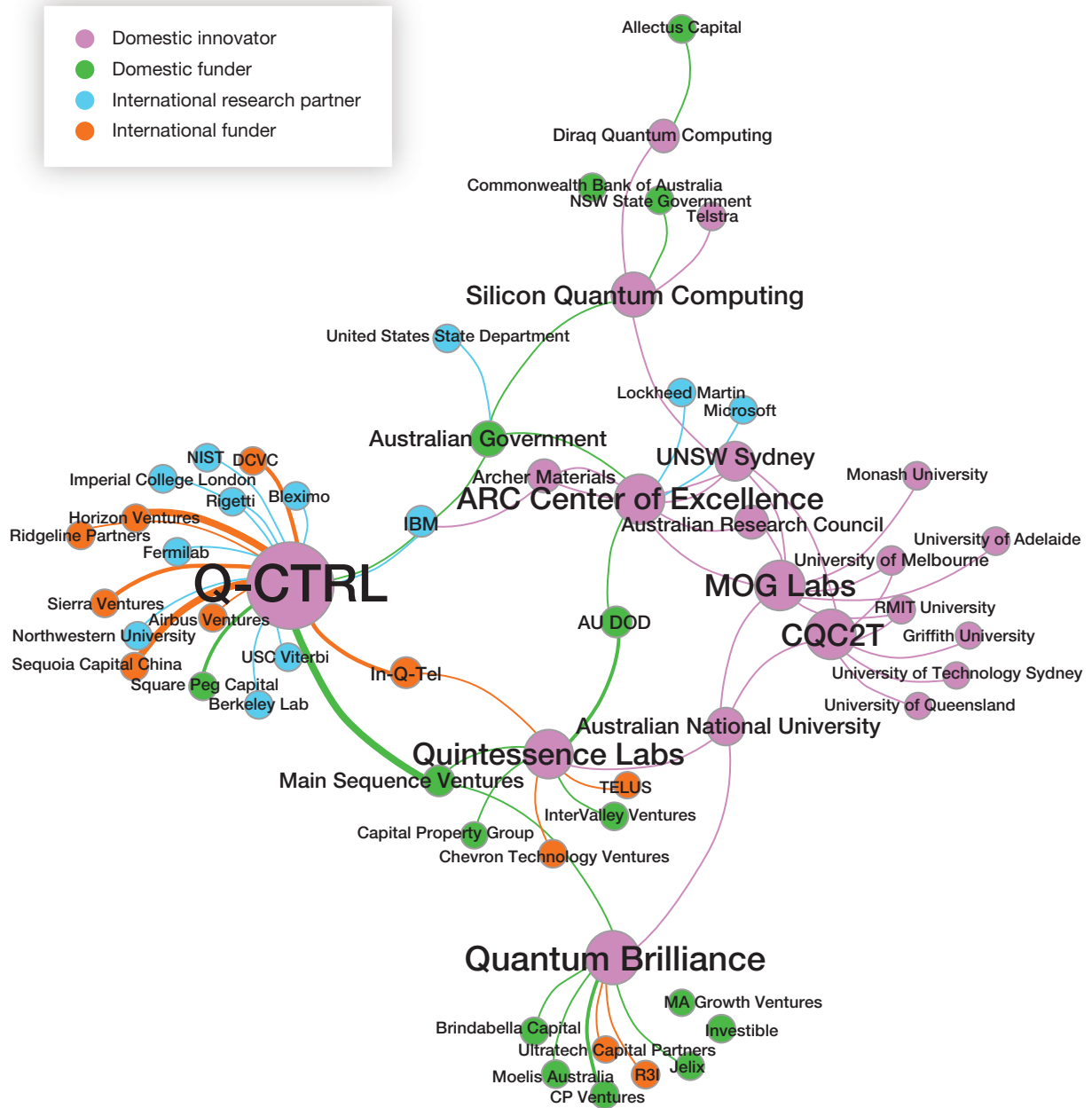


FIGURE 3.16
Total Funds Raised by Australian Quantum Technology Start-Ups



As an entire ecosystem, the Australian quantum industrial base is still fairly consolidated, as compared with the United States, but a few key companies have been able to tap into both international and domestic funding networks. As indicated in Figure 3.17, four key companies draw in most funders in the Australian quantum ecosystem: Silicon Quantum Computing, Q-CTRL, QuintessenceLabs, and Quantum Brilliance. The latter three have also been successful at generating external funding sources. Beyond these four companies, other innovators are largely supported by collaborations with Australian government groups or univer-

FIGURE 3.17
Australia Funding and Collaboration Ecosystem



sities. For this group of entities, ARC and CQC2T—government-organized entities—serve as central hubs to connect innovators.

One noteworthy foreign investor in Q-CTRL is Sequoia Capital China. Sequoia Capital China is a branch of the firm Sequoia Capital, which is headquartered in the United States, but Sequoia Capital China was founded and is managed by a Chinese national. The relationship between the main firm and its China

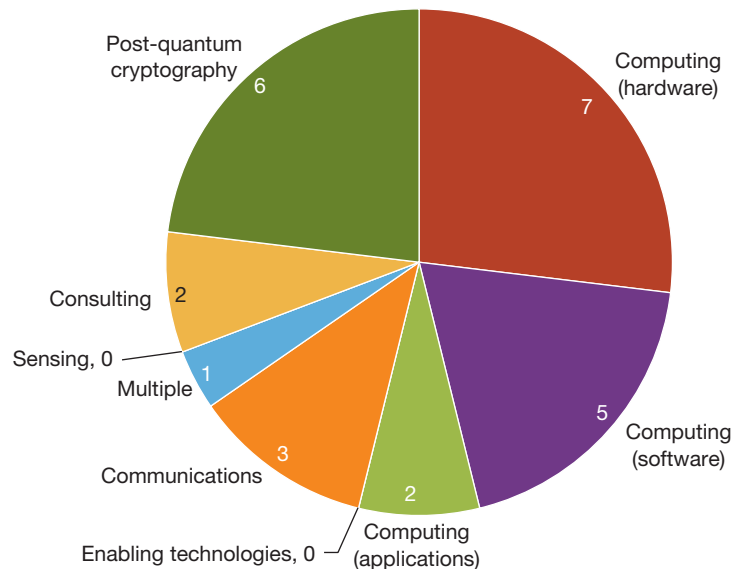
branch had been described as “increasingly complex”; in 2022, the main firm instituted a process to screen for national security concerns in its China branch’s investments in defense-related companies.³⁵

Another characteristic that defines the Australian ecosystem is the fact that the most heavily networked companies are smaller, private companies. There is only one domestic publicly traded company in the ecosystem: Archer Materials. Otherwise, the companies that have established robust funding networks supported by diverse types of financial entities are relatively smaller, private companies that have spun out of university research groups. The vast majority of the international supporters and collaborators are U.S. companies and universities.

United Kingdom

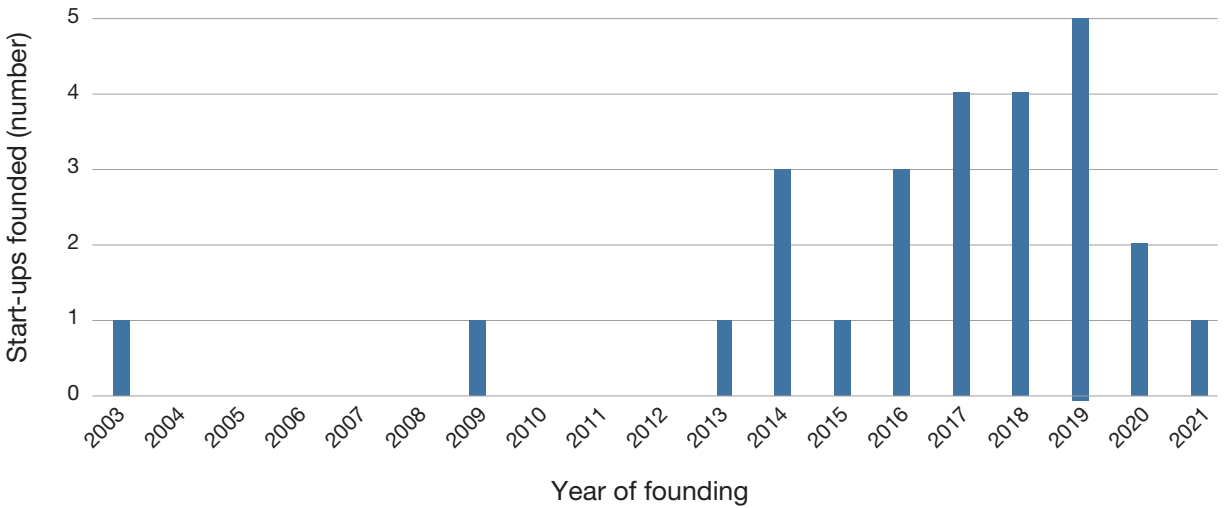
The UK’s quantum technology business sector is dominated by start-ups funded by venture capital firms. The sector is highly diversified, with companies developing and commercializing technologies across quantum computing, communications, enabling technologies, and applications (although we did not identify any UK start-ups dedicated solely to quantum sensing). Figure 3.18 shows the number of start-ups in the UK’s quantum sector working in each technology area, with most companies developing computing technologies, focused on hardware and software. The UK’s quantum technology start-up sector is relatively mature, with the wave of quantum technology start-ups beginning in 2013 and continuing through the present, as shown in Figure 3.19. The UK’s quantum technology sector’s diversity is further illustrated by the variation in the size and capitalization of its companies, shown organized by number of employees and capital raised, in Figure 3.20. Organized by employee count, most UK firms are midsized, with between ten and 50 employees, with significant fractions of the sector consisting of both small and large companies with fewer than ten and more than 50 employees, respectively. Similar results appear at the sector by funding level, where a plurality

FIGURE 3.18
Number of UK Quantum Technology Start-Ups,
by Technology Area



³⁵ Aruna Viswanatha, Jing Yang, and Berber Jin, “Sequoia Turns to Outside National-Security Experts to Vet New China Tech Investments,” *Wall Street Journal*, February 24, 2023. In June 2023, Sequoia Capital announced that it would split off its China branch into a separate firm. Jin Yang and Eliot Brown, “Venture-Capital Firm Sequoia to Separate China Business as Political Tensions Rise,” *Wall Street Journal*, June 6, 2023.

FIGURE 3.19
UK Quantum Technology Start-Ups Founded, by Year



of firms have raised between \$5 million and \$50 million in funds, and a handful have raised both less than \$5 million and greater than \$50 million. However, slightly more than one-quarter of the sector lacks data on funding.

Figure 3.21 shows estimates for the total funds raised by quantum technology firms in the UK. While the UK's quantum technology sector is diverse, with firms in a broad range of sizes, a handful of firms have received most investments thus far. These companies have staffing and funding levels comparable to some of the top global competitors in quantum technology and applications.³⁶ They are mostly concentrated in developing quantum computing hardware, with a few exceptions, including M-Squared Lasers, which is also developing quantum sensors; PQShield, which primarily works on developing quantum-safe conventional cryptography systems; Riverlane, which develops operating systems for quantum computers; and Quantinuum, which develops both software and hardware for quantum computers and applies their functions.

Cooperation between and advocacy for the interests of quantum technology companies in the UK are conducted by a consortium called UK Quantum. The consortium's members consist only of only companies; it is not a group for the coordination of government, industrial, and academic institutions. UK Quantum aims to shape government policies in the UK and abroad in favor of the interests of its companies and to promote government and industry adoption of quantum technologies.

Of all the allied countries evaluated, the UK's quantum ecosystem most resembles that of the United States. As Figure 3.22 indicates, the UK ecosystem consists of a significant network of both international and domestic funders and collaborators, which are distributed across many different UK quantum innovators. There is significantly more variation in nationality of investors in the UK quantum ecosystem than in the other nations we considered.

³⁶ As a point of comparison, our 2022 assessment found that only ten U.S. quantum technology start-ups had raised over \$10 million as of July 2021, and only five had over 50 employees.

