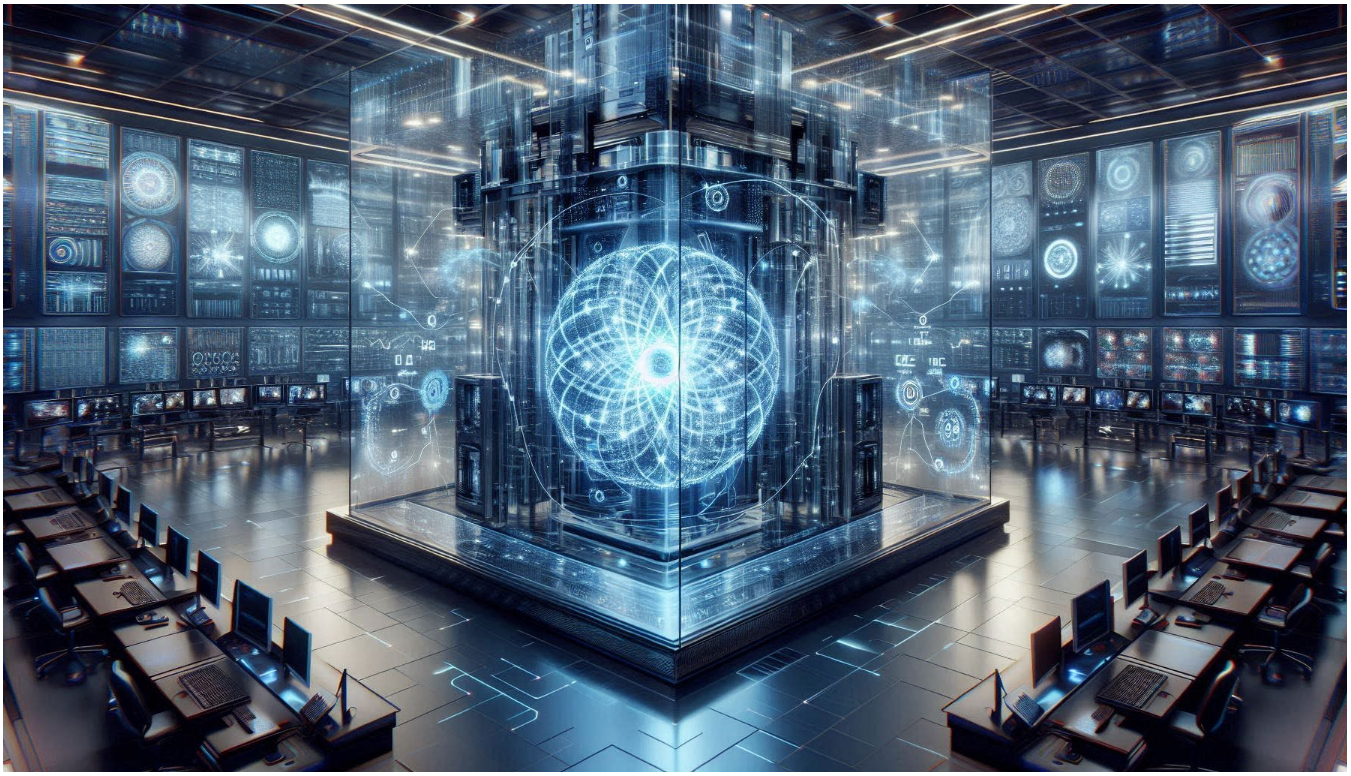

Sutor Group Intelligence and Advisory

Quantum Processing Unit (QPU) Market Landscape (Abridged)

April 3, 2025

About the Sutor Group

Dr. Bob Sutor is the CEO and Founder of Sutor Group Intelligence and Advisory. Sutor Group provides broad market insights and deep technical expertise based on over four decades of experience with startups and large corporations. It advises Deep Tech startups, companies, and investors on quantum technologies, AI, and other emerging tech fields.

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info@sutorgroupintelligenceandadvisory.com.

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Bob Sutor is a former employee of IBM and Infleqtion and holds equity positions or stock options in each company. He is a Non-Executive Director for Nu Quantum and Advisor to the venture capital firm Forma Prime.

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Introduction

The number of companies building quantum processor unit (QPU) hardware for quantum computing has risen significantly in recent years. However, there are signs that fewer companies are now entering the market.

In this abridged market landscape, we look at the dozens of companies now building the processors, their company data, implementation modality, and programming model paradigm.

We provide charts illustrating the distribution of the companies by country and geographic region. We show the breakdown of which companies are implementing each modality and the countries in which these companies are based. An additional chart shows that the digital paradigm is a far more popular approach than analog and, especially, annealing. Finally, we show the years the companies were founded and the significant increase in incorporation in the last ten years.

Appendix A is a table of companies building quantum processing units. For those companies that have published forward-looking roadmaps, we state when they were last updated. Note that many need to be revisited by the vendors as they are getting old or lacking details compared to their competitors. Appendix B lists the countries in each region. Appendix C is a glossary of technical terms used in this report, courtesy of Perplexity.

Contents

Quantum Computing Products, Offerings, Components, and Services

Quantum computing involves much more than the device that implements the qubits. Other hardware components are necessary to create and manufacture the entire system. Software is required to operate the hardware at the lowest level and implement algorithms and applications. Cloud access, consulting, support, and education help support the ecosystem of users.

quantum computing

- cloud platform
- consulting and services
- education
- **hardware**
  - classical integration
  - components
    - amplifiers
    - circulators
    - control systems
    - cryogenic cables
    - cryogenic CMOS
    - cryogenic dilution refrigerators
    - error correction
    - frequency combs
    - glass cells
    - ion traps
    - lasers
    - magneto-optical traps
    - networking
    - photon detectors
    - photon sources
    - photonic integrated circuits
    - pulse generators
    - qubit readout
  - **processor units**
  - system testing
- software
  - AI for quantum
  - algorithms
  - applications
  - benchmarking
  - code compilers & optimizers
  - control, error mitigation, & measurement
  - error correction
  - IDE
  - pulse-level access
  - quantum for AI
  - SDK provider
  - SDK supporter
  - simulation
  - system testing
  - tools and utilities

Number of Companies by Country with Quantum Processing (QPU) Offerings

This chart shows how many companies are based in each country. Each company may have locations in multiple countries, but this chart only refers to its headquarters.

