Quantum Computing: A Sectoral Composition Approach

Technology Series

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1. Introduction: The Rise of Quantum Computers

Quantum computing efforts have made significant strides in recent years, earning quantum technologies a position among many “disruptive” or “emerging” technologies lists.[1] In late 2019, Google self-designated its accomplishment of operating a 53-qubit processor as the achievement of a long-time benchmark of “quantum supremacy,” (where quantum supremacy refers to a quantum computer’s ability to outperform a traditional computer).[2] Meanwhile, competitors in the quantum industry have also improved their quantum computing capabilities. For example, IBM celebrated 2019 as the fourth year in a row that it was able to exceed doubling the qubit, or the smallest computational unit of a quantum computer, capacity of its quantum systems.[3] Computing-adjacent quantum technologies, such as quantum communication, which rely on similar techniques and scientific knowledge, have also seen dramatic improvements. In early 2020, China announced the successful transmission of a message through a quantum satellite at a record-breaking 1,120 kilometers land distance.[4] This introduces the ability to ensure hyper-encrypt communication between reasonably distanced cities. Each of these benchmarks individually marks concrete steps towards operable quantum technologies that offer dramatically increased computing power and security benefits. Together, they signal a resounding interest and commitment to achieving usable quantum-based systems.

2. Security Implications

Given the immense promise of quantum technologies and the surge of interest and investment, scholars and practitioners have been quick to identify potential security implications. Primarily, implications have been categorized based on the major branches of foreseeable quantum technologies: communication and information processing. Although the two technology branches are based on different physical phenomena, they are often conflated due to the crossover of certain techniques and basic research. While technical knowledge in

1 See, for example: “Emerging Technology and National Security,” Department of Homeland Security, 2018 Analytic Exchange Program, 2018,https://www.dhs.gov/sites/default/files/publications/2018_AEP_Emerging_Technology_and_National_Security.pdf; “Long-Range Emerging Threats Facing the United States as Identified by Federal Agencies,” United States Government Accountability Office - Report to Congressional Committees, December 2018, <https://www.gao.gov/assets/700/695981.pdf>; “Emerging Military Technologies: Background and Issues for Congress,” Congressional Research Service, August 4, 2020, <https://crsreports.congress.gov/product/pdf/R/R46458>.

2 Frank Arute, et. al, “Quantum Supremacy Using a Programmable Superconducting Processor,” *Nature*, October 23, 2019, <https://www.nature.com/articles/s41586-019-1666-5>.

3 Smith-Goodson, Paul, “IBM Doubles It’s Quantum Computing Power Again,” *Forbes*, January 8, 2020 <https://www.forbes.com/sites/moorinsights/2020/01/08/ibm-doubles-its-quantum-computing-power-again/#70e2aba961ab>.

4 Juan Yin, et. al, “Entanglement-Based Secure Quantum Cryptography Over 1,120,” *Nature*, June 15, 2020, <https://www-nature-com.proxy-um.researchport.umd.edu/articles/s41586-020-2401-y>.

one area may make one country or organization more prepared to pursue another technology area, when considering specific security threats, the two technology categories should be considered separately.

Quantum communication promises improved security of communication between two separate actors through entanglement of photons or atoms. Primarily, this could benefit actors attempting to secure their communications through advanced encryption and interference detection capabilities. However, a secondary effect is the impact that the application of quantum communication may have on actors who rely heavily on intelligence infiltration of other actors' systems.[5] With respect to these potential security implications, important metrics for the continued development of quantum communication capabilities worth monitoring include achievable distance of communication, method of security improvement, method of entanglement, and scalability.

Quantum information processing encompasses a much broader category of technologies, and thus is associated with a wider set of security concerns; this is typically the implied category when discussed by scholars and practitioners. These concerns are generally less concrete but revolve around the increased computing capability of quantum systems. Identified concerns include increased decryption capability, improved AI power, and more robust data processing/detection capabilities.[6]

Additional concerns that extend beyond strictly dual-use applications have been raised about the importance of American technological advantage, and the potential security impact should America lose technological advantage. These arguments claim that technological advantages could impact military or economic drivers of a state's national power.[7] Thus, under this reasoning, a loss of American technological superiority could result in loss of economic standing (and the associated national power), and/or military technology competency.

Additionally, technology leadership allows a country to maintain robust security and safety measures in non-military areas such as public utilities and critical infrastructure.[8] Furthermore,

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5 Martin Giles, "Explainer: Quantum Communication," MIT Technology Review, February 14, 2019, <https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/>.

6 Biercuk, Michael, and Richard Fontaine, "The Leap into Quantum Technology: A Primer for National Security Professionals," *War on the Rocks*, November 17, 2017, <https://warontherocks.com/2017/11/leap-quantum-technology-primer-national-security-professionals/>.

7 Elsa Kania and John Costello, "Quantum Hegemony? China's Ambitions and the Challenge to U.S. Innovation Leadership," Center for New American Security, 2018.

8 "American Leadership in Quantum Technology," Joint Hearing before the Subcommittee on Research and Technology and

technology leadership in a field like quantum computing, that may yield advances in other industries such as medicine, manufacturing, and AI, creates precedent for national leadership in other critical areas.[9] Although this motive for controls has received criticism, as a potential "weaponization" of trade,[10] it is worth noting that this may be a secondary driver of controls. Depending on the specific motive, different types of controls will be applied.