FIGURE 3.20
UK Quantum Technology Start-Ups, by Number of Employees and Amount of External Funding

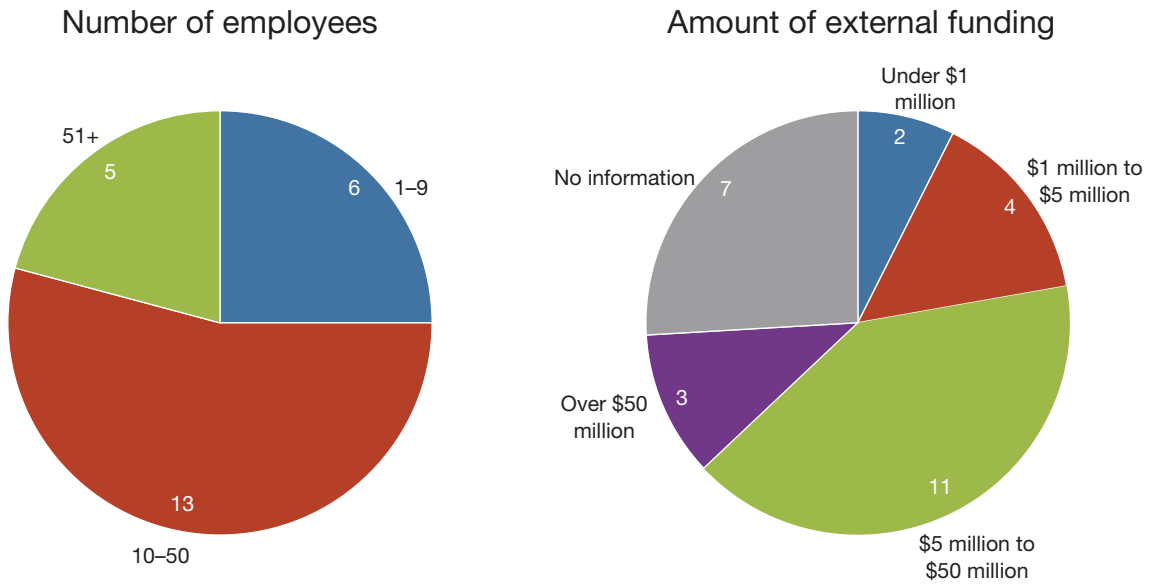
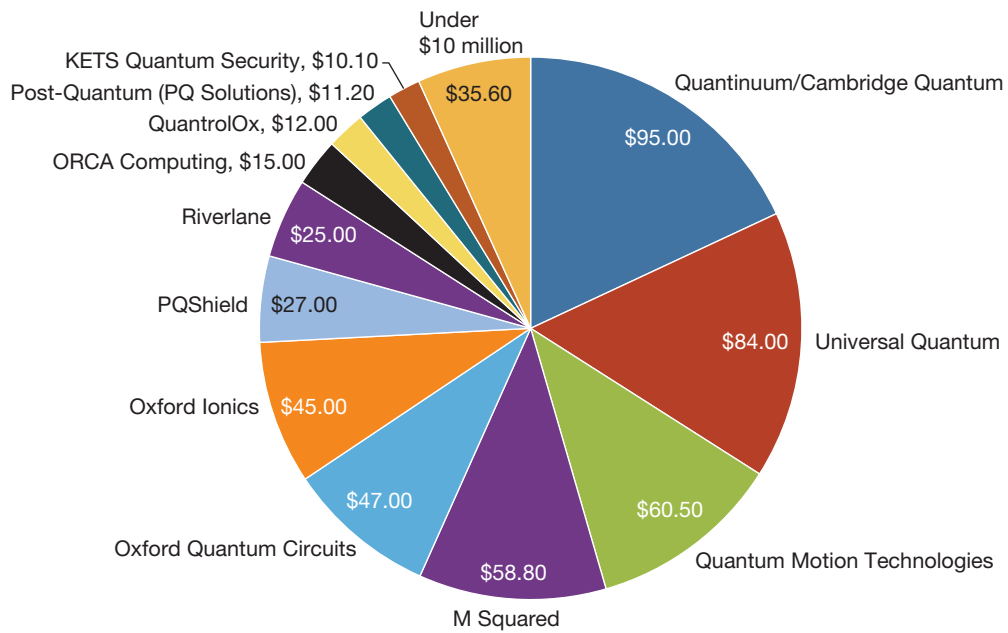


FIGURE 3.21
Total Funding Raised by British Quantum Technology Start-Ups



NOTES: Amounts are in millions of U.S. dollars. Each firm with over \$10 million in funding is shown; the rest are aggregated into the "less than \$10 million" section.

Germany

Germany's quantum technology business sector is less dominated by start-ups than Australia's and the UK's are. Germany's large and developed industrial firms, in combination with robust state support and coordination in the industry, have produced a sector in which both domestic and international start-ups compete and cooperate with large German firms (such as Racyics, Infineon, Bosch, and Rosenberger) and, to a lesser extent, with other European firms. Start-ups constitute a smaller fraction of the German quantum technology companies than in Australia or the UK; German start-ups are diversified technologically but less diversified in funding support. German start-ups are developing and commercializing technologies across quantum computing, communications, enabling technologies, and computing applications. Figure 3.23 shows the number of start-ups in Germany's quantum sector working in each technology area, with most companies developing computing technologies and applications. Germany's quantum technology start-up sector is less mature than that of the UK, with a wave of quantum technology start-ups beginning in 2017 and continuing through the present, as shown in Figure 3.24.

Germany's sector lacks some diversity in the size and capitalization of its companies, shown in Figure 3.25 organized by number of employees and capital raised. By employee count, a plurality of German start-ups are midsized, with between ten and 50 employees; only one company has more than 50, and several lack information on employee count and so are likely at the smaller end of the spectrum. Over three-quarters of firms in the set either have no funding information available or have raised less than \$5 million. As shown in Figure 3.26, of the firms studied for which funding information was available, only two firms have raised more than \$5 million: EleQtron, which develops and operates quantum computers based on trapped ions, and HQS Quantum Simulations, which develops software for quantum computing applications in the chemical industry and academia.

Germany has four quantum industry consortia, each with differing structures, aims, governance, and sets of members: the Quantum technology and Application Consortium (QUTAC), PhoQuant, Quantum-Enabling Services and Tools for Industrial Applications (QuaST), and QSolid. QUTAC is an industrial council intended to advance quantum technology and applications, with a focus on computing in Germany

FIGURE 3.23
Numbers of German Quantum Technology Start-Ups,
by Technology Area

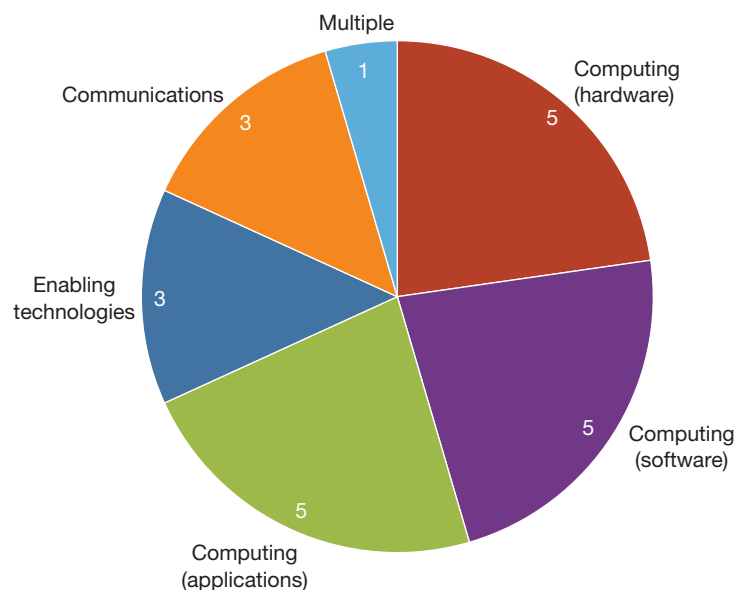


FIGURE 3.24
German Quantum Technology Start-Ups Founded by Year

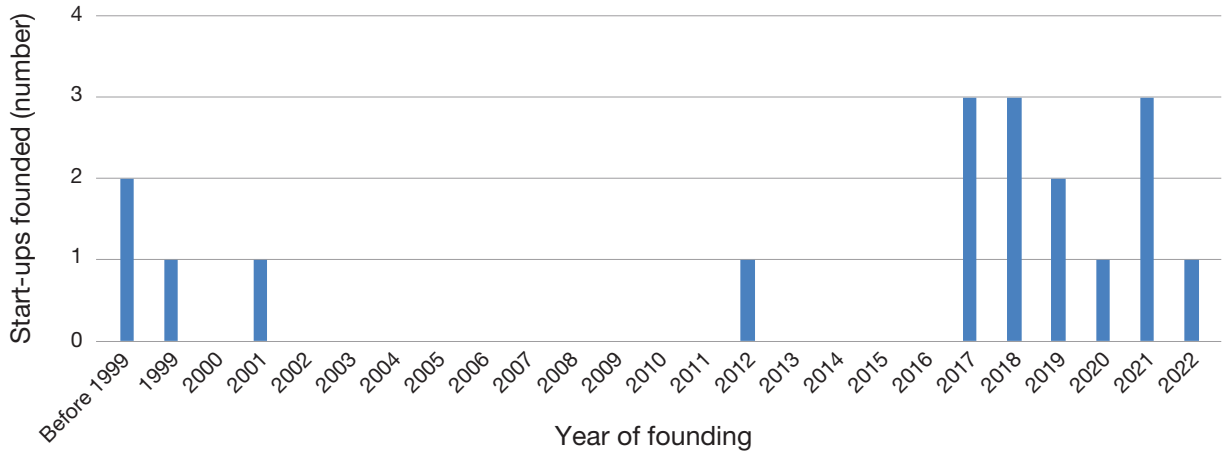
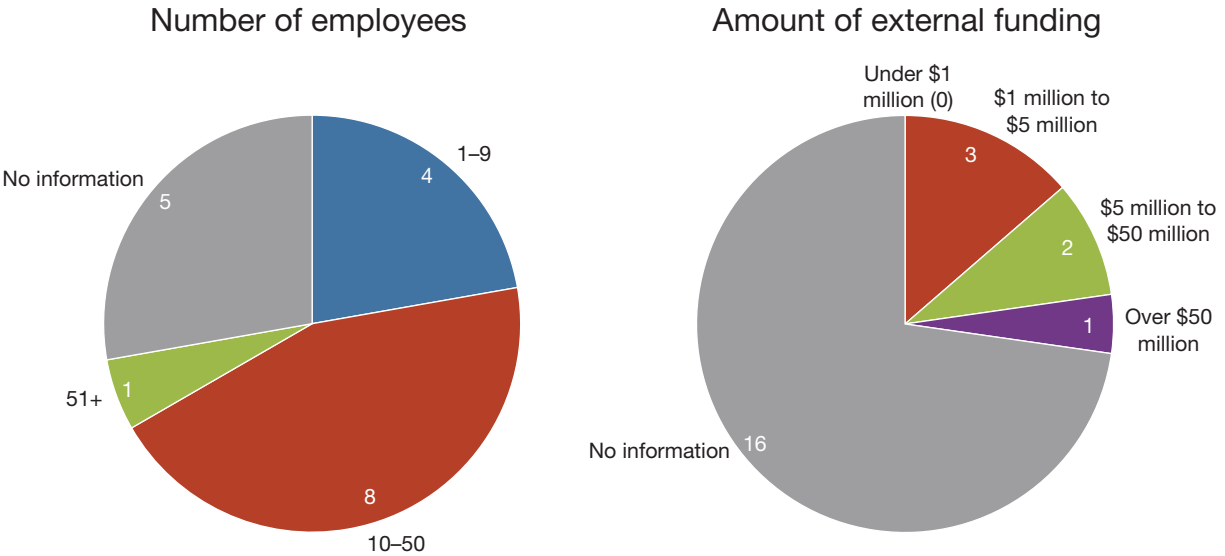
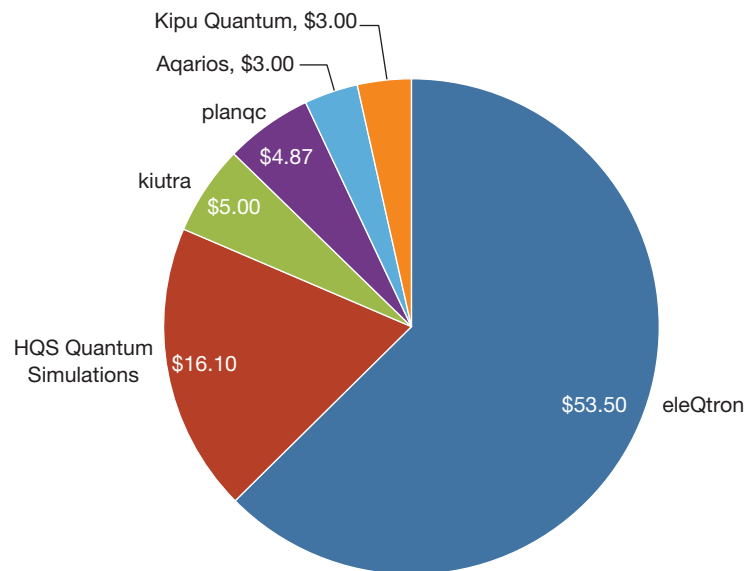


FIGURE 3.25
German Quantum Technology Start-Ups, by Number of Employees and Amount of External Funding



through pooling project findings of its member companies. It also coordinates and advocates for the interests of its member companies in public policy related to scientific R&D. PhoQuant is a consortium of quantum technology start-ups and academic institutions intended to coordinate the development of an indigenous, photonic German quantum computer. This effort is focused on photon-based quantum computing technologies and, lead by Q.ANT, is a wholly owned subsidiary of TRUMPH, a manufacturer of machine tools and industrial lasers. It is aiming to create quantum computer chips that can run on traditional mainframe systems. QuaST is a joint effort of research institutions, companies, and universities, led by the German government, to coordinate activities in transferring technologies from R&D to application and commercialization. Finally, QSolid is a government-funded collaboration between established firms, start-ups, research institutions, and universities to develop a German quantum computer and quantum technology supply chain.