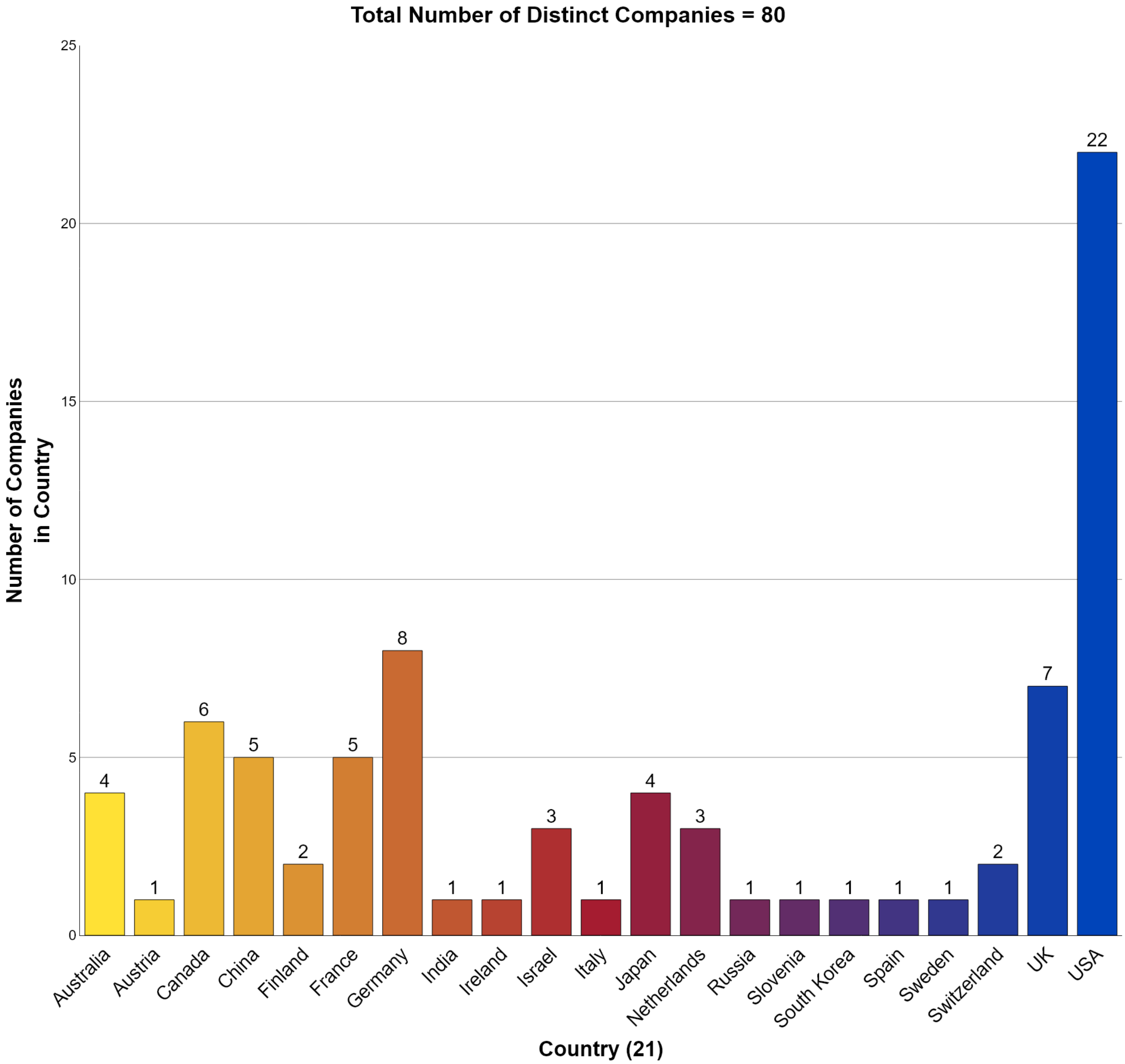

Figure 1

Number of Companies by Region with Quantum Processing (QPU) Offerings

This chart shows how many companies are based in each geographic region. See Appendix B for the assignments of countries to regions.

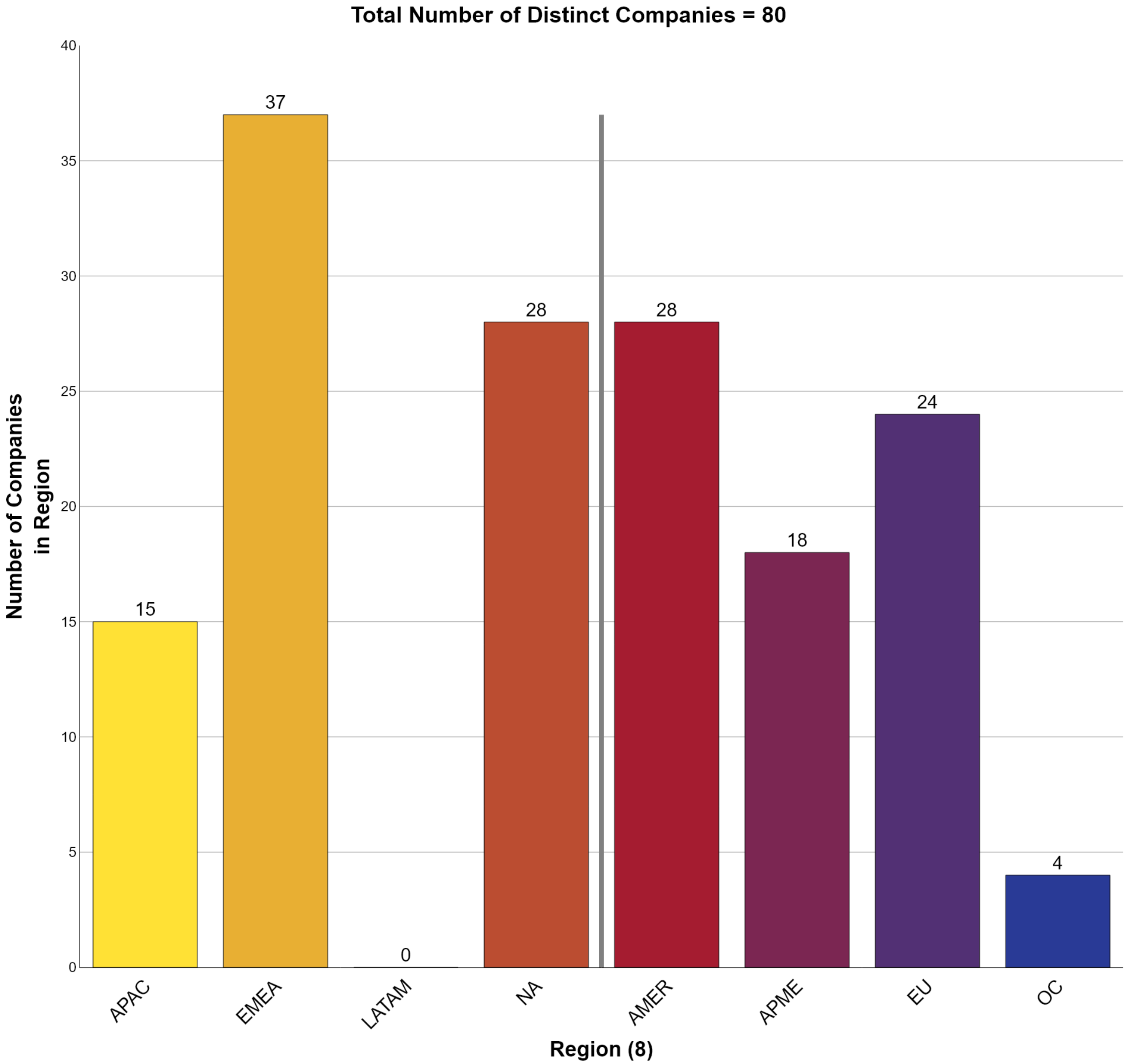

Figure 2

Number of Companies by Modality with Quantum Processing (QPU) Offerings

This chart shows how many companies construct their qubits from each *modality*. Some modalities are *natural* because they use photons, ions, or neutral atoms as qubits, while others, such as Superconducting and Silicon Spin, are manufactured using semiconductor technology. See Appendix C for the modality definitions.

