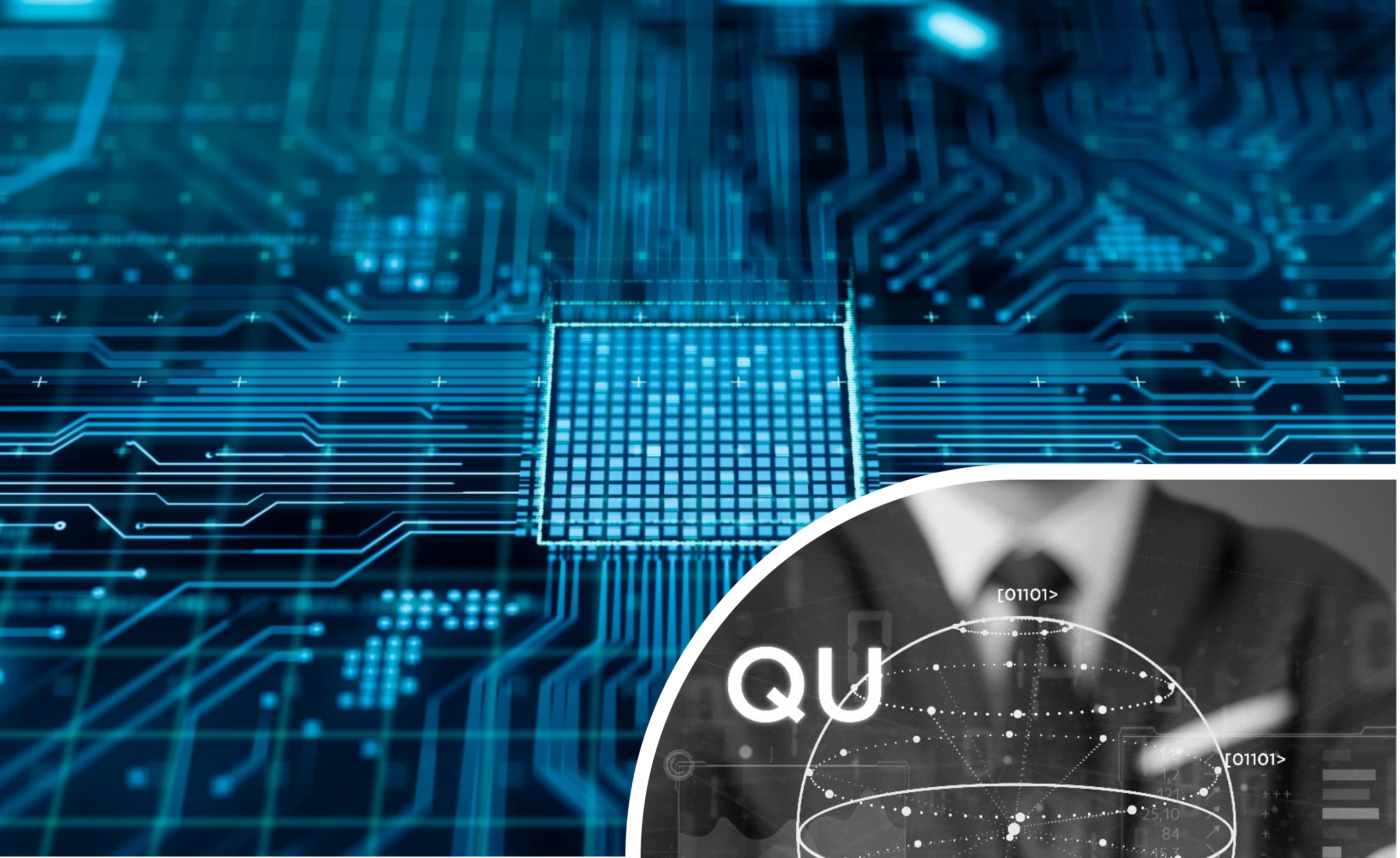

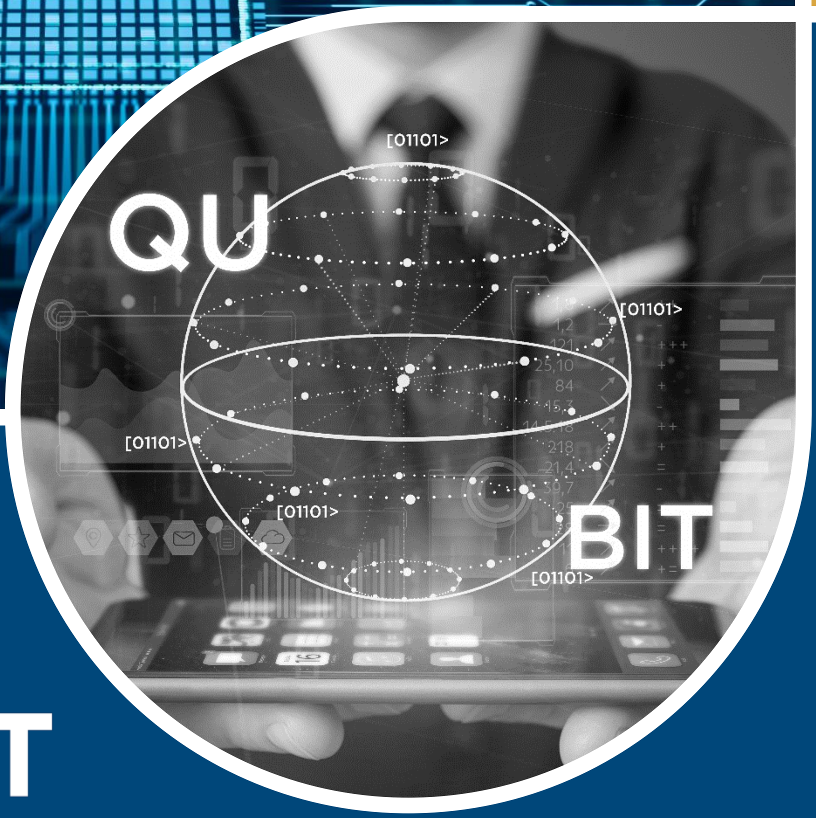

Quantum Computing:
Will There Be a Domino Effect?

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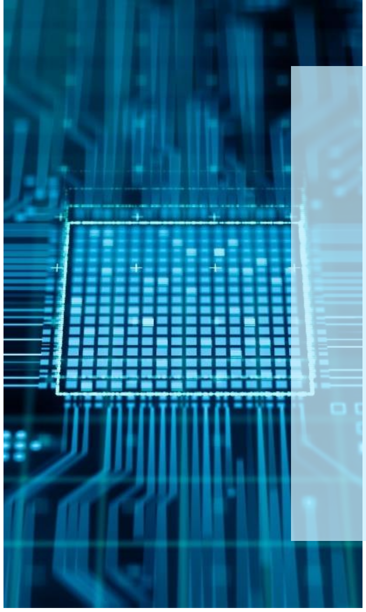


Executive Summary

Quantum technologies—those based on the concepts of quantum physics—have three product categories in play: high-performing quantum computing devices, secure quantum communication systems, and extremely accurate quantum sensing devices. These products utilize phenomena of quantum physics (superposition, entanglement, squeezed states, and decoherence) and are expected to have multiple real-world applications across chemistry and life sciences, cryptography, aviation, logistics, financial services, and government and defense.

Among the three technologies, quantum computing has made significant advances recently and made its way into wide variety of businesses. After nearly eight decades of research in the field, the buzz in quantum computing is no longer limited to academia and research labs. Investments have scaled rapidly in the last 3 years. A surge in investments has led to the emergence of more than 100 start-ups in the space; of these, more than a third already have a working product. With their demonstrated early success, start-ups with an operational product have raised more than $4 billion.

At their current stage of development, quantum computing devices are small in scale and—though useful for research (for example, understanding molecule- and sub-molecule-level interactions, which can lead to breakthroughs in life sciences and chemistry)—are not yet ready for real-world problems. However, within a few years, given the surge of start-ups, rapid pace of technology development, and rising investor confidence, quantum computing is expected to solve problems that are beyond the reach of classical computational methods. Early breakthroughs are expected in logistics and manufacturing optimization, supercharging machine learning, and financial modeling. By the end of this decade, quantum computing may find practical uses in a broad range of applications, including drug discovery, chemistry simulation, and random-number generation. Five promising hardware technologies—superconducting qubits, trapped ions, neutral atom arrays, silicon photonics, and spin-based quantum dots—have emerged, each with its unique set of promises and challenges. With hardware spanning five platforms, software providers have adopted two different approaches: (1) hardware-agnostic software with algorithms across different platforms to eliminate the need for gate-level programming; and (2) software for both classical and quantum computing, which brings improved applications sooner without big investments in quantum computing hardware.

As the technology develops, multiple players are paving the path for commercialization. Software companies are exploring quantum algorithms with enterprises via joint research. Multiple companies have been set up as or are evolving into full-stack providers to understand end-customer needs while also working on their hardware technology.