FIGURE 3.26
Total Funding Raised by German Quantum Technology Start-Ups



NOTE: Amounts are in millions of U.S. dollars.

QSolid aims to develop a comprehensive technical system that can be integrated into the JUNIQ supercomputing infrastructure at Forschungszentrum Jülich and made accessible to external users.

Germany's quantum ecosystem is still in the process of strengthening its funding support mechanisms. As shown in Figure 3.27, few companies have achieved international funding streams, and for those companies, the international funding volumes are still quite small compared with those for Australian and the UK companies. Of the international funders supporting the German ecosystem, most are part of the larger European Union quantum and technology funding initiatives.

The German quantum industrial ecosystem is largely organized around regional hubs that provide resources and access to funding networks. Regional hubs and start-up accelerators, such as Munich Quantum Valley and QUTAC, connect regional companies and universities, enabling them to share resources, personnel, and funding streams. This is likely an intentional element of the German quantum ecosystem design and is probably intended to offset funding constraints until German companies can establish more-robust sources of funding.

FIGURE 3.28
Number of Japanese Quantum Technology Start-Ups, by Technology Area

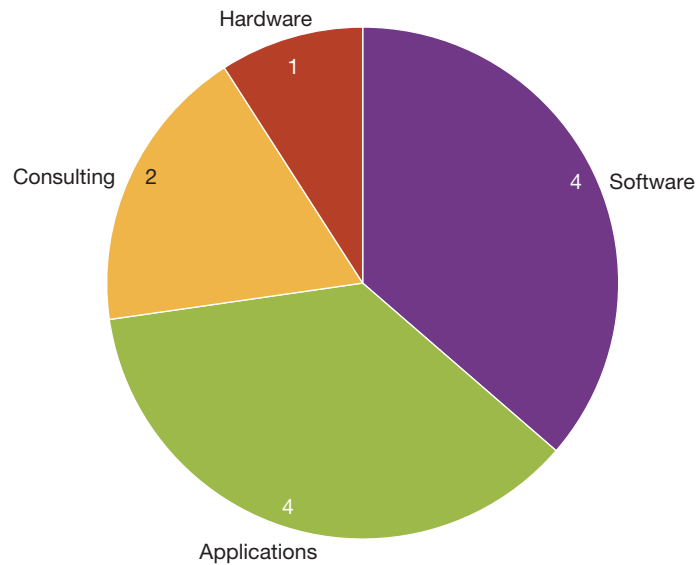
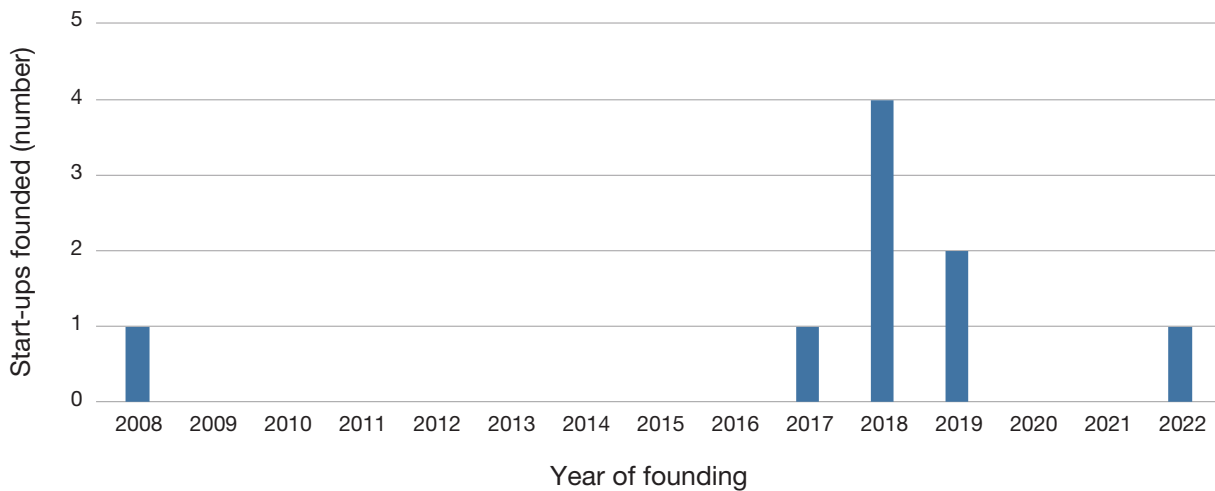


FIGURE 3.29
Japanese Quantum Technology Start-Ups Founded, by Year



plurality of Japanese start-ups are small, with fewer than ten employees. Only two firms employ more than ten people, and employee counts were not available for one-half of firms, likely placing them in the small-sized bin. As shown in Figure 3.31, of the firms for which funding information was available, only one firm has raised more than \$5 million: QunaSys, which develops software for quantum computers, primarily for applications in industry.

Because of the minor role of start-ups and venture capital funding models play in commercialization of the products of basic scientific research, the activities of large Japanese firms, such as Fujitsu and Toshiba, among others, and such metrics as patent filings are more illuminating of the state of the Japanese quantum technological industrial base. As we will show, large Japanese firms are major global players in the quantum commercial industry.

FIGURE 3.30
Japanese Quantum Technology Start-Ups, by Number of Employees and Amount of External Funding

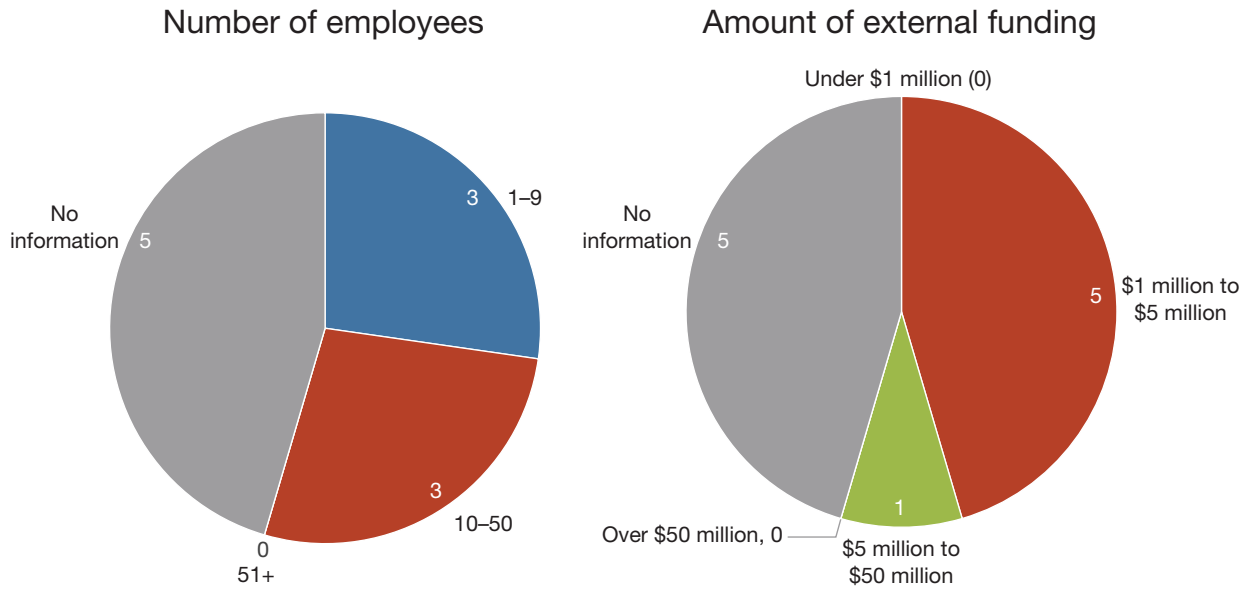
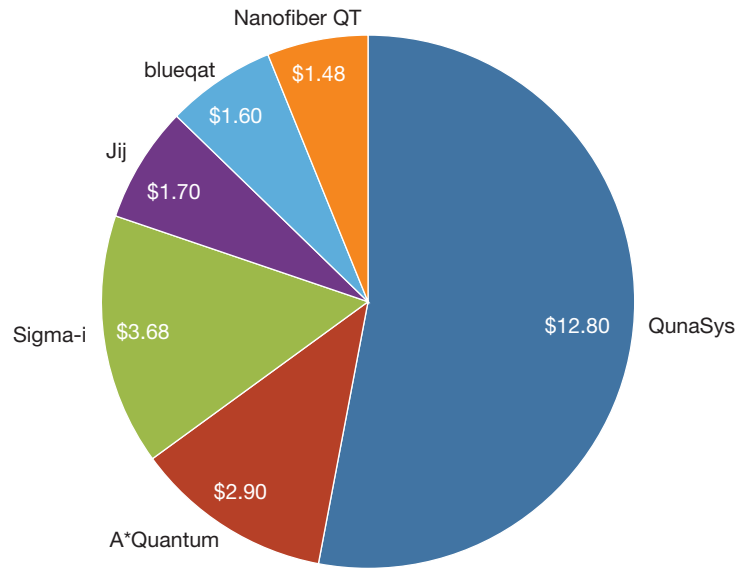