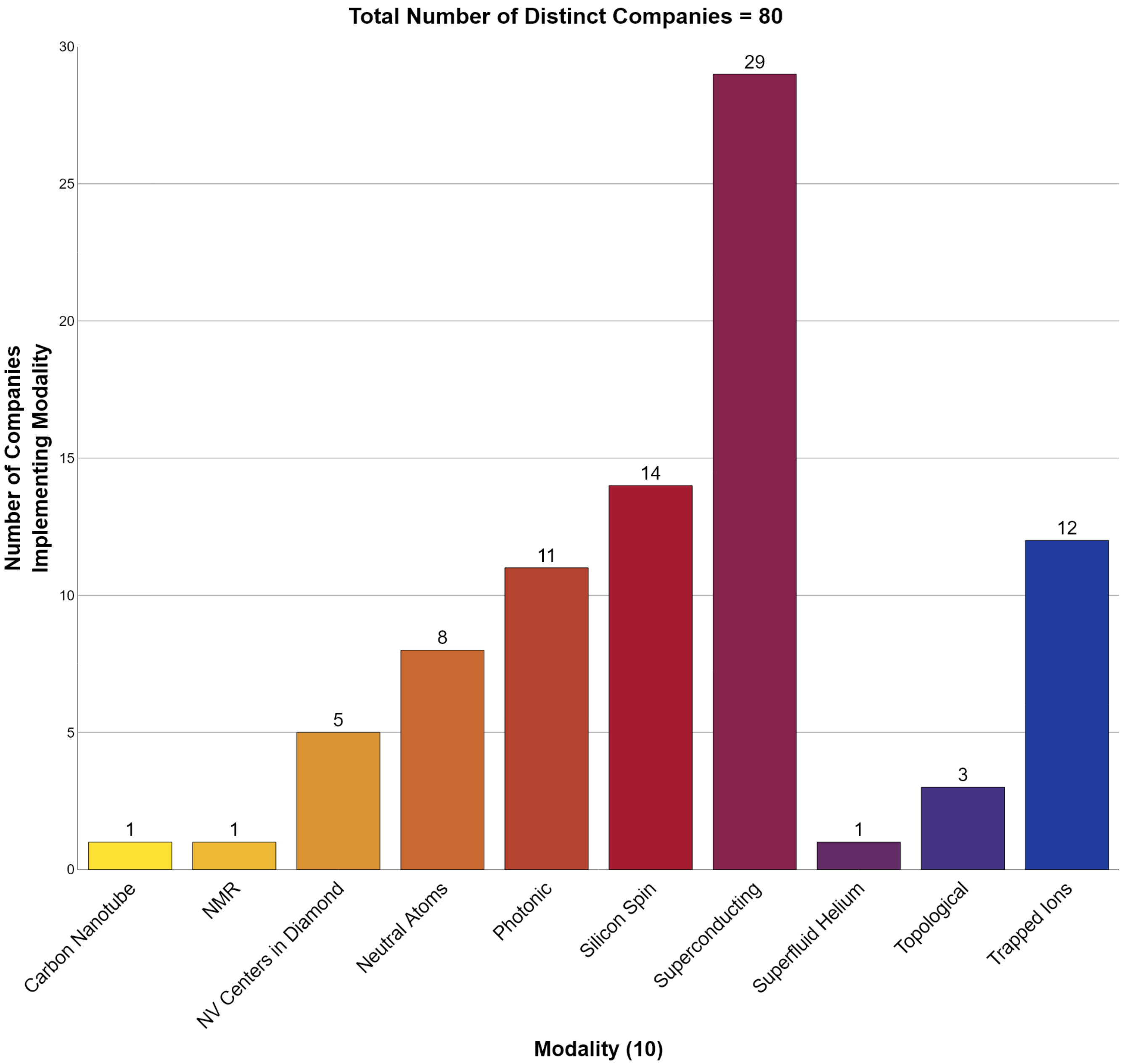

Figure 3

Number of Companies in Countries by Modality with Quantum Processing (QPU) Offerings

This chart refines the previous one by showing how many companies in each country implement each modality. See Appendix C for the modality definitions.