Potential Use of Trade Controls as a Remediation

Given the security concerns regarding quantum computer applications, as well as the highly esoteric and technical nature of quantum computing research, export controls may play a role in guiding early development of quantum computer research and innovation. Compared to some of the other technologies listed in the ANPRM, quantum computer research is at a relatively nascent stage of development. This means that export controls may be effective in limiting final users of the technology through directing the types of research that receive investment in the private sector. Combined, these two factors (the security relevance and the early stage of development/high susceptibility to export controls), make quantum computing an ideal chokepoint technology for trade control policy. However, given the immense promise of quantum computing, early trade controls attempting to mitigate security-relevant activities would likely have to be extremely targeted. Otherwise, overly broad controls risk meriting criticism from the private sector that may ultimately lead to non-compliance, or loss of American technological competence through excessive burden on economic benefits.[11]

3. Technology Overview

Although quantum technologies are in a relatively nascent stage of production, this mapping analysis shows that a number of technical and social trends have shaped the industry thus

Subcommittee on Energy Committee on Science, Space, and Technology House of Representatives, October 24, 2017, p. 9, <https://docs.house.gov/meetings/SY/SY15/20171024/106555/HHRG-115-SY15-20171024-SD003.pdf>.

9 Ibid, p. 28.

10 Mark Linscott, "Should Trade be More Strategic?" *Atlantic Council Blog*, September 10, 2020, <https://www.atlanticcouncil.org/blogs/new-atlanticist/should-trade-be-more-strategic/>.

11 For example: "Comment for the Department of Commerce ANPRM on 'Review of Controls on Certain Emerging Technologies'," Jeffery Rittener, Vice President of Global Trade at Intel Corporation, <https://www.regulations.gov/document?D=BIS-2018-0024-0199>; "Comment for the Department of Commerce ANPRM on 'Review of Controls on Certain Emerging Technologies'," Vern Brownell, CEO at D-Wave, <https://www.regulations.gov/document?D=BIS-2018-0024-0150>; "Comment for the Department of Commerce ANPRM on 'Review of Controls on Certain Emerging Technologies'," Edward Bond, Director of Export Regulation Office at IBM Corporation, <https://www.regulations.gov/document?D=BIS-2018-0024-0122>.

far. As noted above, main technology areas that have emerged are quantum communication and quantum information processing. However, quantum metrology, or the use of quantum technologies to improve measurement and timing capabilities, has also been prioritized among basic research and academia groups. Quantum sensing, which was introduced in the PNT technology section, is an example of a quantum metrology application.

While quantum communication and quantum metrology comprise smaller segments of businesses and research circles, innovation in these areas has the potential to translate to improvement in quantum information processing technologies. This is largely due to the fact that there is still significant uncertainty regarding the fastest path to operable quantum computers and the best system control technologies to apply. Experimental findings related to quantum communication and quantum metrology may illuminate new approaches to quantum computing. Additionally, advances in quantum communication and quantum metrology practical application could provide adjacent technologies needed to meet the extremely difficult criteria for operational quantum computers, including technologies such as quantum repeaters or cryogenics.[12] Thus, given that interactions between the three sectors is likely, the quantum information sector should not be analyzed in isolation from quantum communication and quantum metrology in the context of the mapping exercise.

As will be discussed below, many different quantum computer frameworks are currently being researched. Due to the influx of quantum computer hardware ideas and the lack of a consensus over which development path will yield the best computer, there is a general push to make framework-agnostic quantum computing software. In many cases, the specific hardware or software decisions are made with respect to the applications or types of industries that companies are targeting.

This section will provide a brief overview of the different quantum technologies, the various applications and industries being targeted by quantum innovators, and the relevant policies/ national strategies that are currently in place.

Technical Background

Although there is still no clear technical direction driving quantum computer hardware development, a few pathways are gaining significant momentum and capturing large portions

12 Geza Toth and Iagoba Apellaniz, “Quantum Metrology from a Quantum Information Science Perspective,” Journal of Physics, 2014, <https://iopscience.iop.org/article/10.1088/1751-8113/47/42/424006/pdf>.

of funding and interest. Each of the different system types vary with respect to the type of qubit, where a qubit is analogous to a bit in a traditional computer, that it relies on. Systems may also vary with respect to the specific material used for the qubit, as well as the way in which they harness the quantum phenomenon of the qubit. Most of the pathways currently being pursued are gate-based quantum computing technologies, as they are touted as being building blocks for eventual universal quantum computers; this is in comparison to quantum annealing technologies, which are easier to develop but limited in application. Although quantum annealing technologies have been successfully produced with higher qubit numbers, they tend to not reflect the true quantum benefits of quantum computing and are only able to perform a limited range of tasks. Quantum annealing technologies are able to perform a narrow set of operations based on finding local minima or maxima, but are limited in the extent to which they can be applied to other varieties of computing problems, and the extent to which they can harness the benefits of quantum superposition and entanglement.[13] The main gate-based quantum computer approaches being explored include: trapped ion qubits, superconducting qubits, spin qubits, photonic qubits, and topological qubits.[14]