FIGURE 3.31
Total Funding Raised by Japanese Quantum Technology Start-Ups



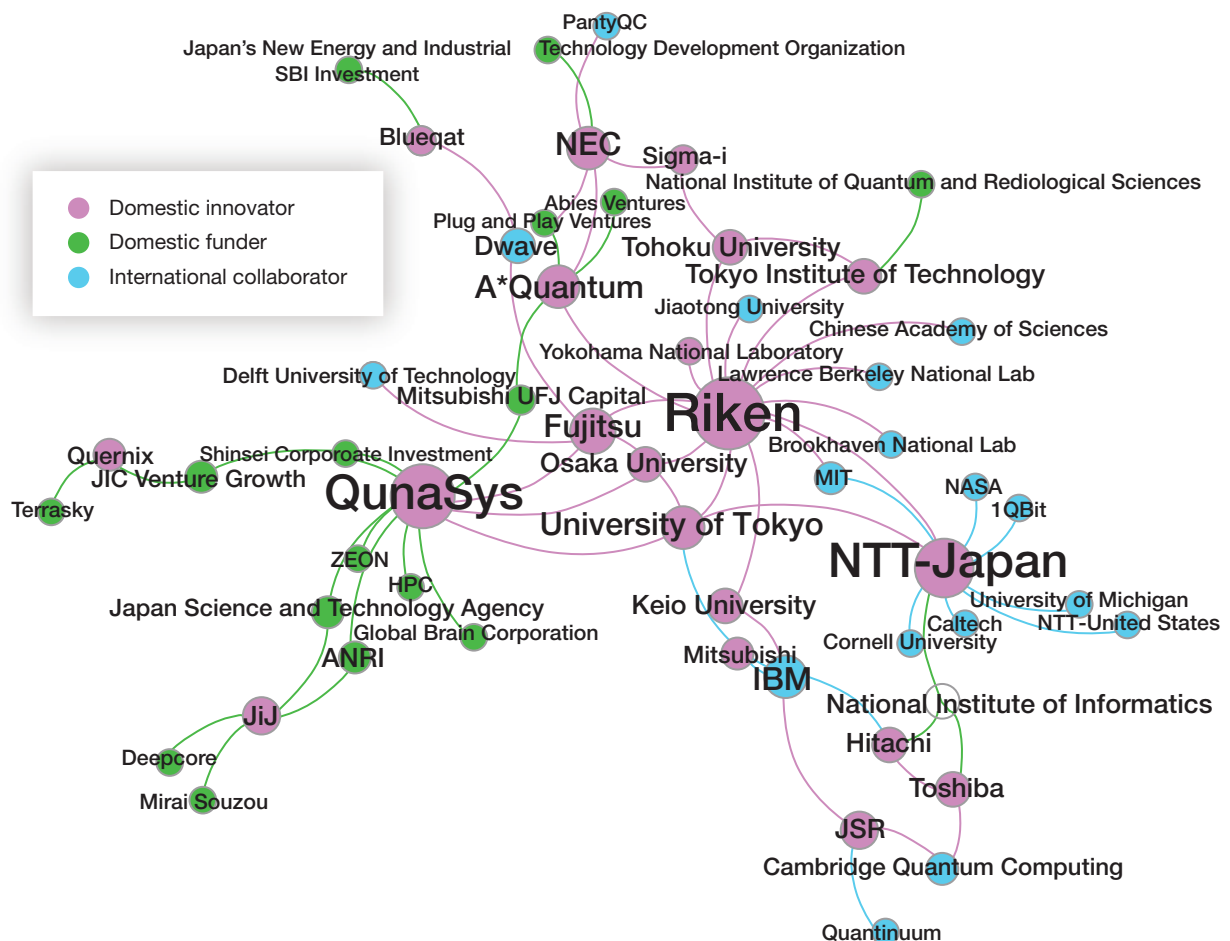
NOTE: Amounts are in millions of U.S. dollars.

Japan has two quantum technology organizations, the Quantum Innovation Initiative Consortium and the Quantum Strategic Industry Alliance for Revolution (Q-STAR). The Quantum Innovation Initiative Consortium aims to accelerate the development of Japanese R&D in quantum computing by coordinating the activities of universities, large companies, and research institutions to develop the country's quantum computing industrial base and technical workforce. Furthermore, the consortium aims to advance the state of scientific research and its applications using quantum technology. Q-STAR is an industrial council intended to coordinate efforts among large Japanese conglomerates in developing quantum technologies and their applications. The council also aims to advocate for the interests of its member companies in Japanese government policy related to quantum science and technology. Q-STAR has several working groups dedicated to investigating progress and applications in different subfields of quantum science and technology.

The Japanese quantum ecosystem relies significantly more on internal funding and support mechanisms than do the other U.S.-allied countries studied in this chapter. As Figure 3.32 indicates, there are no sources of external, private investment in the Japanese quantum industrial base. Instead, the network is supported heavily by domestic funding sources, including Japanese investment firms and government funding agencies. Instead of external funding, domestic funding is supplemented by a considerable network of international collaboration partnerships, especially for the larger actors in the ecosystem.

One factor that could explain the lack of international funders is the considerable involvement of large public companies, including NEC, Fujitsu, NTT-Japan, Quemix, and Mitsubishi. These public companies

FIGURE 3.32
Japan Quantum Funding and Collaboration Ecosystem



are fairly integrated into the national ecosystem, and rely on public funding through stock exchanges and so are able to draw from external sources in addition to sales revenues. Many of these companies also have dual headquarters and facilities abroad. In addition to the public companies, the Japanese ecosystem is also centered on a handful of government funding and research mechanisms, including RIKEN and the National Institute of Informatics.

Technical Achievement

Given the more technical nature of the material in this section, we first order our discussion by quantum information science application domain and then by country rather than vice versa as in the previous sections of this chapter.

Leading Patenting Organizations

The leading patenting organizations—those filing the most patent applications—varied considerably by country investigated and by quantum information science and technology area. These differences are highlighted for the top ten filers in the following sections. Our goal in this subsection was to identify the main technical subareas of high patenting activity; to be consistent with our analysis in Chapter 2, we used the same topical keywords for our search terms as in Tables 2.5 through 2.10. We explain our methodology for generating these keywords in Appendix A. The number of patent applications shown in the tables is the sum of all patent applications that contain any of the keywords, so that applications containing multiple keywords were counted multiple times.

Top Ten Filers of Patent Applications in Quantum Computing

Australia

Table 3.9 lists the top ten organizations filing the most quantum computing patent applications in Australia. The technical areas of greatest interest were superconducting qubits and quantum dots, followed by quantum control, spin qubits, and error correction. U.S. corporations were prominent, with Google filing the most patent applications by far, and Northrop Grumman and Rigetti both in the top seven. New South Innovations, the patent holder for the University of UNSW, was the top Australian filer, followed by the University of Melbourne, Diraq (start-up associated with UNSW), and the University of Sydney.

United Kingdom

Table 3.10 lists the top ten organizations filing the most quantum computing patent applications in the UK. The technical area of greatest interest by far was quantum simulation, followed by Schor’s algorithm (which would greatly accelerate the solution of factorization problems widely used in today’s encryption methods). The most patent applications by far were filed by the Glaxo Group, one of the world’s largest healthcare conglomerates. While most of the top ten were UK companies, multinationals, such as Sumitomo and General Electric, were also part of this group.

Germany

Table 3.11 lists the top ten organizations filing the most quantum computing patent applications in Germany. As with the UK, the technical area of greatest interest by far was quantum simulation, followed in this case by Grover’s algorithm (which could greatly enhance computer search capability). Glaxo Group filed the most patent applications by far in Germany and the UK, followed by Merck, one of the world’s largest pharmaceutical companies. Micromass UK, a manufacturer of spectrometry equipment, was also a top ten filer in both

TABLE 3.9
Top Filers of Quantum Computing Patent Applications
in Australia

Organization	Patent Applications	Primary Keyword(s)
Google	186	Superconducting qubit
NewSouth Innovations	27	Quantum dot
University of Melbourne	20	Quantum control
Diraq	17	Quantum dot
Northrop Grumman Systems	16	Superconducting qubit
University of Sydney	12	Spin qubits Single photon
Rigetti andLLC	10	Error correction
Accenture Global Solutions	9	Quantum annealing Superconducting qubit
Dartmouth College	9	Superconducting qubits Error correction
Somalogic Operating	9	Trapped Ion

TABLE 3.10
Top Filers of Quantum Computing Patent Applications in the UK

Organization	Patent Applications	Primary Keyword
Glaxo Group	105	Quantum simulation
Micromass UK	17	Quantum simulation
Cambridge Display Technology	12	Quantum simulation
Oxford University innovation	12	Shor's algorithm
River Lane Research	12	Quantum simulation
Quantum Motion Technologies	11	Quantum simulation
Sumitomo Chemical	11	Quantum simulation
National Physical Laboratory Management	10	Quantum simulation
UCB Biopharma	9	Quantum simulation
GE Healthcare AS	8	Quantum simulation

Germany and the UK, as was UCB Biopharma, SRL. Each of these companies filed about the same number of patent applications in Germany as in the UK.

Japan

Table 3.12 lists the top ten organizations filing the most quantum computing patent applications in Japan. Quantum simulation was also the technical area of greatest interest. However, in Japan, quantum annealing was a strong second technical area of great interest, with more patents filed in Japan in this area than in the UK and Germany in quantum simulation. As noted in Chapter 2, Japan was the leading filer of quantum patent applications among the allied nations. Accordingly, Japanese organizations filed many more quantum

TABLE 3.11
Top Filers of Quantum Computing Patent Applications
in Germany

Organization	Patent Applications	Primary Keyword
Glaxo Group	89	Quantum simulation
Merck Patent	34	Quantum simulation
HQS Quantum Simulations	16	Quantum simulation
Micromass UK	12	Quantum simulation
Technische Universität Berlin	7	Quantum simulation
UCB Biopharma SRL	7	Quantum simulation
Freie Universitaet Berlin	6	Quantum simulation
BASF SE	5	Quantum simulation
Daicel Evonik	5	Quantum simulation
Bundesdruckerei	4	Grover's algorithm

TABLE 3.12
Top Filers of Quantum Computing Patent Applications in Japan

Organization	Patent Applications	Primary Keyword
Semiconductor Energy Laboratory	878	Quantum simulation
Fujitsu	206	Quantum annealing
Fujifilm	184	Quantum annealing
Hitachi	166	Quantum simulation
Sumitomo Chemical	162	Quantum simulation
Toshiba	95	Quantum annealing
Canon Inc.	87	Quantum simulation
NTT	85	Quantum annealing
NEC	71	Quantum annealing
Japan Science and Technology Agency	50	Quantum simulation

computing patent applications than those in the UK and Germany, with Semiconductor Energy Laboratory alone filing more than twice as many applications as the top ten filers in the UK and Germany combined. Moreover, all of the top ten filers in Japan were Japanese organizations.

Top Filers of Patent Applications in Quantum Communications

Australia

Table 3.13 lists the top ten organizations filing the most quantum communications patent applications in Australia. As for quantum computing, Google was by far the leading filer of patent applications, filing in quantum cryptography. None of the other top ten filed as many as ten patent applications. The Chinese company Baidu filed the ninth most patent applications.

TABLE 3.13
Top Filers of Quantum Communications Patent Applications in Australia

Organization	Patent Applications	Primary Keyword(s)
Google	131	Quantum cryptography
Rigetti Computing	9	Error correction Entanglement
3M Innovative Properties	8	Entanglement
NewSouth Innovations	8	Entanglement
Accenture Global Solutions	7	Quantum memory
Cook Medical Technologies	6	Entanglement
Covidien	6	Entanglement
University of Melbourne	6	Entanglement Error correction
Beijing Baidu Netcom Science and Technology	5	Quantum teleportation QKD
Drylock Technologies	5	Entanglement

United Kingdom

Table 3.14 lists the top ten organizations filing the most quantum communications patent applications in the UK. The technical areas of greatest interest were quantum entanglement and measurement-device-independent QKD. The leading filers in quantum communications in the UK were foreign companies, most notably Toshiba (Japan) and Hewlett Packard (U.S.), although UK companies Element Six and British Telecom were next in line.

Germany

Table 3.15 lists the top ten organizations filing the most quantum communications patent applications in Germany. The technical area of greatest interest was quantum entanglement. German organizations Quantum Technologies and Merck headed the list. However, British Telecom and Hewlett Packard were not far behind, and other allied countries' organizations, Element Six (UK) and Inter-University Research Institute (Japan) were also included.

Japan

Table 3.16 lists the top ten organizations filing the most quantum communications patent applications in Japan. As with quantum computing, all of the top ten filers were Japanese organizations. QKD and quantum cryptography were the technical areas of greatest interest. Many more quantum communications patent applications were filed in Japan than in Germany and many more than those filed in the UK by non-Japanese filers.

TABLE 3.14
Top Filers of Quantum Communications Patent Applications in the UK

Organization	Patent Applications	Primary Keyword
Toshiba	758	Measurement-device-independent
Hewlett Packard Enterprise Development	407	Quantum entanglement
Element Six Technologies	216	Quantum entanglement
British Telecommunications	152	Quantum entanglement
Qubitekk	114	Quantum entanglement
Immatix Biotechnologies	105	Quantum fidelity
Quinetic	94	Measurement-device-independent
Arquit	92	Quantum entanglement
Base4 Innovation	88	Quantum entanglement
Oxford University Innovation	69	Quantum entanglement

TABLE 3.15
Top Filers of Quantum Communications Patent Applications in Germany

Organization	Patent Applications	Primary Keyword
Quantum Technologies	161	Quantum entanglement
Merck Patent	134	Quantum entanglement
British Telecommunications	110	Quantum entanglement
Hewlett Packard Development	95	Quantum entanglement
Individual	79	Quantum entanglement
Element Six Technologies	67	Quantum entanglement
Robert Bosch	52	Quantum entanglement
Forshungzentrum-Jülich	50	Quantum entanglement
HQS Quantum Simulations	47	Quantum entanglement
Inter University Research Institute	42	Quantum entanglement
Giesecke and Devrient Currency Technology	40	Quantum entanglement

Top Filers of Patent Applications in Quantum Sensing

Australia

Table 3.17 lists the top ten organizations filing the most quantum sensing patent applications in Australia. The technical area of greatest interest was magnetometry, followed by Josephson junctions and nitrogen vacancy centers. German company Immatix Biotechnologies filed the most patent applications, followed by the U.S. engineered biologics firm Ambrx, Australia research organization Commonwealth Scientific and Industrial Research Organisation, and several U.S. universities and firms. The University of Melbourne filed the tenth most quantum sensing patent applications.