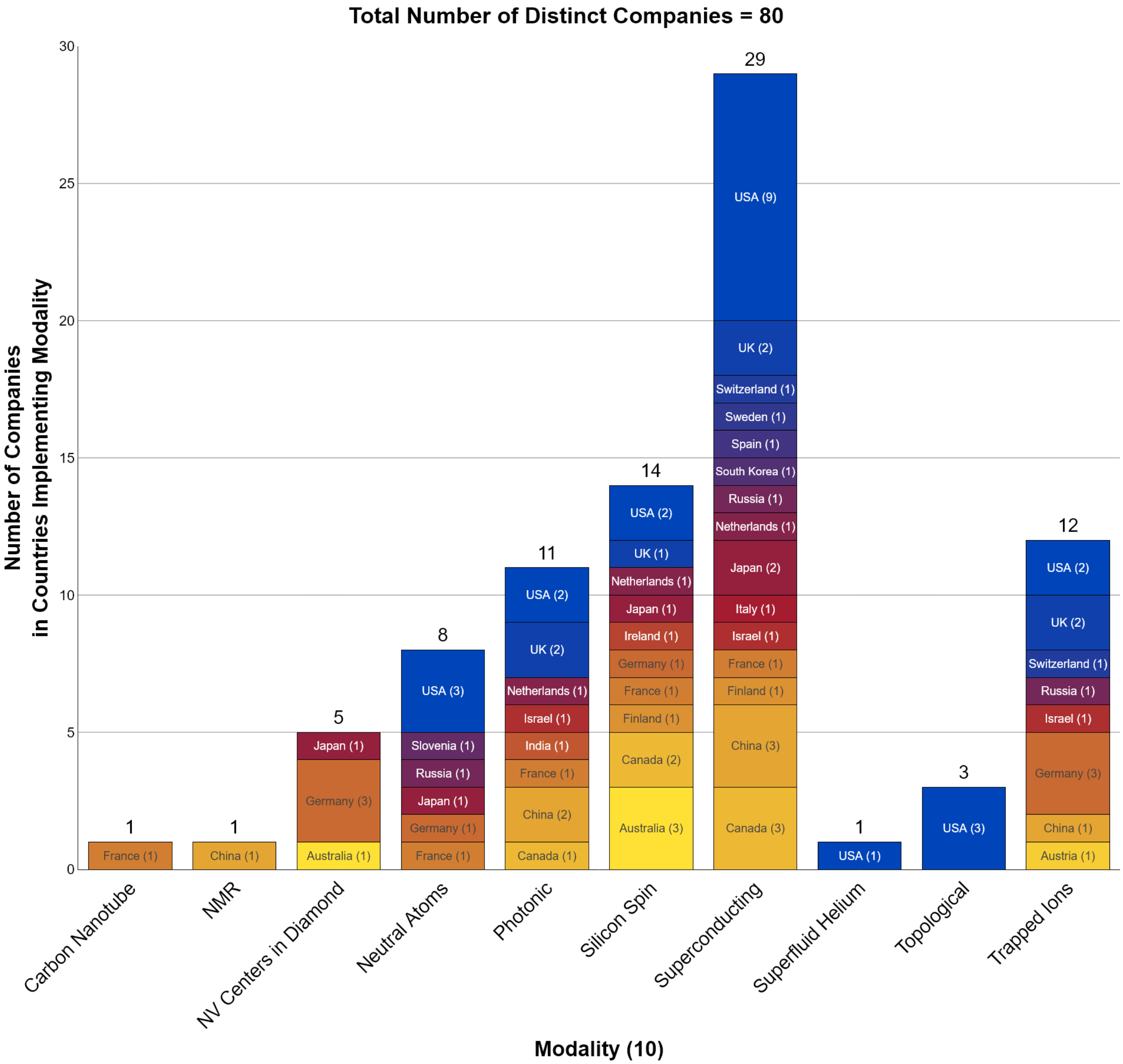

Figure 4

Number of Companies by Paradigm with Quantum Processing (QPU) Offerings

This chart shows the number of quantum computing *paradigms* implemented by the companies. The paradigm is the quantum computation model architected into the hardware and executed via software.The Digital paradigm, also know as the gate-and-circuit or discrete-variable paradigm, is by far the most common. It is taught in most quantum computing books, including *Dancing with Qubits, Second Edition* by Bob Sutor.

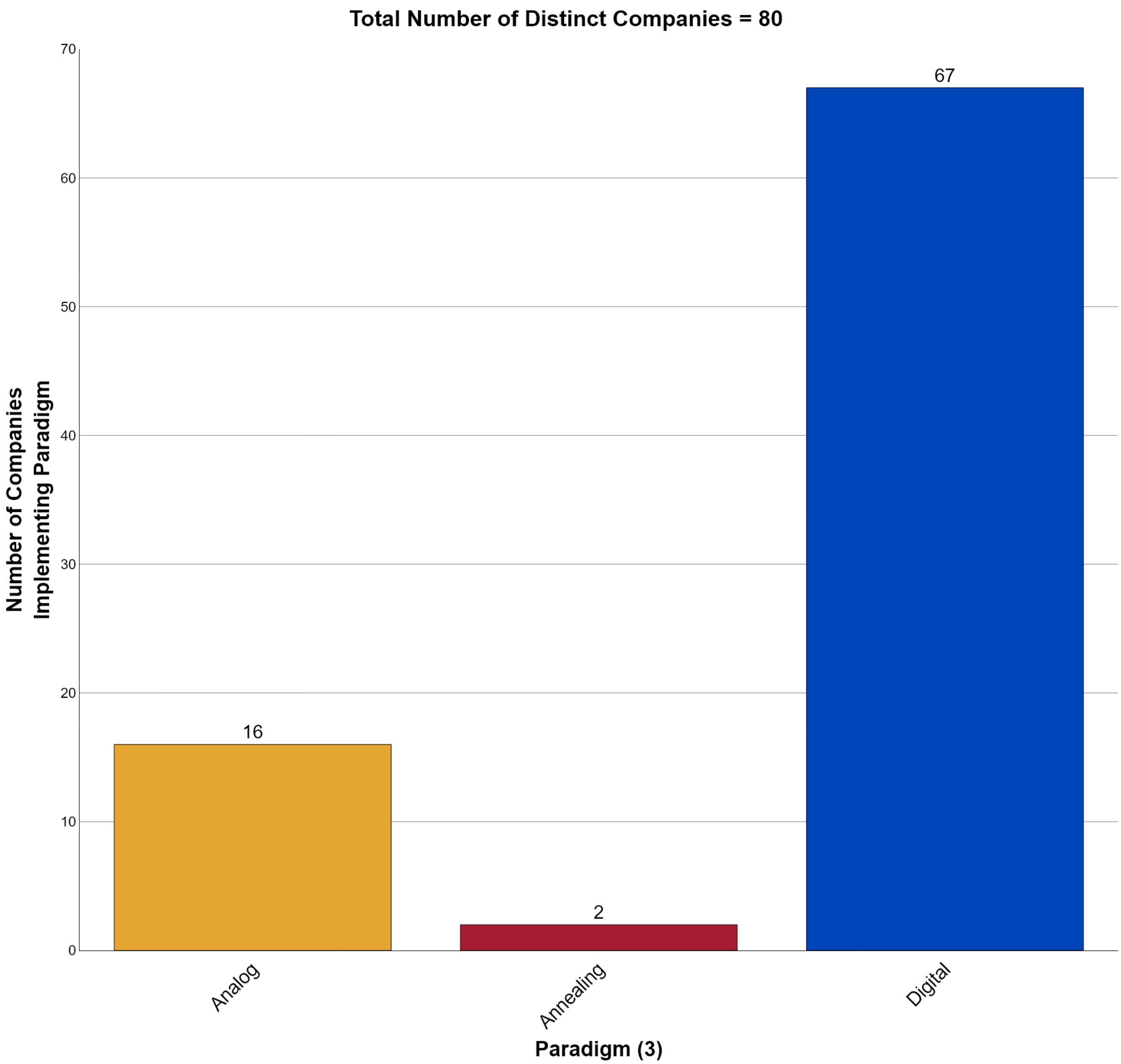

Figure 5

Number of Companies by Year Founded
with Quantum Processing (QPU) Offerings

This chart shows the number of companies that were founded in the last 10 years. The founding year may be earlier than the year the company became fully operational or when it received its first funding.