- *Trapped ion qubits*, which served as the computing unit basis for the earliest quantum computer demonstration in 1995, rely on extensive ancillary hardware, including lasers to cool the ions inside vacuums in order to trap and manipulate them.[15] Trapped ion qubit systems have achieved success at smaller scales, but have faced obstacles in scaling up to larger systems, due to difficulties in maintaining appropriate, consistent ambient environments across qubits.[16]

- *Superconducting qubits*, otherwise known as "artificial atoms," are macroscopic electronic circuits that exhibit quantized energy levels when cooled to extreme temperatures. Superconducting qubits may be applicable to gate-based quantum computation as well as quantum annealing. Similar to trapped ion qubits, superconducting qubits also become more difficult to operate in higher quantities, as qubit quality may decrease due to inter-qubit interactions. Thus, higher order systems will require unique arrays that spatially separate qubits.[17]

13 Arnab Das and Bikas Chakrabarti, "Quantum Annealing and Analog Quantum Computation," *Review of Modern Physics* vol 80, pg 1061, 2008, <https://arxiv.org/pdf/0801.2193.pdf>.
14 *Quantum Computing: Progress and Prospects* (National Academies of Science, Engineering, and Medicine, 2019).
15 Iulia Georgescu, "Trapped Ion Quantum Computing Turns 25," *Nature Review Physics*, May 18, 2020.
16 *Quantum Computing: Progress and Prospects* (National Academies of Science, Engineering, and Medicine, 2019). p. 122.
17 Ibid, pp. 124-125.

- *Spin qubits*, which can be achieved through a number of different methods, have also received significant investment, including support from Intel. Silicon is a leading contender for spin qubits; although silicon qubits require extreme temperatures in order to remain operable, they are known for their stability.[18]

- *Photonic qubits*, based on single units of light, called photons, are in a more experimental stage of research than those listed above. Photonic qubits offer unique strengths in that photons do not notably interact with the environment or with one another. However, they are also uniquely challenging in that they are difficult to localize and manipulate.[19]

- *Topological qubits*, comprising an area that has received less funding and media focus to-date, rely on topological symmetry to increase the fidelity of qubits and to improve the error correction process. However, topological qubits are at such an early stage of research that their existence has yet to be experimentally observed.[20]

Beyond quantum computing hardware, there is also a rapidly growing industry for quantum computing software, encompassing control systems, operating platforms, and programming languages. As enumerated above, quantum computing systems require highly specified environmental conditions, with control systems serving as an important fulcrum for many quantum computer milestones. Thus, significant research and funding has been devoted to control system software (in addition to hardware). Most control system software is necessarily developed specific to the type of quantum computer that it is intended for. Additionally, operating platforms, which are able to harness the benefits of quantum computers in order to more easily address identified problems, are also receiving significant interest. Operating platforms that are intelligently designed under the specific processor parameters, including the computing limits and error bounds of the system, may also play a significant part in fully actualizing the utility of a given quantum computing system. Finally, programming languages serve as a more universal method for coding quantum computer operations. Many programming languages aim to be hardware agnostic, in that they are able to be applied to any of the various quantum computers under development.

In addition to quantum computing, other areas are emerging in the realm of quantum technologies, including quantum metrology and quantum communication. Compared

18 Thaddeus Ladd and Malcolm Carroll, "Silicon Qubits," Sandia National Lab Report – DOI: 10.1016/B978-0-12-803581-8.09736-8, 2018, <https://www.osti.gov/biblio/1429799-silicon-qubits>.

19 Ibid, p. 127.

20 Ibid, p. 128.

to quantum computing, which encompasses technologies that are programmable and able to accomplish a number of different types of computation, quantum metrology and quantum communication are areas that apply specific quantum mechanics principles in order to accomplish explicit tasks. Quantum communication typically applies the quantum entanglement phenomenon to increase the security of communication and to increase the ease of detection if an attempt to hack a communication link occurs.[21] Quantum metrology applies quantized energy levels, quantum coherence, and quantum entanglement to measure extremely sensitive physical quantities.[22]

Applications/Target Industries

Given the wide variety of technologies and strategies currently applied to quantum information technology research, many applications and target industries have been identified. In some cases, the target application or industry is specific to a certain type of quantum computer/technology, in other cases the target application or industry is relevant to an advancement in any type of quantum computer/technology approach. For example, early analyses have been conducted to determine ways in which quantum computers could be applied to solve complex problems in the financial industry.[23] Such surveys attempt to identify what specific problems quantum computers would be ideal for, and furthermore which types of quantum computers and quantum computing software would be most suitable.

4. Policy Background

American policymakers are eagerly pursuing strategies for governance in the quantum computing field for a variety of reasons. Specifically, policymakers are seeking actionable strategies that enable domestic firms to reap economic gains from developing quantum computers, that ensure national competence and technological advantage on quantum computing, and that mitigate potential security risks from global quantum computing development.[24] In an effort to encompass all of these objectives, the largest overarching

21 Martin Giles, “Explainer: Quantum Communication,” MIT Technology Review, February 14, 2019, <https://www.technologyreview.com/2019/02/14/103409/what-is-quantum-communications/>.

22 Stuart Wolf, et. al., “Overview of the Status of Quantum Science and Technology and Recommendations fro the DoD,” *Institute for Defense Analysis*, June 2019, <https://www.ida.org/-/media/feature/publications/o/ov/overview-of-the-status-of-quantum-science-and-technology-and-recommendations-for-the-dod/d-10709.ashx>.