TABLE 3.16
Top Filers of Quantum Communications Patent Applications in Japan

Organization	Patent Applications	Primary Keyword
NEC	626	Quantum key distribution
Toshiba	560	Quantum key distribution
NTT	392	Quantum cryptography
Mitsubishi Electric	337	Quantum cryptography
Japan Science and Technology Agency	172	Quantum cryptography
National Institute of Information and Communications Technology	162	Quantum cryptography
Fujitsu	130	Quantum cryptography
Hitachi	111	Quantum cryptography
Oki Electric Industry	106	Quantum cryptography
Canon	75	Quantum cryptography

TABLE 3.17
Top Filers of Quantum Sensing Patent Applications in Australia

Organization	Patent Applications	Primary Keyword
Immatix Biotechnologies	29	Magnetometry
Ambrx	25	Magnetometry
Commonwealth Scientific and Industrial Research Organization	25	Josephson junction
University of California	25	Josephson junction
Massachusetts Institute of Technology	22	Josephson junction
Harvard College	20	Josephson junction
ModernaTx	20	Magnetometry
Brilliant Light Power	18	Magnetometry
Somalogic Operating	18	Magnetometry
University of Melbourne	17	Nitrogen vacancy center

United Kingdom

Table 3.18 lists the top ten organizations filing the most quantum sensing patent applications in the UK. The technical area of greatest interest by far was magnetometry, followed by quantum-dot qubit sensors and single-photon detectors. As was the case for Australia, the top filer was German company Immatix Biotechnologies. However, the next four top filers were UK organizations. The top ten UK filers in quantum sensing included UK companies that also appear in the top ten in computing and/or communications, e.g. Glaxo and Element Six, as well as multinational General Electric.

Germany

Table 3.19 lists the top ten organizations filing the most quantum sensing patent applications in Germany. The technical area of greatest interest was atomic interferometry, followed by quantum dots, and the great majority of filings were by Japanese companies, which were nine of the top ten filers. The German firm,

TABLE 3.18
Top Filers of Quantum Sensing Patent Applications
in the UK

Organization	Patent Applications	Primary Keyword
Immatic Biotechnologies	296	Magnetometry
Glaxo Group	105	Magnetometry
Oxford University Innovation	70	Magnetometry
Element Six Technologies	70	Magnetometry
Cambridge Enterprise	59	Magnetometry
GE Healthcare	53	Magnetometry
Sharp	51	Quantum dot qubit sensor
Plasticell	51	Magnetometry
BTG International	51	Magnetometry
Toshiba	47	Single-photon detector

TABLE 3.19
Top Filers of Quantum Sensing Patent Applications
in Germany

Organization	Patent Applications	Primary Keyword
Canon Inc.	357	Atomic interferometry
Panasonic	279	Atomic interferometry
Immatic Biotechnologies	154	Magnetometry
Sony	149	Quantum dots
Mitsubishi Electric	146	Quantum dots
Seiko Epson	143	Quantum dots
Toyota Motor	107	Quantum dots
Nikon	106	Quantum dots
Fujitsu	105	Atomic interferometry
Hitachi	94	Quantum dots

Immatic Biotechnologies, the leading quantum sensing filer in Australia and the UK, filed the third most quantum sensing patent applications in Germany, with a focus on magnetometry.

Japan

Table 3.20 lists the top ten organizations filing the most quantum sensing patent applications in Japan. The technical area of greatest interest was magnetometry (which agrees with the focus of scientific publications), with strong interest in single photons, Josephson junctions, gyroscopes, and atom interferometry. As with quantum computing and quantum communications, all ten top filers were Japanese organizations (in this case all companies), with the top filer by far Semiconductor Energy Laboratory, which was also the top filer in quantum computing.

TABLE 3.20
Top Filers of Quantum Sensing Patent Applications in Japan

Organization	Patent Applications	Primary Keyword(s)
Semiconductor Energy Laboratory	1,269	Magnetometry Gyroscope
Hitachi	557	Magnetometry Single photon
Toshiba	487	Single photon
NTT	461	Atom interferometer
Canon Medical Systems	372	Single photon
NEC	293	Josephson junction Single photon
Shimadzu	285	Single photon
Fujitsu	271	Josephson junction
Mitsubishi Chemical	208	Magnetometry
Fujifilm	202	Magnetometry

Notable Technical Achievements

In this subsection, we present the results of an analysis of the technical scholarly literature in which we searched for technical achievements by researchers based in Australia, the UK, German, or Japan that our subject-matter experts (SMEs) judged to be at or near the global cutting edge. Given the enormous scope of this question, our review was not intended to be comprehensive, and much more work could be done. We identified one major area—SSQs for quantum computing—in which some of these countries (and others) were technically competitive with both the United States and China, so we present a fairly deep dive on this topic in this section. Our (noncomprehensive) review did not identify any technical domains of comparably large scope within quantum communications or sensing in which U.S.-allied nations are competitive with the United States or China. Therefore, for these application domains, we only briefly note a few specific achievements within these nations that are particularly notable. Given the technical variety of the achievements, we do not present the full necessary technical background, so this material may be of interest primarily to technical experts.

Quantum Computing

In this subsection, we describe recent developments in SSQ quantum processors. Appendix A provides some technical background for readers who are not familiar with this technology. These processors have individual qubit quality that is comparable to that of processors based on superconducting transmon or trapped-ion qubits. But overall, this class of processor is less mature than either of those, because no one has demonstrated the ability to entangle together more than a very small number of these qubits (six SSQs, as compared to 433 superconducting qubits and at least 20 trapped-ion qubits). It is not clear whether this processor architecture will be able to sustain higher numbers of entangled qubits. But there is significant overlap in the fabrication processes for SSQ processors and for conventional semiconductors—much more so than for any other qubit architecture under exploration. So, if the SSQ architecture does prove scalable, developers could take advantage of an extensive existing semiconductor fabrication infrastructure to scale up very rapidly.

Table 3.21 summarizes significant advances in SSQ systems that have been reported in the academic literature in 2022 and 2023. These developments have been made by research teams in Australia, the Nether-

TABLE 3.21
Notable Demonstrations of Silicon-Spin-Qubit Processors

Study	Type	No. of Qubits	1-Qubit Gate Fidelity (%)	2-Qubit Gate Fidelity (%)	SPAM Fidelity (%)	Coherence Time (ms)	Gate Speed (ms)	Lead Country and Institution
1 Madzik et al., 2022	1P-1P donor ²⁸ Si SiMOS	3	99.95	94.37 (nuclear spins)	98.95	100 (electron spins)	10–20 (nuclear spins)	Australia (UNSW)
2 Gilbert et al., 2023	²⁸ Si SiMOS	4	99.93	99.87	NR	50	0.003	Australia (UNSW and Diraq)
3 Philips et al., 2022	²⁸ Si/SiGe	6	99.86	86.00	NR	>>100	NR	Netherlands (TU Delft, QuTech)
4 Noiri et al., 2022 ^a	²⁸ Si/SiGe	2	99.80	99.50	98.00	~30	NR	Japan (RIKEN)
5 Xue et al., 2022 ^b	²⁸ Si/SiGe	2	99.72	99.62	NR	~20	NR	Netherlands (TU Delft, QuTech)
6 Takeda et al., 2022 ^c	NatSi/SiGe	3	99.70	NR	NR	43	NR	Japan (RIKEN)
7 Weinstein et al., 2023 ^d	²⁸ Si/SiGe	2 of 6	99.30	97.10	NR	NR	NR	United States (HRL Laboratories)
8 Mills et al., 2022 ^e	²⁸ Si/SiGe	2 of 6	99.13	99.80	97.50	63	NR	United States (Princeton, NIST, Sandia)
9 He et al., 2019 ^f	2P-3P donor in natural Si	2	96.5/91.80	94.00	NR	480,000/ 110,000	0.008	Australia (Silicon Quantum Computing)
10 Zwerver et al., 2022	²⁸ Si/ ²⁸ SiO ₂	2 of 7	99.05	NYD	NR	24	NR	Netherlands (TU Delft, QuTech), United States (Intel)
11 Hu et al., 2023 ^g	²⁸ Si SiMOS	2	NYD	NYD	NR	4.46	NR	China (USTC Hefei)

NOTE: ²⁸Si = silicon-28; SPAM = state preparation and measurement; SiMOS = silicon metal oxide semiconductor; P = phosphorus; NYD = not yet demonstrated; NR = not reported; NIST = National Institute of Standards and Technology; USTC = University of Science and Technology of China.

^a Akito Noiri, Kenta Takeda, Takashi Nakajima, Takashi Kobayashi, Amir Sammak, Giordano Scappucci, and Seigo Tarucha, "Fast Universal Quantum Gate Above the Fault-Tolerance Threshold in Silicon," *Nature*, Vol. 601, January 2022.

^b Xiao Xue, Maximilian Russ, Nodar Samkharadze, Brennan Undseth, Amir Sammak, Giordano Scappucci, and Lieven M. K. Vandersypen, "Quantum Logic with Spin Qubits Crossing the Surface Code Threshold," *Nature*, Vol. 601, January 2022.

^c Kenta Takeda, Akito Noiri, Takashi Nakajima, Takashi Kobayashi, and Seigo Tarucha, "Quantum Error Correction with Silicon Spin Qubits," *Nature*, Vol. 608, August 2022.

^d Aaron J. Weinstein, Matthew D. Reed, Aaron M. Jones, Reed W. Andrews, David Barnes, Jacob Z. Blumoff, Larken E. Euliss, Kevin Eng, Bryan H. Fong, Sieu D. Ha, et al., "Universal Logic with Encoded Spin Qubits in Silicon," *Nature*, Vol. 615, February 6, 2023.

^e Adam R. Mills, Charles R. Guinn, Michael J. Gullans, Anthony J. Sigillito, Mayer M. Feldman, Erik Nielsen, and Jason R. Petta, "Two-Qubit Silicon Quantum Processor with Operation Fidelity Exceeding 99%," *Science Advances*, Vol. 8, No. 14, April 2022.

^f Y. He, S. K. Gorman, D. Keith, L. Kranz, J. G. Keizer, and M. Y. Simmons, "A Two-Qubit Gate Between Phosphorus Donor Electrons in Silicon," *Nature*, Vol. 571, July 2019.

^g Rui-Zi Hu, Rong-Long Ma, Ming Ni, Yuan Zhou, Ning Chu, Wei-Zhu Liao, Zhen-Zhen Kong, Gang Cao, Gui-Lei Wang, et al., "Flopping-Mode Spin Qubit in a Si-MOS Quantum Dot," *Applied Physics Letters*, Vol. 122, No. 13, March 27, 2023.

lands, Japan, and the United States. For comparison purposes, the table also reports a demonstration of the state of the art within China.

As with all quantum processors, there are many different technical metrics that capture the performance of SSQ quantum processors. The systems listed in Table 3.21 are ordered by the average fidelity of their single-qubit gates (the fourth column in the table), with the systems with the highest level of performance shown at the top. The Chinese group's demonstration is significantly behind all the other groups listed in the table. They isolated electrons in a two-qubit system and measured the coherence time of their electron spin states but have not yet demonstrated benchmarked one- or two-qubit operations (perhaps because the coherence times of their qubits are so short).

Row 1 describes the work of a research group associated with the Australian company Diraq.³⁷ This group has the highest-fidelity SSQs yet demonstrated, with an average single-qubit gate performance of 99.95 percent.³⁸ This system uses two phosphorous nuclear spins and one electron localized above the two phosphorous atoms to form a three-qubit quantum processor.