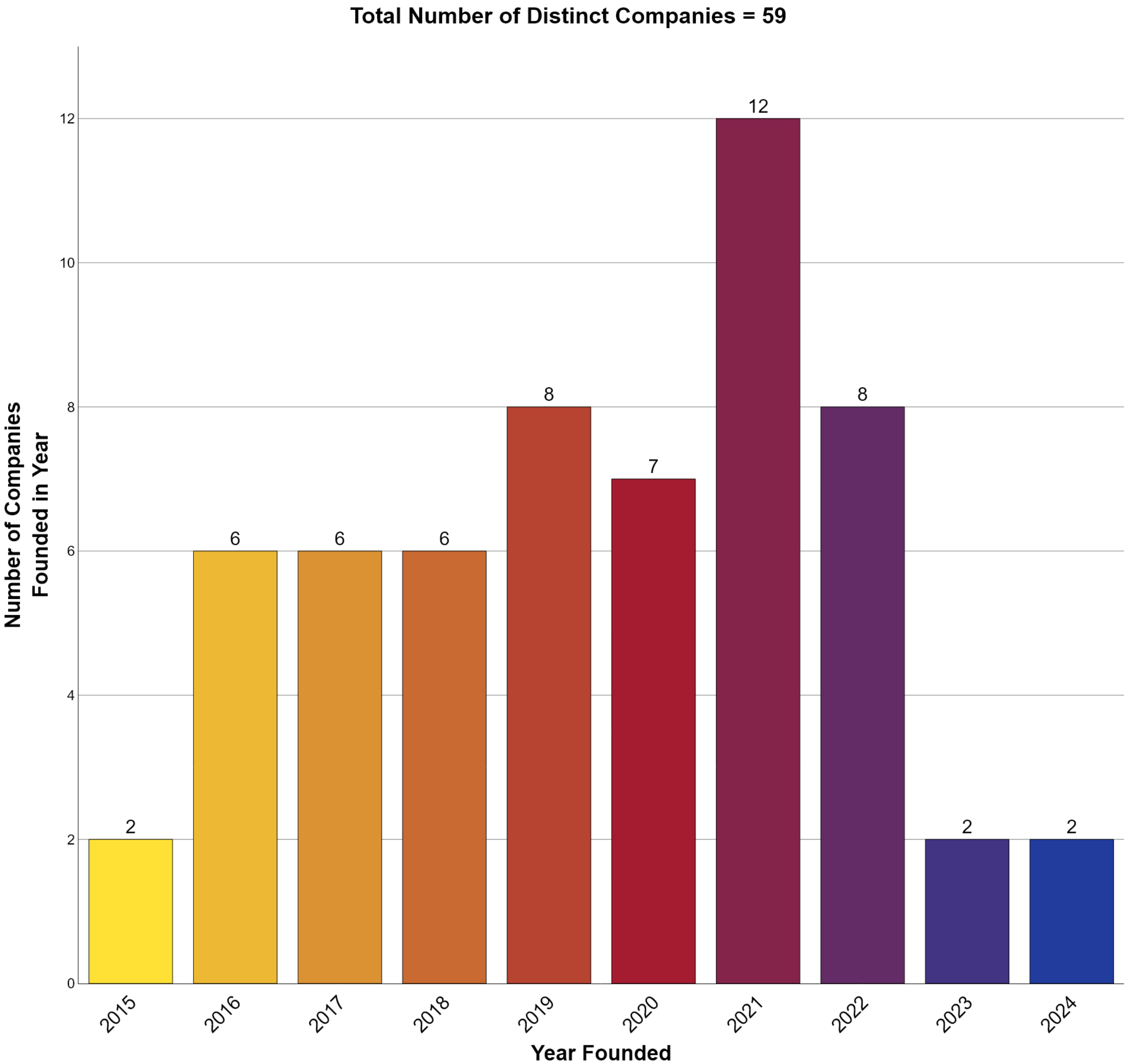

Figure 6

Appendix A: Companies Building Quantum Processing Units

The following table shows the companies creating quantum processing units (QPUs), the collections of qubits that work together to perform quantum computations.

We created this list by using information from press releases, news articles, search engines, and company websites. We also used our personal knowledge and that gleaned from business and technology experts.

Company

The name of the company with a link to its website.

Company Headquarters

The location of the company headquarters. When a company has multiple locations, this site is its base of operations.

Public or Private

Whether the company is publicly traded or is private.

Year Founded

The year the company was founded. If a company's website lists the year it was founded, we use that. In some cases, other public information may state the year the company was founded, became operational, or received its first funding. If available, we use one of those years in that priority order.

Modality / Paradigm

The *modality* is the kind of qubit technology the company uses to implement its QPUs. The *paradigm* is the quantum computation model architected into the hardware and executed via software. The glossary defines each modality and paradigm.

Roadmap Publication Date

If the company has published a non-trivial roadmap with milestone dates and technology specifications expected on that date, we list the date of the roadmap. A "vision" does not constitute a roadmap.

Roadmap Detail Level

When a roadmap is available, we characterize the detail level as low, medium, or high. We consider IBM's quantum computing roadmap to be the most detailed in the industry.

low: At least two generations of technology listed but no specific delivery dates. Very sparse details on the capabilities to be delivered.

medium: At least three generations of technology listed. Delivery dates are not necessarily required if the company provides significant text explaining each generation.

high: At least three generations of technology listed with at least two delivery dates. Highly detailed descriptions of the capabilities to be delivered.

	Company	Company Headquarters	Public or Private	Year Founded	Modality / Paradigm	Roadmap Publication Date	Roadmap Detail Level
1.	Aegiq	Sheffield, England, UK	Private	2019	Photonic / Analog		
2.	Alice & Bob	Paris, Île-de-France, France	Private	2020	Superconducting / Digital	December 2024	high
3.	Alpine Quantum Technologies	Innsbruck, Austria	Private	2018	Trapped Ions / Digital		
4.	Amazon	Seattle, WA, USA	Public	1994	Superconducting / Digital		
5.	Anyon Computing	Walnut Creek, CA, USA	Private	2016	Superconducting / Digital		
6.	Anyon Systems	Dorval, QB, Canada	Private	2014	Superconducting / Digital		
7.	Archer Materials	Haymarket, NSW, Australia	Private	2007	Silicon Spin / Digital		
8.	ARQUE Systems	Aachen, North Rhine-Westphalia, Germany	Private	2022	Silicon Spin / Digital	2023	low
9.	Atlantic Quantum	Cambridge, MA, USA	Private	2022	Superconducting / Digital		
10.	Atom Computing	Berkeley, CA, USA	Private	2018	Neutral Atoms / Digital		
11.	Atom Quantum Labs	Ljubljana, Slovenia	Private	2021	Neutral Atoms / Digital		
12.	C12 Quantum Electronics	Paris, Île-de-France, France	Private	2020	Carbon Nanotube / Digital		
13.	ConScience AB	Göteborg, Sweden	Private	2012	Superconducting / Digital		
14.	D-Wave Quantum	Burnaby, BC, Canada	Public	1999	Superconducting / Annealing	October 2021	medium
15.	Diatope Gmbh	Ulm, Baden-Württemberg, Germany	Private	2021	NV Centers in Diamond / Digital		
16.	Diraq	Sydney, NSW, Australia	Private	2014	Silicon Spin / Digital	2022	medium
17.	EeroQ	Chicago, IL, USA	Private	2016	Superfluid Helium / Digital		
18.	eleQtron	Siegen, North Rhine-Westphalia, Germany	Private	2021	Trapped Ions / Digital		
19.	Equal1 Labs	Dublin, Ireland	Private	2017	Silicon Spin / Digital	2024	low