23 Roman Orus, Samuel Mugel, Enrique Lizaso, “Quantum Computing for finance: Overview and prospects,” Review in Physics, 2019.

24 Domestic Manufacturing Capabilities for Critical DOD Applications: Emerging Needs in Quantum-Enabled Systems: Proceedings of a Workshop. National Academies of Science, Engineering, and Medicine. 2019.

policy agenda was introduced as a congressional bill in 2018 under the name of the National Quantum Initiative Act.[25] This bill was quickly followed by an Executive Office publication titled the "National Strategic Overview for Quantum Information Science," which outlines more specific steps in advancing U.S. quantum competency.[26] In addition to providing financial assistance for basic research projects and companies pursuing novel quantum computing efforts, the national strategy includes plans to capitalize on the economic benefits of quantum computing leadership. To further this effort, the National Institute of Standards and Technology convened the Quantum Economic Development Consortium (QED-C), in order to support a robust American manufacturing base and supply chain for quantum technologies.[27]

The private sector is also pursuing the development of its own standards for quantum technologies. In 2018, the Institute of Electrical and Electronics Engineers (IEEE) published two standards, P7130 and P7131, which establish specific terminologies for quantum technologies and performance metrics for quantum computers, respectively.[28] Other members in the industry have also been calling for the development of quantum computing ethics research.[29]

5. Mapping Analysis

Overview

Although there is a significant amount of R&D that must be completed in order to produce more usable quantum computers, there is a rapidly burgeoning manufacturing base, including entities with diverse characteristics. In fact, the diversity of entities may be the result of the nascency of the R&D, allowing for organizations that tackle the problem of quantum computing through different types of funding methods, specific foci, and unique partnerships.

25 S.31433 - National Quantum Initiative Act, 115th Congress, 2017-2018, <https://www.congress.gov/bill/115th-congress/senate-bill/3143>.

26 National Strategic Overview for Quantum Information Science, The White House, 2018, <https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf>.

27 The Quantum Consortium, <https://quantumconsortium.org/>.

28 P7130- Standard for Quantum Technologies Definitions, IEEE Standards Associations, 2019, https://standards.ieee.org/project/7130.html. P7131 - Standard for Quantum Computing Performance Metrics & Performance Benchmarking, IEEE Standards Association, 2018, <https://standards.ieee.org/project/7131.html>.

29 "The Time to Talk About The Ethics of Quantum Computing is Now," QC Ethics, <https://qcethics.org/>.

This research surveys the different types of components that firms are pursuing, the geographical dispersion of the industry, and firm characteristics, such as organization type, government involvement, and academic partnerships. Although many of the quantum computing firms are researching and investing in specific hardware approaches to quantum computing (largely based on the type of qubit used), this research found that the number of firms developing hardware-agnostic software for quantum computers has been increasing substantially within the last ten years. With respect to geographical dispersion of the manufacturing base, a large number (43.5%) of quantum companies are based in North America, but there is also a global presence, with other regions such as Europe and Asia capturing sizable fractions of the market as well. Most of these entities are private, although there are a handful of government-specific entities (such as national labs) and larger, public companies pursuing quantum computing technologies as well.

Selection of Organizations

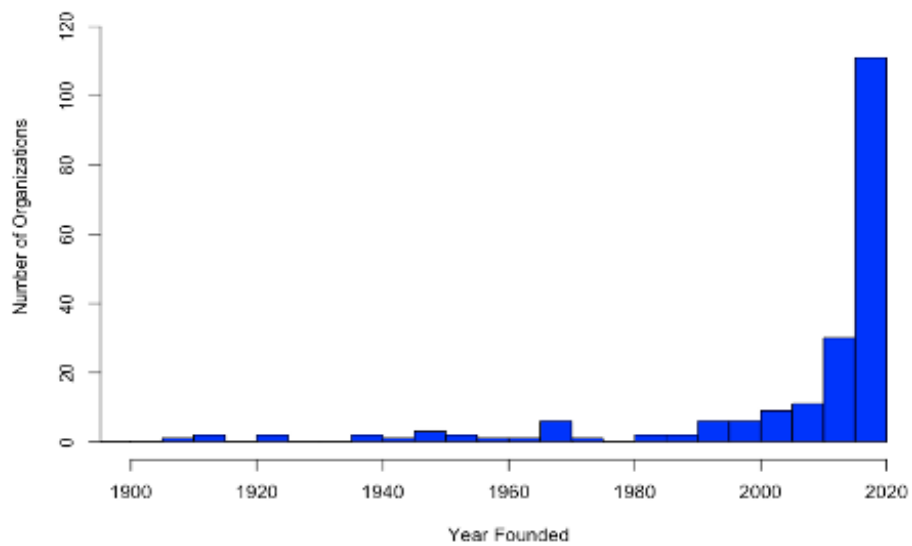
Organizations were selected for this quantum computing analysis based on whether they currently operate, actively develop, or pursue quantum computing (or, in a few cases, quantum computing-adjacent) technologies. This overarching categorization includes large companies that have added quantum computing branches to their current portfolios, as well as small companies that have sought out investment in hopes of developing quantum computer technology. This also includes certain government labs and non-governmental organizations that are pursuing quantum computing technology on the basis that they are in partnerships with companies and corporations that could eventually disperse the technologies. Notably, the decision was made to include quantum computing software companies for the purposes of gaining a better understanding of how quantum computers will ultimately reach various industries. Additionally, certain software companies are involved in partnerships to share quantum computer processing time once computers are developed. In total, this report includes the analysis of exactly 200 quantum computing companies; at the time that the data acquisition was completed, this was deemed to be a fairly comprehensive scope of the quantum computing manufacturing base. However, it is worth noting that, given the young age of many of the organizations, the growth of the sector is rapid and there is a need to keep the mapping research up to date, as well as continuously account for organizations that collapse, merge, or become acquired by other entities.