Another group associated with Diraq has demonstrated a four-qubit SSQ quantum processor that uses only electron spins in isotopically pure ²⁸SiMOS (see row 2).³⁹ This quantum processor is based on two quantum dots and has two electrons isolated in the energy well of each quantum dot. This research team has developed techniques to individually probe and control more than one electron in a single quantum dot. This development is also noteworthy because it is based solely on ²⁸SiMOS and does not require the implantation of any donor atomic species like phosphorus. It may be easier to scale up manufacturing of ²⁸SiMOS quantum dot processors that do not rely on donor atoms because standardized semiconductor manufacturing tools and methods can be used to build larger quantum processors with more qubits.⁴⁰

A team based in the Netherlands has demonstrated the largest fully functional SSQ quantum processor to date, containing six fully functioning qubits (see row 3).⁴¹ The research group, from TU Delft and QuTech, has demonstrated single- and two-qubit gate operations for all six qubits in the linear array of quantum dots in the ²⁸Si/SiGE quantum processor. But the average fidelity of the device's two-qubit gates was the lowest of those shown in the table, and the SPAM errors may have been relatively high and were not reported in the technical paper. Nevertheless, this quantum dot system demonstrated exceptionally long qubit coherence times.

Row 4 describes a ²⁸Si/SiGE quantum dot system that uses two electrons as qubits.⁴² This quantum processor, developed by a research team from Japan, has demonstrated a single qubit gate fidelity of 99.8 percent, just six hundredths of 1 percentage point below that of the Gilbert group in the Netherlands. The Japanese group reported a high SPAM fidelity level, second only to that achieved by the Mądzik group from Australia.

The results shown in row 5 are for another research group from the Netherlands, also from TU Delft and QuTech. This group has also developed a ²⁸Si/SiGE quantum dot system that also uses two electrons as

³⁷ One lead author has moved to TU Delft in the Netherlands since this paper was submitted.

³⁸ Madzik et al., 2022.

³⁹ Gilbert et al., 2023.

⁴⁰ Quantum dot devices that use phosphorus donors implanted in silicon require very precise positioning of single donor atoms in each quantum dot. At least some research teams have used specialized tools that are not typically used in commercial microchip manufacturing to implant donor atoms into silicon, such as scanning tunneling microscopes. See He et al., 2019.

⁴¹ Philips et al., 2022.

⁴² Noiri et al., 2022.

qubits.⁴³ The average single-qubit gate fidelity was just a little below the performance achieved by Noiri et al. in Japan, while the two-qubit gate fidelity is better than that achieved by the Noiri group.⁴⁴

Another group in Japan developed a three-qubit quantum dot system in natural Si/SiGe, where interactions with ²⁹Si nuclear spins is a known problem that reduces electron spin coherence times (see row 6).⁴⁵ Despite this limitation, this group reported high-fidelity single qubit gates, but so far has not reported any two-qubit gate or SPAM fidelity results.

Two U.S. groups have published results for SSQ quantum dot systems that also have high-fidelity single-qubit gates. Row 7 reports that the group at HRL Laboratories demonstrated slightly higher-performance single-qubit gates with a fidelity of 99.3 percent.⁴⁶ This group fabricated a six-quantum-dot ²⁸Si/SiGe quantum processor; in the results published so far, however, only two electrons were loaded into the quantum processor. The other four quantum dots remained empty, which is why, in the table, this result is listed for two of six qubits.

The other U.S. group, from Princeton, NIST, and Sandia National Laboratory, has also developed a six-quantum-dot ²⁸Si/SiGe quantum processor (see row 8).⁴⁷ The performance of the group's quantum processor was also evaluated, with only two of the six quantum dots filled with electron spin qubits. This quantum processor has a slightly lower single-qubit gate fidelity than the other U.S. group but has the second-highest two-qubit gate fidelity of all the systems listed in Table 3.21—a significant technical achievement.

In row 9, the next entry in the table is for another group in Australia led by Michelle Simmons at UNSW in Australia.⁴⁸ This group has fabricated donor-based quantum dot system with two and three phosphorus atoms in two quantum dots. Notably, this quantum processor has demonstrated the fastest single-qubit gate speed of any SSQ system yet—0.8 ns. Theoretical modeling from the group suggests that this architecture could sustain a qubit coherence time 1 million times longer than the gate operation time.⁴⁹

Row 10 in Table 3.21 is for a joint research group from the Netherlands and the United States.⁵⁰ The quantum processors developed by this group are based on designs from TU Delft and QuTech, which have been modified to enable their mass production using extreme ultraviolet (EUV) lithography and other advanced semiconductor manufacturing tools.⁵¹ The devices developed by this group were fabricated using state-of-the-art commercial semiconductor fabrication equipment at an Intel foundry in the United States. The manufacturing process uses 300-mm wafers made of natural silicon with a layer of silicon-28 deposited on the wafer in selected areas by means of molecular beam deposition. The quantum dot structures are built in this isotopically pure layer. The research group loaded two qubits into a seven-quantum-dot array for detailed testing and measured an average fidelity for single-qubit gates of 99.05 percent. The largest quantum dot

⁴³ Xue et al., 2022.

⁴⁴ Noiri et al., 2022.

⁴⁵ Takeda et al., 2022.

⁴⁶ Weinstein et al., 2023.

⁴⁷ Mills et al., 2022.

⁴⁸ He et al., 2019. Simmons is also the CEO of Silicon Quantum Computing in Australia.

⁴⁹ Abhikbrata Sarkar et al., Joel Hochstetter, Allen Kha, Xuedong Hu, Michelle Y. Simmons, Rajib Rahman, and Dimitrie Culcer, "Optimisation of Electron Spin Qubits in Electrically Driven Multi-Donor Quantum Dots," *NPJ Quantum Information*, Vol. 8, No. 127, November 2022.

⁵⁰ Zwerver et al., 2022.

⁵¹ Most SSQ quantum processors developed to date have been made using electron beam tools or STMs. These tools create circuit features in a linear fashion. EUV lithography enables large complex arrays of two-dimensional circuit features to be created simultaneously, greatly speeding up the production process.

arrays fabricated in this production run had a total of 16 quantum dots—12 for qubits and four for charge sensors—which may be the largest quantum-dot arrays in the world, although these quantum processors have yet to undergo testing.

Row 11 in Table 3.21 reports the best results that we found from a Chinese research group.⁵² The only performance parameter for this system yet reported is a relatively short qubit coherence time, suggesting significantly lower performance than any of the other entries in the table.

In summary, research groups from many countries have recently reported significant developments in SSQ quantum processors. Several groups are working on developing systems with more qubits, with systems with six to 12 qubits now under development. In addition, many groups have demonstrated systems with high single- and two-qubit gate fidelity and fast gate speeds. Australia and the Netherlands are arguably the countries leading in SSQ quantum processor developments, with Japan and the United States very close behind.⁵³ Intel (in collaboration with academic researchers from the Netherlands) is the only company that has yet demonstrated the mass production of SSQ quantum dot devices using EUV lithography and other advanced semiconductor manufacturing techniques.

Quantum Communications

We found several notable recent technology demonstrations for quantum communications, particularly in the UK and Germany.

Notable demonstrations by UK groups include the following:

- a standalone chip-scale QKD system in an integrated processor⁵⁴
- twin-field QKD over a very long transmission distance of 605 km (with a U.S. coauthor)⁵⁵
- entanglement-based device-independent QKD (with Swiss and French coauthors)⁵⁶
- a high-speed ion-memory transfer link between two trapped-ion quantum computers.⁵⁷

Notable demonstrations by German groups include the following:

- quantum teleportation of logical qubits (with Austrian and Swiss coauthors)⁵⁸
- another demonstration of device-independent QKD (with Singaporean coauthors)⁵⁹

⁵² Hu et al., 2022.

⁵³ However, one could also make a case that the United States is ahead of the Netherlands because the United States has achieved a higher two-gate fidelity. It is somewhat meaningless to try to characterize the performance of a quantum computer with only two qubits, so there is inherently some subjectivity here.

⁵⁴ Taofiq K. Paraíso, Thomas Roger, Davide G. Marangon, Innocenzo De Marco, Mirko Sanzaro, Robert I. Woodward, James F. Dynes, Zhiliang Yuan, and Andrew J. Shields, “A Photonic Integrated Quantum Secure Communication System,” *Nature Photonics*, Vol. 15, October 2021.

⁵⁵ Mirko Pittaluga, Mariella Minder, Marco Lucamarini, Mirko Sanzaro, Robert I. Woodward, Ming-Jun Li, Zhiliang Yuan, and Andrew J. Shields, “600-km Repeater-Like Quantum Communications with Dual-Band Stabilization,” *Nature Photonics*, Vol. 15, June 2021.

⁵⁶ D. P. Nadlinger, P. Drmota, B. C. Nichol, G. Araneda, D. Main, R. Srinivas, D. M. Lucas, C. J. Ballance, K. Ivanov, E. Y.-Z. Tan, et al., “Experimental Quantum Key Distribution Certified by Bell’s Theorem,” *Nature*, Vol. 607, July 2022.

⁵⁷ Akhtar et al., 2023.

⁵⁸ Alexander Erhard, Hendrik Poulsen Nautrup, Michael Meth, Lukas Postler, Roman Stricker, Martin Stadler, Vlad Negnevitsky, Martin Ringbauer, Philipp Schindler, Hans J. Briegel, et al., “Entangling Logical Qubits with Lattice Surgery,” *Nature*, Vol. 589, January 2021.

⁵⁹ Wei Zhang, Tim van Leent, Kai Redeker, Robert Garthoff, René Schwonnek, Florian Fertig, Sebastian Eppelt, Wenjamin Rosenfeld, Valerio Scarani, Charles C.-W. Lim, and Harald Weinfurter, “A Device-Independent Quantum Key Distribution System for Distant Users,” *Nature*, Vol. 607, July 2022.

- entanglement of single atoms over 33 km of fiber⁶⁰
- fast generation of up to 14 entangled photons⁶¹
- two-second quantum memory with integrated error detection (with U.S. and Dutch coauthors)⁶²
- quantum interference of photons emitted by quantum dots separated by 300 km of fiber (with Chinese coauthors).⁶³

We did not find any comparably advanced demonstrations of quantum communication technology from research institutions within Australia or Japan, but two of the demonstrations listed earlier from UK institutions were performed within the Japanese corporation Toshiba's UK laboratory.

Quantum Sensing

Our (noncomprehensive) review of the academic literature returned fewer recent examples of applied quantum sensing technology demonstrations at the global technology forefront from the four deep-dive countries.⁶⁴ We did identify two examples of notable demonstrations:

- A group of UK researchers fielded a gravity-gradient sensor capable of detecting a 2-m-wide underground tunnel.⁶⁵
- A group of UK, Swiss, and German researchers demonstrated a new class of optical atomic clock based on highly charged ions.⁶⁶

⁶⁰ Tim van Leent, Matthias Bock, Florian Fertig, Robert Garthoff, Sebastian Eppelt, Yiru Zhou, Pooja Malik, Matthias Seubert, Tobias Bauer, Wenjamin Rosenfeld, et al., "Entangling Single Atoms Over 33 km Telecom Fibre," *Nature*, Vol. 607, July 2022.

⁶¹ Phillip Thomas, Leonardo Ruscio, Olivier Morin, and Gerhard Rempe, "Efficient Generation of Entangled Multiphoton Graph States from a Single Atom," *Nature*, Vol. 608, August 2022.

⁶² P.-J. Stas, Y. Q. Huan, B. Machielse, E. N. Knall, A. Suleymanzade, B. Pingault, M. Sutula, S. W. Ding, C. M. Knaut, D. R. Assumpcao, et al., "Robust Multi-Qubit Quantum Network Node with Integrated Error Detection," *Science*, Vol. 378, No. 6619, November 2022.

⁶³ Xiang You, Mingyang Zheng, Si Chen, Run-Ze Liu, Jian Qin, Mo-Chi Xu, Zheng-Xuan Ge, Tung-Hsun Chung, Yu-Kun Qiao, Yang-Fan Jiang, et al., "Quantum Interference with Independent Single-Photon Sources Over 300 km Fiber," *Advanced Photonics*, Vol. 4, No. 6, November/December 2022.

⁶⁴ As discussed in a previous RAND report (Parker et al., 2022), quantum sensing is the most challenging application domain to assess through the open scientific literature. Quantum sensing is generally a more mature technology than the other quantum applications domains, and many of the biggest challenges have to do with practical fielding rather than basic science. So, some of the leading capabilities may be business proprietary. Moreover, there is no agreed-on set of metrics for quantifying the performance of quantum sensors.