20.	Fujitsu	Tokyo, Japan	Public	1935	Superconducting / Digital NV Centers in Diamond / Digital		
21.	Google	Mountain View, CA, USA	Public	1998	Superconducting / Digital	February 2023	medium
22.	Groove Quantum	Delft, Netherlands	Private	2024	Silicon Spin / Digital		
23.	Hitachi	Tokyo, Japan	Public	1910	Silicon Spin / Digital		
24.	HRL Laboratories	Malibu, CA, USA	Private	1948	Silicon Spin / Digital		
25.	Huawei	Shenzhen, China	Private	1987	Superconducting / Digital Photonic / Analog		
26.	IBM	Armonk, NY, USA	Public	1911	Superconducting / Digital	August 2024	high
27.	Infleqtion	Louisville, CO, USA	Private	2007	Neutral Atoms / Digital	February 2024	medium
28.	Intel	Santa Clara, CA, USA	Public	1968	Silicon Spin / Digital		
29.	IonQ	College Park, MD, USA	Public	2015	Trapped Ions / Digital	June 2024	high
30.	IQM Quantum Computers	Espoo, Finland	Private	2018	Superconducting / Digital	November 2024	high
31.	Microsoft	Redmond, WA, USA	Public	1975	Topological / Digital	June 2023	medium
32.	NanoQT	Tokyo, Japan	Private	2020	Neutral Atoms / Digital		
33.	NEC	Tokyo, Japan	Public	1899	Superconducting / Annealing		
34.	neQxt GmbH	Erlenbach am Main, Bavaria, Germany	Private	2022	Trapped Ions / Digital		
35.	Nokia Bell Labs	New Providence, NJ, USA	Public	1925	Topological / Digital		
36.	Nord Quantique	Sherbrooke, QB, Canada	Private	2020	Superconducting / Digital		
37.	Norma	Seoul, South Korea	Private	2011	Superconducting / Digital		
38.	ORCA Computing	London, England, UK	Private	2019	Photonic / Analog		
39.	Origin Quantum	Hefei, Anhui, China	Private	2017	Superconducting / Digital		
40.	Oxford Ionics	Oxford, England, UK	Private	2019	Trapped Ions / Digital		
41.	Oxford Quantum Circuits	Reading, England, UK	Private	2017	Superconducting / Digital		

42.	Pasqal	Palaiseau, Île-de-France, France	Private	2019	Neutral Atoms / Analog	June 2024	high
43.	Photonic	Coquitlam, BC, Canada	Private	2016	Silicon Spin / Digital		
44.	Planckian	Pisa, Italy	Private	2021	Superconducting / Digital		
45.	planqc	Garching, Bavaria, Germany	Private	2022	Neutral Atoms / Digital		
46.	PsiQuantum	Palo Alto, CA, USA	Private	2016	Photonic / Analog	2021	medium
47.	QC82	College Park, MD, USA	Private	2020	Photonic / Analog		
48.	Qilimanjaro Quantum Tech	Barcelona, Catalonia, Spain	Private	2019	Superconducting / Analog		
49.	Qolab	Los Angeles, CA, USA	Private	2022	Superconducting / Digital		
50.	QuamCore	Modi'in-Maccabim-Re'ut, Israel	Private	2022	Superconducting / Digital		
51.	Quandela	Palaiseau, Île-de-France, France	Private	2017	Photonic / Analog	October 2024	high
52.	Quanfluence	Bangalore, India	Private	2021	Photonic / Analog		
53.	Quantinuum	Broomfield, CO, USA	Private	2021	Trapped Ions / Digital	September 2024	medium
54.	Quantum Art	Ness Ziona, Israel	Private	2022	Trapped Ions / Digital		
55.	Quantum Brilliance	Haymarket, NSW, Australia	Private	2019	NV Centers in Diamond / Digital		
56.	Quantum Circuits Inc.	New Haven, CT, USA	Private	2015	Superconducting / Digital		
57.	Quantum Motion	London, England, UK	Private	2017	Silicon Spin / Digital		
58.	Quantum Silicon	Edmonton, AB, Canada	Private	2011	Silicon Spin / Digital		
59.	Quantum Source	Rehovot, Israel	Private	2021	Photonic / Analog		
60.	QuantWare	Delft, Netherlands	Private	2021	Superconducting / Digital		
61.	QuDoor	Beijing, China	Private	2016	Trapped Ions / Digital		
62.	QUDORA Technologies	Braunschweig, Lower Saxony, Germany	Private	2020	Trapped Ions / Digital		
63.	QuEra	Boston, MA, USA	Private	2020	Neutral Atoms / Analog	November 2023	medium
64.	QuiX Quantum	Enschede, Netherlands	Private	2019	Photonic / Analog		

65.	Quobly	Grenoble, Auvergne-Rhône-Alpes, France	Private	2022	Silicon Spin / Analog		
66.	Quoherent	Huntsville, AL, USA	Private	2021	Topological / Digital		
67.	Rigetti Computing	Berkeley, CA, USA	Public	2013	Superconducting / Digital	November 2024	medium
68.	Rosatom State Corporation	Moscow, Russia	Private	2007	Trapped Ions / Digital Neutral Atoms / Digital Superconducting / Digital		
69.	SaxonQ	Leipzig, Lower Saxony, Germany	Private	2021	NV Centers in Diamond / Digital		
70.	SeeQC	Elmsford, NY, USA	Private	2018	Superconducting / Digital		
71.	SemiQon	Espoo, Finland	Private	2023	Silicon Spin / Digital		
72.	Shenzhen SpinQ Technology	Shenzhen, Guangdong, China	Private	2018	Superconducting / Digital NMR / Analog		
73.	Silicon Quantum Computing	Sydney, NSW, Australia	Private	2017	Silicon Spin / Digital	2023	low
74.	Terra Quantum AG	St. Gallen, Switzerland	Private	2019	Superconducting / Digital		
75.	TreQ	London, England, UK	Private	2023	Superconducting / Digital		
76.	TuringQ	Shanghai, China	Private	2021	Photonic / Analog		
77.	Universal Quantum	Haywards Heath, England, UK	Private	2018	Trapped Ions / Digital		
78.	Xanadu	Toronto, ON, Canada	Private	2016	Photonic / Analog		
79.	XeedQ GmbH	Ulm, Baden-Württemberg, Germany	Private	2021	NV Centers in Diamond / Digital		
80.	ZuriQ	Zürich, Switzerland	Private	2024	Trapped Ions / Digital		

Appendix B: Countries in Geographic Regions

AMER – North, Central, and South America

Anguilla, Antigua and Barbuda, Argentina, Aruba, Barbados, Belize, Bermuda, Bolivia, Brazil, British Virgin Islands, Canada, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Greenland, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, The Bahamas, Trinidad and Tobago, Turks and Caicos Islands, U.S. Virgin Islands, United States, Uruguay, Venezuela