Findings

1. Organization Age and Type

A significant number of new firms have emerged over the past ten years seeking to benefit from growing interest among global investment groups. This large recent surge of organizations since 2010 is shown in Figure 4. Given the growing investment channels available to the younger small, private companies, it may be worth specifically analyzing the characteristics of the new firms in order to understand in what specific areas investors are interested. Throughout the research presented, we will attempt to compare differences between the newer wave of companies and the older, pre-existing companies.

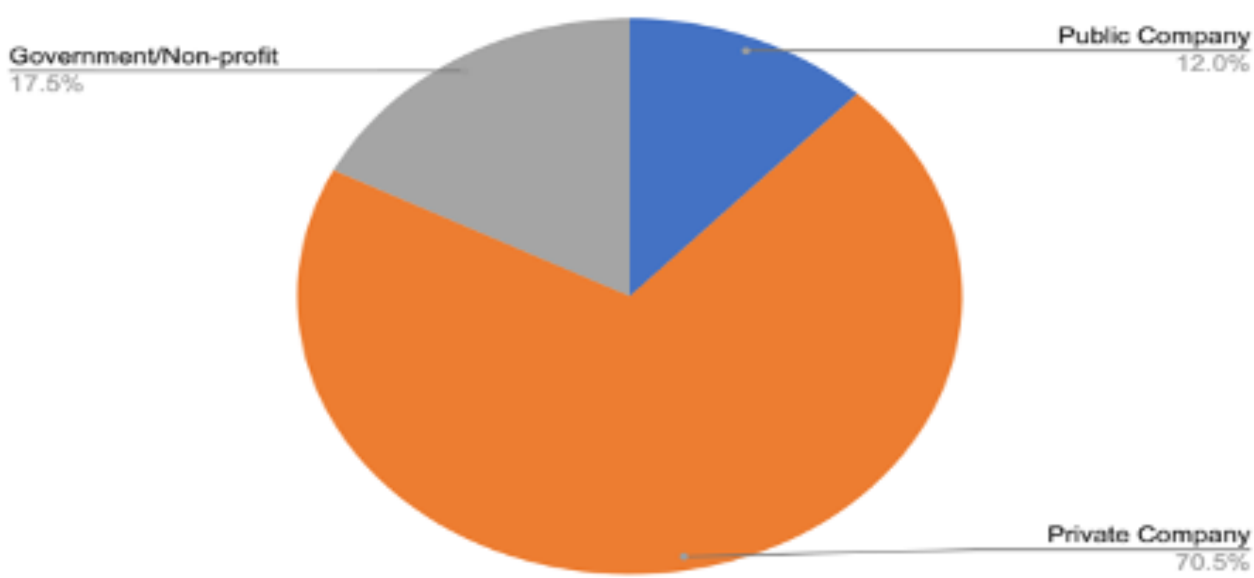
Figure 1. Founding Years of Quantum Computing Organizations (1900-2000)



As mentioned, most of the quantum computing firms are private and for-profit, although there are some public for-profit, government, and non-profit organizations as well. This breakdown is provided in Figure 5. Private companies make up the lion's share, likely because they are able to be more agile in changing R&D foci and scope of technology development. They are also able to better maintain a certain amount of privacy and information control over how their development of the new technology is progressing. This is important in a nascent field, like quantum computing, where any given breakthrough may yield significant profit or acclaim for a company. Private companies are also able to engage in international, academic, and government partnerships more easily, as there is less oversight. Finally, it is worth noting that a large number of the private quantum computing firms are start-ups that have been backed by various global investors.

The fact that there are so many private companies, supprted by a large cohort of interested investors, substantiates the notion that quantum computers are predicted to be a potentially big windfall once they can be successfully built. This is because there are many different applications of quantum computers, extending well beyond military and defense applications. Furthermore, because there is still so much uncertainty over what the best technical approach is to quantum computer development, there may be a significant amount of profit for the first few companies to exemplify the benefits and usability of their own quantum computer type. However, because it is a nascent field and many of the younger, smaller firms are performing cutting-edge research, it is possible that many of them will be acquired after a few years if they show promising results and are open to the idea of being acquired by a larger company or organization.