⁶⁵ Ben Stray, Andrew Lamb, Aisha Kaushik, Jamie Vovrosh, Anthony Rodgers, Jonathan Winch, Farzad Hayati, Daniel Boddice, Artur Stabrawa, Alexander Niggebaum, et al., "Quantum Sensing for Gravity Cartography," *Nature*, Vol. 602, February 2022.

⁶⁶ Steven A. King, Lukas J. Spieß, Peter Micke, Alexander Wilzewski, Tobias Leopold, Erik Benkler, Richard Lange, Nils Huntemann, Andrey Surzhykov, Vladimir A. Yerokhin, José R. Crespo López-Urrutia, and Piet O. Schmidt, "An Optical Atomic Clock Based on a Highly Charged Ion," *Nature*, Vol. 611, November 2022.

Summaries of National Quantum Industrial Bases

In this chapter, we briefly summarize our findings for the quantum industrial bases of the four allied countries for which we performed deep dives: Australia, the UK, Germany, and Japan. In these summaries, we sought to highlight the important characteristic of each country's quantum industrial base, as well as notable areas in which there are differences from other allied countries or the United States that might provide insights for future planning. Chapter 3 provided a more detailed account, including types and amounts of funding, publications, patents, and technical achievement.

Australian Quantum Industrial Base

The Australian quantum industrial base benefits from support from the Government of Australia and from the governments of New South Wales and Victoria. Australian government funding is focused on two major university-based CoEs: EQUUS at the University of Sydney and CQC2T at the UNSW. Each of these centers has associated start-up companies: MOG Laboratories (electronics and laser developer) with EQUUS and Silicon Quantum Computing and its spin-off Diraq (SSQ-based quantum computer developers) with CQC2T. These centers provide support for a broad range of research efforts at ten different Australian universities, two of which are present in both centers. Through these CoEs, the Australian quantum industrial base is connected to a large group of international universities and multinational companies, including IBM, Microsoft, and Lockheed Martin. Due to its smaller population, Australia produces fewer total scientific publications and patents in quantum technology than the UK, Germany, or Japan.

Australian academics working in quantum R&D also have connections with U.S. companies Google, Northrop Grumman, HRL Labs, and Infleqtion. Notably, Google, Microsoft, and Infleqtion each have quantum technology research centers physically located in Australia. International funding of and research collaborations with Australian universities include agencies and institutions in the United States, allied countries, and China.

The corporate component of the Australian quantum industrial base consists of a small number of start-ups. (We identified nine start-ups with venture capital support but no large, established companies.) Moreover, a handful of companies are responsible for the large majority of both domestic and international funding. However, Australia had the highest quantum technology VC funding as a percentage of GDP of any of our four deep-dive countries. Moreover, Australia is home to two companies that are among the world leaders in SSQ quantum computing, and its quantum industrial base includes companies active in quantum communications and sensing, as well as quantum supply chain providers. Most notable in the last category is Silex Systems, user of state-of-the-art laser techniques to provide the enriched silicon-28 that is required for SSQ-based quantum computing. Australia was the only deep-dive nation from which we identified a company dedicated solely to quantum sensing. It also hosts a software company, Q-CTRL, that provides unique capabilities in quantum device control. Like the UK (but unlike Germany or Japan), Australian quantum technology companies receive significant venture capital investment from U.S. investors.

United Kingdom Quantum Industrial Base

The quantum industrial base of the UK is much larger than that of Australia and most similar to that of the United States among the allied countries we investigated, with many start-ups and a diverse network of domestic and international funders and collaborators. The UK government funds quantum R&D through its NQTP, which supports four regional hubs: Quantum Technology Sensors and Training, led by the University of Birmingham; Quantum Enhanced Imaging, led by the University of Glasgow; Quantum Computing and Simulation, led by the University of Oxford; and Quantum Communications, led by the University of York. NQTP also sponsors special quantum projects and a quantum challenge fund for cooperative investment with private industry in quantum technology commercialization and industrialization.

UK universities and companies working in quantum technologies have strong interactions with the United States and other allied countries, with most publishing collaborations with Japan and the largest number of quantum communications publications among the allied countries we investigated. Two U.S. quantum companies, Quantinuum and Rigetti, operate primary research facilities in the UK (and Quantinuum is dual-headquartered there). While most international funding is from the U.S. and allied countries, UK academia receives significant funding from the National Natural Science Foundation of China.

Most quantum technology companies in the UK are start-ups, but there is also significant research activity from the research laboratories of large foreign companies, such as Japan's Toshiba.

German Quantum Industrial Base

The German quantum industrial base is supported by the German government and state governments in North Rhine Westphalia and Bavaria. Its Quantum Alliance funds six CoEs: Matter and Light for Quantum Computing, led by University of Köln; Quantum Science and Technology, led by University of Munich and Technical University of Munich; Quantum Frontiers, led by University of Bremen; Complexity and Topology in Quantum Matter, led by University of Würzburg and Technical University of Dresden; Advanced Imaging of Matter, led by University of Hamburg; and Integrated Quantum Science and Technology, led by University of Stuttgart and Ulm University.

Unlike Australia and the UK, large corporations dominate the German quantum industrial base, which features two separate industry consortia, QUTAC and QSolid, the latter of which has the objective of developing an indigenous quantum computer to be integrated with existing supercomputing infrastructure, together with an indigenous quantum computer supply chain. The start-up sector is less well developed than in Australia and the UK. However, there is a consortium of start-ups and academics, PhoQuant, whose objective is to build an indigenous photonic quantum computer. The relatively few non-German investors in German quantum technology companies are all from other parts of the European Union.

An important feature of the German quantum industrial base is the close coupling of academia, industry, and research institutes, aimed at facilitating rapid technology transfer. This is illustrated by regional hubs, such as the Munich Quantum Valley, and institutions, such as Fraunhofer Gesellschaft and Forschungszentrum Jülich.

Japanese Quantum Industrial Base

The Japanese quantum industrial base is largely supported by the Japanese government and large Japanese companies, with its quantum start-up sector much less well developed than in the other allied countries we investigated. Japan's academic community is very well supported through two quasi-governmental organiza-

tions, RIKEN and the Japan Society for the Promotion of Science, as well as the Japan Science and Technology Agency.

RIKEN appears to play the combined role of a national funding source for academic research, similar to the U.S. National Science Foundation, and a research agency with research laboratories similar to those of such U.S. agencies as the Departments of Energy and Defense but without specific mission responsibilities. Among its ten campuses throughout Japan is the RIKEN Center for Quantum Computing at its Wako Branch and Headquarters campus. (RIKEN also maintains research facilities at Brookhaven National Laboratory in the United States and Harwell Science and Innovation Campus in the UK.)

Japan's quantum industrial base is strongly domestically focused. The few international academic collaborations are with the University of Michigan, the Chinese Academy of Sciences, and the National University of Singapore. Notably, we did not identify any foreign investors in Japanese quantum technology start-ups. But unlike the other three deep-dive countries, Japan's commercial quantum technology R&D is heavily dominated by large, established, and diversified corporations, such as Toshiba, Fujitsu, and NTT, rather than by start-ups.

Japan has filed the most quantum patent applications by far among the allied countries that we investigated, and the top filers are all Japanese companies. The Q-STAR consortium of 24 companies, including some of Japan's largest corporations, was founded in 2021. Its objectives include collaboration with industry, academia, and government in promoting initiatives that apply new (quantum) technologies and establishing related technology platforms. Also in 2021, IBM installed one of its System One quantum computers at the University of Tokyo. In March 2023, RIKEN announced the availability to outside users of its first indigenous quantum computer, developed in collaboration with Fujitsu.¹

¹ Nippon Communications Foundation, 2023.

Findings and Recommendations

Findings

Both universities and private companies are already engaging in extensive international collaboration in quantum technology R&D among the United States and allied nations. There is a strong network of academic copublishing among allied nations, and several leading U.S. quantum technology companies have established locations in the UK and Australia. There is even one leading quantum company (Quantinuum) headquartered in both the United States and the UK. But there are very few formal policy agreements or jointly funded R&D programs between governments, beyond bilateral joint statements of cooperation.¹ Most international collaboration in quantum R&D will likely continue to happen organically and outside policy-makers' direct control.

Other than the United States and China, Germany and the UK are the two nations with the highest output of scientific research in each of the three quantum information science application domains. Japan is either third or fourth in each application domain. The United States and China have by far the highest outputs in both publications and patenting in all three domains. Most other nations have a fairly similar distribution of scientific research activity across technical subtopics, with some relatively minor differences. (For example, South Korea is the only nation we examined in detail that published more papers on quantum communications or sensing (combined) than on quantum computing.) The relative proportions of allied nations' research output do not change much if we only consider highly cited publications.

Germany and the UK are the U.S.-allied nations with the highest government investment in quantum technology R&D. Japan and the Netherlands invest a roughly similar amount, which is significantly less than what the UK and Germany invest. But the Netherlands invests the most government funding in quantum technology R&D as a percentage of GDP.

Japan has the highest level of patenting in each of the three application domains. The UK is second in each.

The cutting edge of quantum technology is rapidly shifting from open research institutions to private industry, and it is becoming more difficult to determine the technical state of the art from nonproprietary sources. For example, the UK company ORCA Computing and the Japanese RIKEN research institute (in collaboration with Fujitsu and other Japanese companies) both claim to have built cutting-edge quantum computers. However, as of April 2023, neither has released detailed technical specifications, such as gate fidelities.

Many nations have announced ambitious plans to domestically develop their own quantum computers over the next few years. But as of April 2023, Austria is the only nation (other than the United States and China) to have developed a universal quantum computer prototype with more than six qubits and

¹ Parker, 2023.

precisely documented technical specifications.² But given the previous finding, other nations may have produced similarly powerful prototypes whose performance they have not publicly documented in detail.

The quantum industrial bases of Australia, the UK, Germany, and Japan each have distinct organizational structures and foci. For example, the Australian and UK commercial quantum technology industries consist mostly of start-ups, many of which receive capital funding from U.S.-based companies. Several large U.S. quantum technology companies have research centers in Australia and the UK. The German commercial quantum industry consists of both start-ups and large corporations and receives most of its funding from domestic funders (with some from the rest of Europe). Japan's quantum technology industry has very little start-up activity, receives no foreign capital that we could find, and performs most of its R&D in large established corporations.

Moreover, the national governments have different patterns of collaboration with industry and academia. The Australian government's R&D investment is channeled through two major centers based in universities; the UK's is through four hubs that include industry partners; Germany's includes two research institutes that work closely with German industry; and Japan's includes a unified national laboratory system that is closely coupled to both Japanese academia and industry and includes laboratories in the United States and UK.³ Like the United States, most of these nations' quantum technology start-ups are focused on quantum computing, including all of their highest-funded start-ups.

In particular, the German and Japanese commercial quantum industries have a relatively high proportion of large established companies, and German and Japanese companies are closely linked to government-funded R&D programs. On the other hand, the Australian and UK quantum industries are more reliant on start-up companies, and these countries' industries are less directly tied to government funding. The Australian and UK industries are therefore more reliant on venture capital, which might make them more vulnerable during an economic downturn.

Each of these four countries engages in significant scientific collaboration with and receives significant research funding from both U.S. and Chinese organizations. We identified several different types of potential or actual connections between strategic competitor nations and researchers or firms in U.S.-allied nations:

- *Academic collaboration between U.S.-allied and competitor nations' research institutions*—We did not find any major research collaboration between Russia and U.S.-allied nations, but we did find that China is a major scientific collaborator with Australia in all three application domains, with Japan in quantum computing and sensing, and with the UK and Germany in quantum sensing.
- *Competitor-nation funding of academic research in allied nations*—We found that the National Natural Science Foundation of China was one of the top six funders of academic research produced in all four deep-dive countries (as measured by the number of funded publications).
- *Competitor-nation funding of commercial firms in allied nations*—We found one instance of a foreign financial investment of potential concern: Sequoia Capital China is a financial investor in the Australian company Q-CTRL. While Sequoia Capital is headquartered in the United States, its China branch

² Six qubits is nowhere near enough to perform useful calculations. The minimum threshold for surpassing conventional supercomputers is about 50 qubits, although many more might be required for useful calculations. The Austrian computer (built by AQT) has 20 qubits. The Canadian company Xanadu, in collaboration with U.S. researchers, has produced a prototype quantum computer called Borealis capable of extremely powerful computation. However, this quantum computer performed boson sampling and is not capable of universal quantum computing, which is required for most or all practically useful algorithms. See Lars S. Madsen, Fabian Laudenbach, Mohsen Falamarzi Askarani, Fabien Rortais, Trevor Vincent, Jacob F. F. Bulmer, Filippo M. Miatto, Leonhard Neuhaus, Lukas G. Helt, Matthew J. Collins, et al., "Quantum Computational Advantage with a Programmable Photonic Processor," *Nature*, Vol. 606, June 2022.