APAC – Asia-Pacific

Afghanistan, Australia, Bangladesh, Bhutan, Brunei, Cambodia, China, Cook Islands, Fiji, India, Indonesia, Japan, Kiribati, Laos, Malaysia, Maldives, Marshall Islands, Micronesia, Mongolia, Myanmar, Nepal, New Caledonia, New Zealand, Niue, North Korea, Pakistan, Palau, Papua New Guinea, Philippines, Singapore, Solomon Islands, South Korea, Sri Lanka, Thailand, Timor-Leste, Tonga, Tuvalu, Vanuatu, Vietnam

APME – Asia Pacific and Middle East

Australia, Bahrain, Bangladesh, Bhutan, Brunei, Cambodia, China, Fiji, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Kiribati, Kuwait, Laos, Lebanon, Malaysia, Maldives, Marshall Islands, Micronesia, Mongolia, Myanmar (Burma), Nauru, Nepal, New Zealand, North Korea, Oman, Pakistan, Palau, Papua New Guinea, Philippines, Qatar, Samoa, Saudi Arabia, Singapore, Solomon Islands, South Korea, Sri Lanka, Syria, Taiwan, Thailand, Timor-Leste, Tonga, Tuvalu, United Arab Emirates, Vanuatu, Vietnam, Yemen

EMEA – Europe, Middle East, and Africa

Albania, Algeria, Andorra, Angola, Armenia, Austria, Azerbaijan, Bahrain, Belarus, Belgium, Benin, Bosnia and Herzegovina, Botswana, Bulgaria, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Croatia, Cyprus, Czech Republic, Denmark, Djibouti, Egypt, Equatorial Guinea, Eritrea, Estonia, Eswatini, Ethiopia, Faroe Islands, Finland, France, Gabon, Gambia, Georgia, Germany, Ghana, Gibraltar, Greece, Guernsey, Guinea, Guinea-Bissau, Hungary, Iceland, Iran, Iraq, Ireland, Isle of Man, Israel, Italy, Ivory Coast, Jersey, Jordan, Kenya, Kuwait, Latvia, Lebanon, Lesotho, Liberia, Libya, Liechtenstein, Lithuania, Luxembourg, Macedonia, Madagascar, Malawi, Mali, Malta, Mauritania, Mauritius, Moldova, Monaco, Montenegro, Morocco, Mozambique, Namibia, Netherlands, Niger, Nigeria, Norway, Oman, Palestine, Poland, Portugal, Qatar, Romania, Russia, Rwanda, San Marino, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Slovakia, Slovenia, Somalia, South Africa, Spain, Sudan, Sweden, Switzerland, Syria, Tanzania, Togo, Tunisia, Turkey, Uganda, Ukraine, United Arab Emirates, United Kingdom, Vatican City, Western Sahara, Yemen, Zambia, Zimbabwe

EU – European Union

Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden

LATAM – Latin America

Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela

NA – North America

Antigua and Barbuda, Bahamas, Barbados, Belize, Canada, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, United States

OC – Oceania

Australia, New Zealand, Papua New Guinea, Fiji, Solomon Islands, Vanuatu, Samoa, Kiribati, Tonga, Micronesia, Marshall Islands, Palau, Tuvalu, Nauru

Appendix C: Glossary of Terms

Analog paradigm

Analog quantum computing is a paradigm that leverages continuous quantum systems to perform computations, in contrast to the discrete gate operations used in digital quantum computing. This approach utilizes quantum components such as neutral atoms, trapped ions, or photonic circuits to directly simulate physical processes. In analog quantum computing, qubits are manipulated through continuous interactions, such as laser-induced couplings or magnetic field gradients, allowing for a more direct mapping between the quantum computer and the physical system being simulated. Photonics-based analog quantum computers use light to process information, taking advantage of the quantum properties of photons. The continuous nature of analog quantum computing offers potential advantages in efficiency for certain tasks, but also presents challenges in managing noise and implementing error correction. (*Source:* Perplexity)

Annealing paradigm

Quantum annealing is a specialized quantum computing technique designed to solve complex optimization problems. It leverages quantum mechanics principles, particularly superposition and quantum tunneling, to explore a vast solution space efficiently. The process begins with qubits in a superposition state, representing all possible solutions simultaneously, and then slowly evolves the system towards a final state that corresponds to the optimal or near-optimal solution. During this evolution, the system's energy landscape is manipulated through a carefully controlled Hamiltonian, guiding the qubits towards the lowest energy state. At the end of the annealing process, the qubits collapse into classical states, providing a solution to the original problem. (*Source:* Perplexity)

Carbon Nanotube modality

Carbon nanotube quantum computing is an emerging modality that utilizes the unique properties of carbon nanotubes to create and manipulate qubits. These nanotubes, which are cylindrical structures of carbon atoms, offer exceptional characteristics such as minimal charge noise, high stability, and the ability to protect qubits from environmental interference. The one-dimensional nature of carbon nanotubes allows for precise alignment of qubits along their length, potentially enabling scalable quantum processors with numerous qubits. This approach leverages the nanotubes' ability to bridge quantum and classical mechanics, creating an ideal environment for quantum operations. Carbon nanotube-based qubits have demonstrated promising coherence times and could potentially operate at higher temperatures compared to other quantum computing modalities. (*Source:* Perplexity)

Digital paradigm

Digital quantum computing is a paradigm that utilizes quantum bits, or qubits, as the fundamental units of information processing. Unlike classical bits, qubits can exist in multiple states simultaneously due to the principle of superposition, allowing for parallel computation. This approach employs discrete quantum gates to manipulate and entangle qubits, enabling complex quantum operations. Digital quantum computers leverage quantum interference to amplify desired outcomes while canceling out others, potentially offering exponential speedups for certain algorithms. However, maintaining qubit coherence and minimizing errors remain significant challenges in developing practical, large-scale digital quantum systems. (*Source:* Perplexity)

modality

In quantum computing, a modality refers to the specific physical implementation or technology used to create and manipulate qubits, the fundamental units of quantum information. Different modalities utilize various physical systems to represent qubits, such as superconducting circuits, trapped ions, neutral atoms, silicon quantum dots, or photons. Each modality has its own unique characteristics, advantages, and challenges in terms of qubit control, coherence time, scalability, and error rates. The choice of modality significantly influences the design, operation, and performance of a quantum computer, as well as the types of quantum gates and operations that can be efficiently implemented. As the field of quantum computing advances, researchers continue to explore and refine various modalities to improve the overall capabilities and reliability of quantum systems. (*Source:* Perplexity)