Figure 2. Quantum Computing Organization Type



2. Global Dispersion

The global dispersion of the quantum computing manufacturing base was analyzed using two methods: sheer visualization of the company headquarters locations (Maps 2 and 3) and analysis of multinational operations. As Map 2 shows, quantum computing organizations are located predominantly throughout North America, Europe, and Asia, with smaller bases in the Middle East and Australia. However, as Map 2 and 3 demonstrate, information can be drawn out from sorting the companies by age (older companies compared to those formed in the past ten years), and by the type of technology the company is developing (hardware, software, or both). As Map 2 shows, the newer organizations have a more global presence than the older organizations. As Map 3 shows, companies building hardware, which may be more directly impacted by trade controls, are located in a narrower set of countries, but are still fairly global.

Map 1. Quantum Computing Global Dispersion by Age

Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute • Created with Datawrapper

Map 2. Quantum Computing Global Dispersion by Technology Focus

Source: Center for International and Security Studies at Maryland/Strategic Trade Research Institute • Created with Datawrapper

Although visualizing the location of the headquarters can be useful to gain cursory insight into the potential effectiveness of trade controls, a deeper analysis into the types of global transactions that companies are involved in is also necessary given the interconnectedness of the current globalized marketplace. Table 4 provides a summary of the data analyzing the extent to which companies engage in multinational interactions. The overarching multinational category is dictated by whether or not companies engage in international research partnerships, have international manufacturing or distribution bases, have international headquarters, or receive international investment. These individual characteristics are also provided in Table 4. The data concludes that 62.5% of companies are engaged in multinational relations, with the largest driver being international investment (at 48%) and international research partnerships (at 51%). This can be explained through the large number of small, private companies. The large amount of international investment is due to the rise of quantum computing start-up companies which require investment in order to get initial funding. Additionally, start-ups are frequently engaged in international research partnerships in order to help share the burden of researching the entire quantum computing process.

Table 1. Quantum Computing Summary Table

Category	Percent of Quantum Computing Sector
Government Involvement	56%
Academia Ties	55%
Multinational – Umbrella Category	63%
International Partnership	51%
International Manufacturing	16%
International Distribution	20%
International Headquarters	13%
International Investment	48%
Explicitly Dual-Use	26%

3. Partnerships with Academia and Government

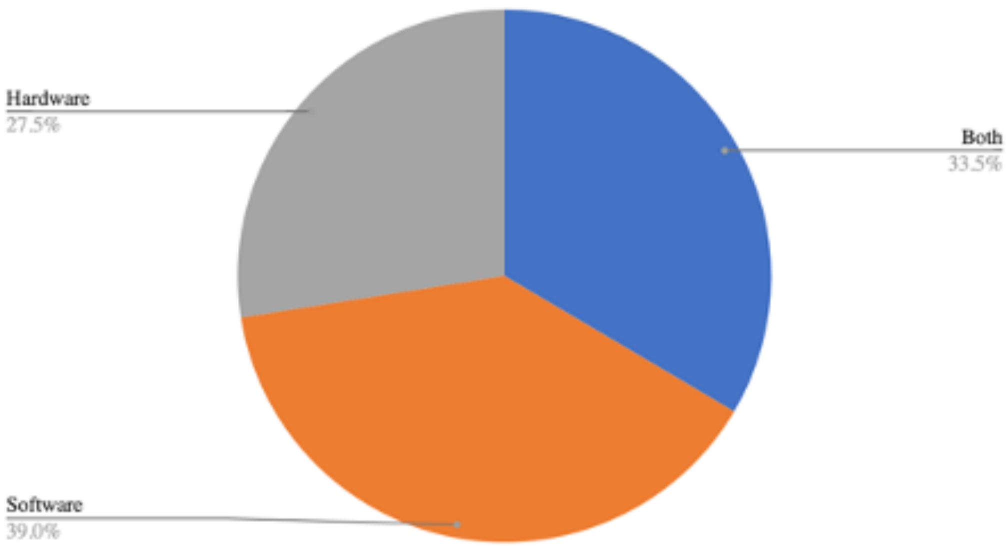
Relations to academia and government can also be a good indicator for the stage of the research in a given field and whether or not the government deems a technology to be security-relevant. As Table 4 above shows, about 55% of companies in the quantum computing manufacturing base have government involvement, which entails research partnerships or direct funding. This is fairly high considering the fact that many of these companies are private. This means governments are considerably engaged in developments or may even be trying to shape the direction of the research. Roughly 55% of companies are also engaged in partnerships with academia. This may include the sharing of facilities or scholars, or it may be a more overt research partnership. Again, this is a fairly high percent of companies with academic partnerships, indicating that the field is nascent and that research is being shared not only within the private industry (as was noted in the previous section), but also across different sectors.

4. Technology Trends

Under the broader scope of quantum computing, this research also attempted to tease out the specific focus areas for the industry, in order to determine which areas of research have been prioritized. Interestingly, this research found a fairly even three-way split between companies working explicitly on hardware, software, and both.