³ See Chapter 4 for a more detailed discussion.

enjoys significant autonomy and has been described as having an “increasingly complex” relationship with its parent company. In 2022, the parent company instituted a process to screen for national security concerns in its China branch’s investments in defense-related companies.⁴

We identified one technical area—SSQ quantum computing—in which other nations are arguably ahead of both the United States and China. Australia and the Netherlands are arguably the technical leaders in this area, with the United States and Japan close behind (and China significantly further behind). So far, this approach to quantum computing has proven significantly less scalable than other qubit architectures. But it has significantly more overlap with standard semiconductor fabrication processes than do other qubit approaches. If the extensive physical capital and expertise in these processes could be adapted for qubit fabrication, this technical approach might become highly scalable. We identified several notable technical demonstrations by U.S.-allied nations in quantum communications (and to a lesser extent, quantum sensing) but none that were clearly the most advanced in the world.

U.S.-allied nations provide various key components in the quantum technology supply chain. Our previous report documented that U.S. quantum technology companies purchased components from allied nations in Finland, France, Germany, Italy, Japan, the Netherlands, Sweden, and the UK.⁵ Although we did not conduct an extensive supply chain analysis for this project, we did identify enriched silicon-28 as an important new critical material for many designs of SSQs. We were not able to determine the main manufacturers of enriched silicon-28, but the open literature indicates that the Leibniz Institute for Crystal Growth in Berlin and Keio University in Japan (among others) have historically been key centers of material synthesis for enriched silicon.⁶ We did identify the Australian company Silex Systems (which is using an advanced form of laser enrichment) as one current supplier of enriched silicon-28.

Recommendations for Policymakers

Focus quantum technology R&D collaboration with U.S.-allied nations on areas where their technical strengths are complementary with those of the United States. Several questions influence the importance of international R&D collaboration in a given quantum subtechnology:

1. Is the technology likely to eventually deliver high value?
2. Do U.S. allies have unique technical strengths in this technology?
3. Do U.S. competitor nations have unique technical strengths in this technology?
4. Does the collaboration risk putting a strong U.S. commercial industry at a competitive disadvantage?

All else equal, a “yes” answer to the first three questions strengthens the case for international R&D collaboration, while a “yes” answer to the fourth question weakens it.

There are several technical subareas, such as superconducting, trapped-ion, and neutral-atom qubits, in which the United States is the global technical leader and has multiple companies at or near the technical forefront. These areas should not be priorities for R&D collaboration with allies because the United States already has access to a (relatively) strong domestic production capacity.

⁴ Viswanatha, Yang, and Jin, 2023.

⁵ Parker et al., 2022.

⁶ Kohei M. Itoh and Hideyuki Watanabe, “Isotope Engineering of Silicon and Diamond for Quantum Computing and Sensing Applications,” *MRS Communications*, Vol. 4, No. 4, December 2014.

Given the wide range of uncertainty in eventual applications, the United States should maintain some level of access to as broad a range of technologies as possible in case of technological surprise.⁷ Collaboration with allies can be a useful way to diversify the portfolio of technologies in which U.S.-allied nations have strong expertise. This collaboration can, in the words of the 2022 U.S. National Security Strategy, help the United States “pool technical expertise and complementary industrial capacity with our allies and partners.”⁸

We identified two technical categories in which certain U.S.-allied nations are even with or ahead of the United States: silicon-spin quantum computer processors and certain applications of quantum communications (particularly involving QKD). These two technologies have different trade-offs regarding collaboration. Allied nations have strong technical expertise in SSQs, and few U.S. companies are working in this area.⁹ These two facts make SSQs a promising area for collaboration, even though they are not yet technically competitive with other qubit approaches. Quantum communications technology has fewer immediately clear applications, but China is very strong in it, and U.S.-allied nations have certain technical strengths in this area that the United States does not. These facts may indicate that quantum communications could be another promising focus area for international collaboration—but on the other hand, there are already several U.S. quantum communications companies that could be affected by international collaboration, which introduces complex trade-offs for policymakers to consider.

U.S. policymakers could choose to prioritize either risks (by focusing on closing the gap in technical areas where China is stronger than the United States and its allies) or opportunities (by focusing on increasing the lead in technical areas where U.S. allies are already ahead). The former priority might indicate prioritizing international collaboration in long-distance quantum communications technology, while the latter might indicate prioritizing collaboration in SSQ technology.¹⁰ Photonic boson-sampling quantum computing is an interesting case that crosses both strategies, and Canada and China are both very strong in this area (although again, the eventual utility is unclear).

Leverage the complementary organizational aspects of the quantum industrial bases of the United States and its allies. As discussed earlier, under “Findings,” the quantum industrial bases of the leading U.S. allies are organized differently from each other and from that of the United States along such dimensions as the level of direct government-industry partnership, the balance between large and small corporations, the ratio of established firms to start-ups, the mix of funding sources, the balance of focus between components and integrated systems, and the areas of topical focus. These different approaches could provide opportunities for synergies that strengthen both the U.S. and allied quantum industrial bases. A detailed prescription would require further research, but one example might be having U.S. organizations focus on assembling final systems while ensuring that trusted allies maintain a reliable supply of certain key components and materials.

Moreover, U.S. policymakers should study allied nations’ models for lessons that might apply within the United States. In particular, the U.S. Chips and Science Act of 2022 established the Directorate for Technology, Innovation, and Partnerships within the National Science Foundation; the directorate focuses on help-

⁷ Parker, 2023.

⁸ White House, *National Security Strategy*, October 2022.

⁹ Intel has published work on silicon-spin quantum dots, but in collaboration with Dutch universities and companies, and it is not clear whether the company holds exclusive intellectual property whose value could be threatened by technical progress in allied nations.

¹⁰ Patenting data indicate that Japan is also strongly focused on quantum annealing applications, although the situation here for U.S. policymakers is complicated by the fact that the major quantum annealing company, D-Wave, has a subsidiary in the United States.

ing to commercialize technology that is closer to application than the rest of the foundation’s research.¹¹ U.S. policymakers should study such organizations as Germany’s regional innovation hubs and Fraunhofer-Gesellschaft, and Forschungszentrum Jülich research centers and Japan’s RIKEN laboratories for models and best practices that might be useful for commercializing advanced technologies, such as quantum.

Identify and monitor critical component and material suppliers based in U.S.-allied nations. Because of the many different fundamental quantum technology approaches being developed in parallel, the quantum technology supply chain is complicated and poorly understood. Previous RAND research found critical U.S. supply chain dependencies on several allied nations (primarily in Europe and Japan) for advanced components.¹² This project did a deeper dive into the ecosystem for SSQs and uncovered an additional material (enriched silicon-28) that could prove critical for developing that particular technical approach. The main sources for enriched silicon-28 are not clear from public sources, but Germany, Japan, and Australia all have strong expertise in synthesizing these materials.

Allied nations’ governments and firms will probably have a better understanding of critical component and material manufacturers than U.S. policymakers. A fruitful area of international policy cooperation would be to characterize the global quantum technology supply chain—and then potentially set policies to strengthen it.

Identify and monitor potential sources of technology leakage in allied nations’ funding and collaboration networks. Our research has demonstrated that there are several potential avenues for intellectual property leakage (listed in the key findings) that can be monitored using open sources, and some of these show existing connections between U.S.-allied nations and the People’s Republic of China. These connections are not inherently a cause for alarm, particularly regarding scientific collaboration. But policymakers (in both the United States and allied nations) should monitor these open-source information channels for signs of potential intellectual property loss from allied nations to competitor nations. The appropriate policy response (if any) will depend on both the likelihood that proprietary intellectual property is leaving the United States and the consequence of that loss.

Organize a recurring multilateral meeting of quantum technology experts from the U.S. and leading allied nations’ governments to facilitate information-sharing and planning. Most official U.S. diplomacy with allied nations regarding quantum technology has taken place through bilateral joint statements issued by the U.S. Department of State.¹³ By contrast, in December 2022, the Netherlands, France, and Germany signed a trilateral joint statement on cooperation in quantum technology.¹⁴ U.S. policymakers should also explore multinational models of agreement; as far as we know, the U.S. government is not a party to any official multilateral agreements or programs that are specific to quantum technology.

More concretely, we recommend that the U.S. government organize a regularly recurring meeting (perhaps annual or every two years) with representatives from allied governments that is specifically dedicated to sharing information on quantum technology development. Specific areas of focus might include the following:

- technical progress within each nation
- the status of the domestic commercial industry (including its financial health, which could be a concern in a new era of high interest rates)¹⁵

¹¹ White House, “CHIPS and Science Act Will Lower Costs, Create Jobs, Strengthen Supply Chains, and Counter China,” fact sheet, August 9, 2022.

¹² Parker et al., 2022.

¹³ Parker, 2023.

¹⁴ Quantum Delta NL, “The Netherlands, France and Germany Intend to Join Forces to Put Europe Ahead in the Quantum Tech Race,” webpage, December 18, 2022.

¹⁵ Parker, 2023.

- policy concerns, e.g., around such issues as intellectual property loss or potentially coordinating multilateral export controls¹⁶
- technical developments in competitor nations that could indicate threats to U.S. and allied-nation technical leadership.

While carefully selected industry representatives could possibly be invited to attend certain sessions, this meeting should probably not be public; this would allow government representatives to speak frankly about potential weaknesses or challenges they are facing in quantum technology. Given the complex and rapidly changing nature of the quantum technology ecosystem; ongoing technical, economic, financial, and policy developments; and the lack of existing multilateral fora for discussing these developments, such a meeting would improve cooperation and shared situational awareness among U.S. and allied stakeholders.¹⁷

¹⁶ Parker, 2023.

¹⁷ On May 5–6, 2022, the White House Office of Science and Technology Policy and U.S. Department of State hosted an international roundtable with representatives of 12 nations that might serve as a possible precedent for such a recurring meeting. See National Quantum Coordinating Office, “Readout: International Roundtable on Pursuing Quantum Information Together: 2^N vs 2N,” press release, May 9, 2022.

Abbreviations

ARC	Australian Research Council
AUKUS	Australia, the United Kingdom, and the United States
AUS	Australian currency
AQT	Alpine Quantum Technologies
BMBF	Federal Ministry of Education and Research (Germany)
CoE	center of excellence
COVID-19	coronavirus disease 2019
CQC2T	Centre for Quantum Computation and Communications Technology (Australia)
EQUUS	Centre for Engineered Quantum Systems (Australia)
EUV	extreme ultraviolet
GDP	gross domestic product
NQTP	National Quantum Technologies Programme (UK)
NTT	Nippon Telegraph and Telephone Corporation
QAOA	quantum approximate optimization algorithm
QKD	quantum key distribution
Q-STAR	Quantum Strategic Industry Alliance for Revolution
QTFP	Quantum Technologies for Fundamental Physics
QUTAC	Quantum technology and Application Consortium
R&D	research and development
SQA	Sydney Quantum Academy
SSQ	silicon spin qubit
TU Delft	Delft University of Technology
UK	United Kingdom
UKRI	United Kingdom Research and Innovation
UNSW	University of New South Wales

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The U.S. government has identified quantum technology as important for future U.S. economic prosperity and national security because it could eventually offer groundbreaking new capabilities in information collection, processing, and communication. RAND researchers had previously developed a set of metrics for holistically assessing a nation's industrial base in quantum technology and had applied those metrics to the industrial bases of the United States and China. For this report, the authors used a similar methodology to assess the quantum industrial bases of several other nations. The report begins with a broad look at the entire global quantum ecosystem, and then focuses in more detail on Australia, Germany, Japan, and the United Kingdom (UK). The authors considered four categories of metrics: scientific research, government support, industry activity, and technical achievement. Whenever possible, they assessed the metrics separately across the three technology application domains of quantum computing, quantum communications, and quantum sensing. The report concludes with recommendations for how policymakers could strengthen international collaboration in quantum technology research and development (R&D) between the United States and its allied nations.

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