Neutral Atoms modality

Neutral atom quantum computing utilizes individual uncharged atoms, typically alkali elements like rubidium or cesium, as qubits. These atoms are trapped and manipulated using laser beams, which act as optical tweezers to arrange them in precise configurations. The quantum states of these atoms, such as their energy levels or spin orientations, are controlled and manipulated to perform quantum operations. Neutral atom platforms offer inherent scalability due to the atoms' lack of strong interactions with each other, allowing for the potential creation of large qubit arrays. Stationary qubits remain fixed in their positions, while shuttled qubits can be coherently moved within the computing array, enabling any qubit to interact with any other regardless of their original positions, thus enhancing the system's flexibility and connectivity. (*Source:* Perplexity)

NMR modality

Nuclear Magnetic Resonance (NMR) quantum computing utilizes the spin states of atomic nuclei in molecules as qubits. This approach involves placing these molecules in a strong magnetic field and manipulating the nuclear spins using precisely tuned radio-frequency pulses. NMR quantum computers operate at room temperature and leverage the quantum properties of large ensembles of molecules, typically in a liquid solution. The qubits in NMR quantum computing are controlled and read out through sophisticated pulse sequences that exploit the interactions between nuclear spins. While NMR quantum computing has demonstrated the implementation of basic quantum algorithms, it faces challenges in scalability and maintaining quantum coherence for extended periods. (*Source:* Perplexity)

NV Centers in Diamond modality

NV centers in diamond are quantum systems created when a nitrogen atom replaces a carbon atom in the diamond lattice, with an adjacent vacancy. These defects exhibit spin states that can be manipulated and read out using optical and microwave pulses, functioning as qubits. NV centers offer long coherence times, even at room temperature, and can be controlled with high precision using electromagnetic fields. The solid-state nature of diamond allows for the integration of NV centers with nanofabricated structures, enabling scalable quantum devices. This quantum computing modality combines atom-like properties with the robustness of a solid-state platform, making it a promising candidate for quantum information processing. (*Source:* Perplexity)

paradigm

In quantum computing, a paradigm refers to a specific approach or model for designing and implementing quantum computers. These paradigms encompass different physical implementations, computational models, and methods for manipulating quantum information. Examples of quantum computing paradigms include digital gate-based quantum computing, quantum annealing, and analog quantum computing, each with its own unique principles and challenges. Different paradigms use various physical systems to represent qubits, such as superconducting circuits, trapped ions, or photons, and employ distinct techniques for quantum state manipulation and error correction. The diversity of quantum computing paradigms reflects the ongoing exploration of multiple paths towards realizing practical and scalable quantum computers, with each approach offering distinct advantages and trade-offs in terms of qubit control, coherence time, and computational capabilities. (*Source:* Perplexity)

Photonic modality

Photonic quantum computing uses particles of light, or photons, as qubits to perform quantum computations. This approach leverages the unique properties of photons, such as their ability to maintain coherence over long distances and operate at room temperature. Photonic quantum computers manipulate qubits using optical components like beam splitters, phase shifters, and interferometers, with quantum information typically encoded in photon properties such as polarization or presence/absence in a given mode. One of the main challenges in photonic quantum computing is creating two-qubit gates, as photons do not naturally interact with each other, leading to the development of techniques like measurement-induced nonlinearity and cluster-state quantum computing. (*Source:* Perplexity)

qubit

A qubit, short for quantum bit, is the fundamental unit of information in quantum computing, analogous to the classical bit in traditional computers. Unlike classical bits that can only be in a state of 0 or 1, qubits can exist in a superposition of both states simultaneously, allowing them to represent and process multiple values at once. Qubits can be created using various physical systems, such as the spin of electrons, the polarization of photons, or superconducting circuits. The unique properties of qubits, including superposition and entanglement, enable quantum computers to perform certain calculations exponentially faster than classical computers. However, qubits are extremely fragile and sensitive to their environment, requiring sophisticated techniques to maintain their quantum states and mitigate errors. (*Source:* Perplexity)

Silicon Spin modality

Silicon spin quantum computing utilizes the spin states of individual electrons or atomic nuclei in silicon as qubits. This approach leverages existing semiconductor fabrication techniques, potentially allowing for scalable qubit production using familiar CMOS technology. Silicon spin qubits can be implemented in two main forms: quantum dot spin qubits, where electrons are confined in transistor-like structures, and donor spin qubits, which use dopant atoms embedded in the silicon lattice. These qubits benefit from the exceptionally clean environment of isotopically purified silicon, resulting in long coherence times. Recent advancements have demonstrated high-fidelity single- and two-qubit gates, with researchers successfully operating a six-qubit quantum processor in silicon. (*Source:* Perplexity)

Superconducting modality

Superconducting quantum computing utilizes artificial atoms created from superconducting circuits as qubits. These qubits operate based on the principles of quantum superposition and entanglement, typically using Josephson junctions to create two distinct energy states. The system requires extremely low temperatures, often close to absolute zero, to maintain quantum coherence and minimize decoherence effects. Superconducting qubits can be manipulated using microwave pulses or magnetic fields, allowing for precise control of quantum states and operations. This modality offers advantages in scalability and compatibility with existing semiconductor manufacturing technologies, making it a prominent approach in the development of quantum processors. (*Source:* Perplexity)

Superfluid Helium modality

Superfluid Helium quantum computing is an innovative approach that utilizes electrons floating above a layer of liquid helium cooled to near absolute zero. In this system, the electrons serve as qubits, leveraging their charge and spin states to store and manipulate quantum information. The superfluid helium provides a defect-free environment, allowing electrons to move freely across its surface with minimal interference, resulting in exceptionally long coherence times. Researchers have proposed using an array of tiny ferromagnetic pillars to trap electrons above the helium, potentially enabling the creation of millions of uniform qubits in a compact area. This quantum computing modality combines the advantages of solid-state systems with the purity of a vacuum, offering a promising platform for scalable quantum processors. (*Source:* Perplexity)

Topological modality

Topological quantum computing is a unique approach that leverages the principles of topology to create more stable and fault-tolerant qubits. This method uses exotic quasiparticles called anyons, which can exist in two-dimensional systems, to store and manipulate quantum information. The quantum states are encoded through a process called braiding, where anyons are moved around each other in specific patterns, creating a topologically protected state that is highly resistant to decoherence and environmental noise. Researchers are particularly interested in Majorana zero modes, a type of non-Abelian anyon, as potential building blocks for topological qubits. By utilizing the non-local nature of topological states, this approach offers the potential for more reliable quantum computations compared to other quantum computing modalities. (*Source:* Perplexity)

Trapped Ions modality

Trapped-ion quantum computing uses individual ions, or charged atomic particles, as qubits. These ions are confined and suspended in free space using electromagnetic fields, typically in a device called a Paul trap. Qubits are stored in stable electronic states of each ion, and quantum information can be transferred through the collective quantized motion of the ions in a shared trap. Lasers are applied to induce coupling between the qubit states for single-qubit operations or to create entanglement between qubits. This approach offers several advantages, including long coherence times, high-fidelity quantum gates, and the potential for scalability to larger numbers of qubits. (*Source:* Perplexity)