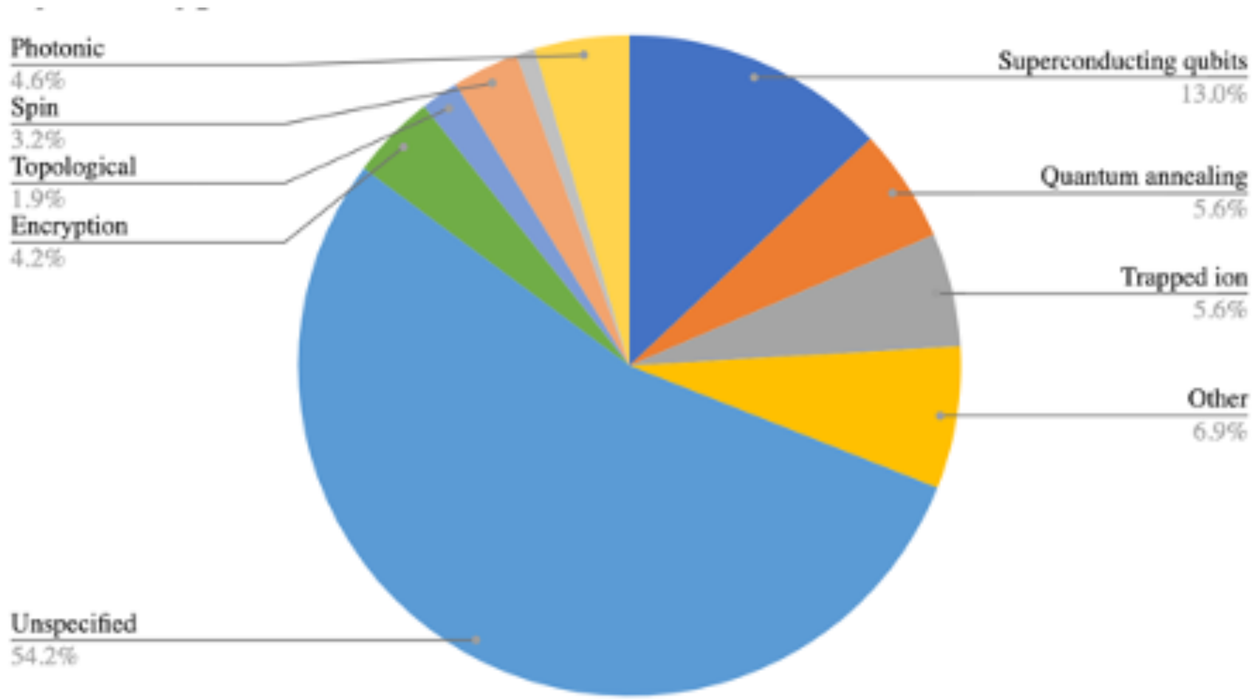
Perhaps the least-expected conclusion from this analysis is that there is already a significant base of companies working specifically on software for quantum computers, despite the fact that wide-scale use of quantum computers still lies in the future. A couple of factors could account for the number of companies working on quantum computing software. Likely some of the companies are seeking to profit from software that utilizes quantum computers for a specific industry or purpose that may return large profits. In this case, stating that a software is being designed for use by a quantum computer, even without a specific quantum computer in mind, may increase investment interest. However, another group of those companies is seeking to maximize the use of limited or rudimentary quantum computers through specific software approaches. For example, the sheer limit in the number of quantum computers is being tackled through quantum clouds, where companies can provide software that allows users to access quantum computer time remotely. Another example is software that is able to compensate for high error rates in early generation quantum computers through highly specified and elaborate algorithms.

Figure 3. Quantum Computing by Technology Focus



In terms of hardware, it is also interesting to analyze the different approaches taken by the quantum computer hardware (or hardware and software) companies. Figure 7 shows that there is still a wide variety in qubit approaches being pursued. Superconducting qubits, trapped ions, and photonic qubits are certainly gaining a lot of interest. However, there are also a few other avenues being pursued by the manufacturing base, including spin-based qubits and topological qubits. Interestingly, most companies that are pursuing a specific type of qubit are also identifying specific industries where their qubit focus may be best applied. Notably, this type of analysis is limited in its ability to account for the variation in the size of companies. Although certain qubit approaches, such as the spin qubit, may appear to have a smaller share of the manufacturing base, it is supported by Intel, which is one of the largest companies in the manufacturing base. Finally, as indicated by the Technology Overview section, there may be overlap between some of the qubit types and certain companies may be pursuing multiple different approaches.

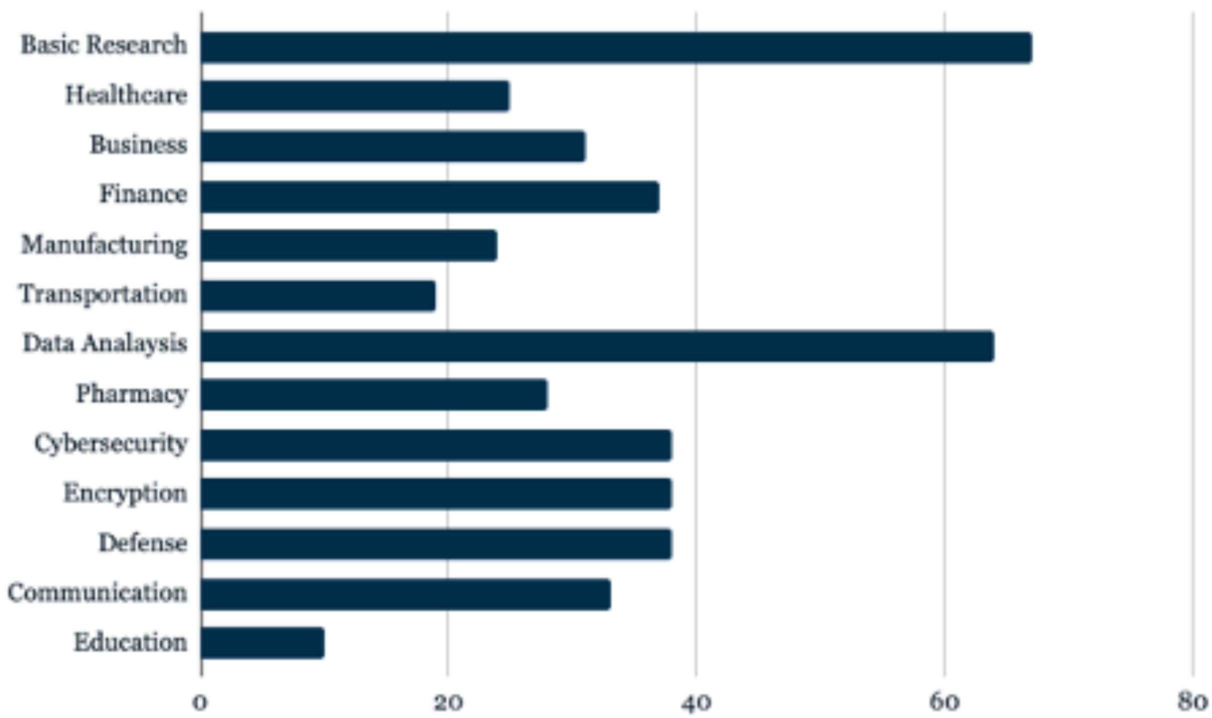
Figure 4. Quantum Computing by System Type Focus



5. Targeted Industries

In this analysis, the "target industries" for each firm were also recorded. This involved identifying the types of industries to which each firm was advertising the utility of their product. The purpose of this analysis was to determine if there was a specific priority industry that was driving investment interest. Although there was a large spread in the target industries for quantum computing firms, the leading industries targeted were "Basic Research" and "Data Analysis." The high prevalence of "Basic Research" suggests either that a large number of firms are targeting scientific endeavors for their quantum computing development, or that they are applying basic research in developing new quantum computing methods. The two were often conflated across the different types of firms. "Data Analysis" was likely used as a catch-all term to signify that quantum computers could also generally be used to compute and analyze data. Beyond these two industries, there was also considerable emphasis on the impact that quantum computers could have on finance, cybersecurity, encryption, defense, and communication industries, as well as healthcare, business, manufacturing, pharmacy, and education.

Figure 5. Quantum Computing Target Industries



With respect to the defense industry specifically, 40 organizations (translating to roughly 20 percent of the manufacturing base) have potential dual-use applications. Of those organizations that indicated the defense industry as a target industry, many identified operation analysis and automation (for vehicles and drones) as potential industry applications. Additionally, cybersecurity, and the potential for quantum computers to break standard encryption models, may be another key source of dual-use tension.[30]

6. Comments Data

Despite efforts to maintain timely and comprehensive management of the data used for this report, a few limitations exist that could be skewing the data collected and the analysis produced. A primary limitation is the potential for data omission due to covert companies and organizations. Because all of the data was collected using open source means, entities that are less forthcoming about their ties to quantum computing might have been omitted. This

30 Jake Tibbetts, "Quantum Computing and Cryptography: Analysis, Risks, and Recommendations for Decisionmakers," Lawrence Livermore National Laboratory, Center for Global Security Research, September 2019, <https://cgsr.llnl.gov/content/assets/docs/QuantumComputingandCryptography-20190920.pdf>.

may be occurring at the national level for countries in which such data might only be shared in a less public setting. There is also a potential limitation with respect to the timeliness of data updates. Because the industry includes a large number of younger, smaller companies, there is a higher than normal turnover and transition rate, where companies may either halt operations or be acquired by a larger company. Finally, the challenge of designating the dual-use potential should be noted. Companies were only coded as having dual-use potential if they specifically claimed the defense industry or defense applications as targets. However, in many cases it may be beneficial or required for companies to omit this type of information from their public profiles. Thus, it is possible that the dual-use category could be undercoded. Despite these limitations, the data produced in this report is still useful in capturing as many trends in the industry as possible, even if specific numeric values prove fallible.

7. Conclusions and Trade Control Implications

Technology Conclusion

This analysis has found that the quantum computing manufacturing base is made up largely of private companies that have extensive global, academic, and government partnerships. A large number of the firms are young, shifting towards hardware-agnostic software relevant to specific applications, and actively involved in partnerships to help fill gaps in the services and components they provide. Given the fact that the hardware manufacturing base is not expanding as rapidly as the software manufacturing base, it is likely that much of the industry will be supported by a smaller number of large companies that produce the hardware, and ultimately computers, needed to drive the industry. However, among those companies developing quantum computing hardware, there is significant uncertainty over which quantum computing pathway will be most fruitful.

Trade Control Implications

Given the potential security concerns that have been identified here and that have been voiced by policymakers, the findings that this data analysis has produced will prove useful in determining policy strategies for implementing trade controls on the quantum computing manufacturing base. By determining major evolving trends in the industry, more targeted and practicable trade implications are able to be identified, such as hardware and end-use specific trade controls. Additionally, security concerns associated with quantum computing, such as decryption, automation, and optimization augmentation, must be ranked based on strategic priority.