Hardware-focused companies are getting a few steps closer to end-users by forging partnerships or merging with software and algorithm companies that already have a prestigious list of enterprise customer relationships. Multiple large enterprises are engaged in developing use cases with providers for identified business problems. The major cloud players (Amazon AWS, Google Cloud, and Microsoft Azure) have entered the quantum computing ecosystem by partnering with quantum computing hardware providers to offer their qubit systems via their cloud services.

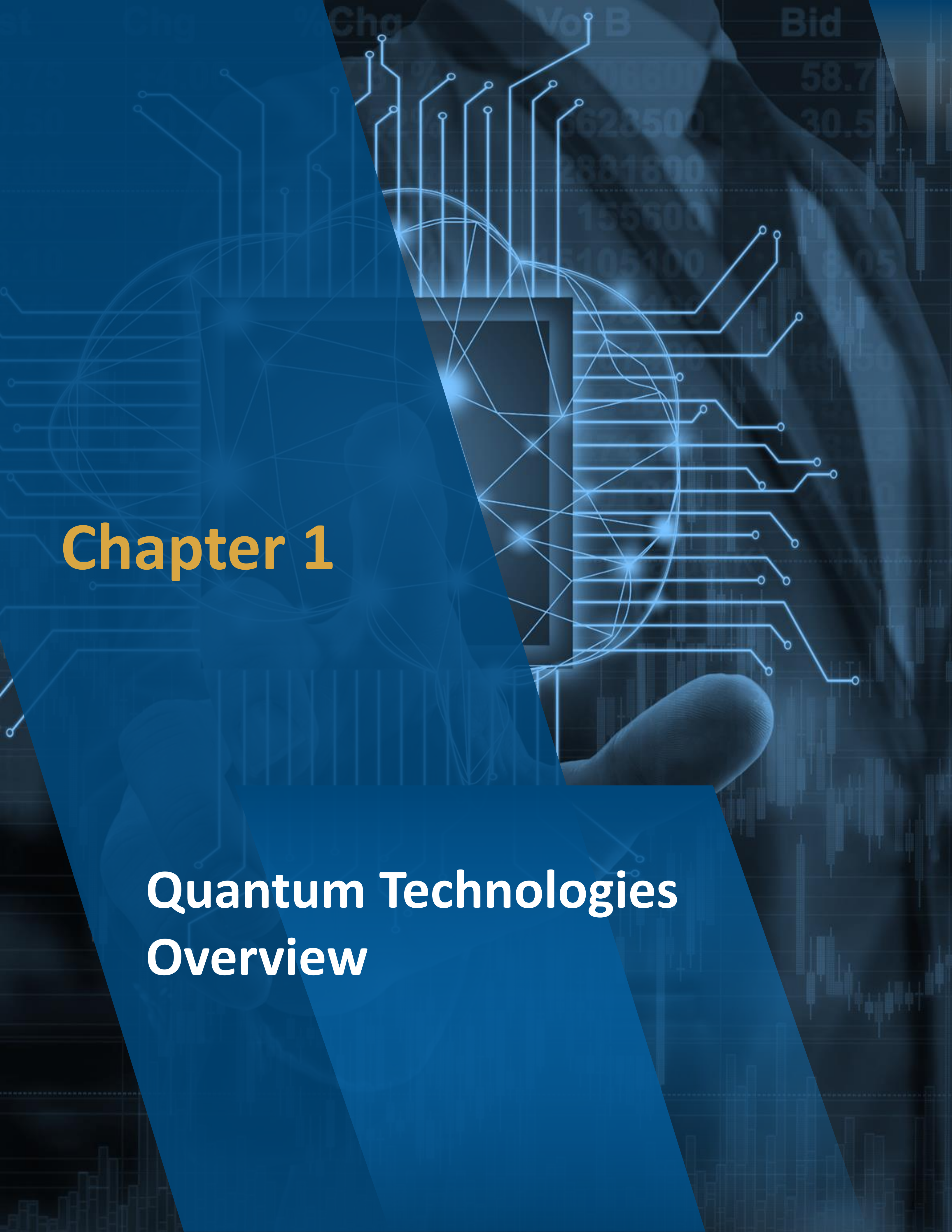
Even as companies engage in healthy competition to be the first to achieve quantum advantage, the industry is expected to undergo consolidation. Quantum providers are forming alliances with enterprises and institutes to speed up development of a scalable commercial quantum computer. Industry experts and providers forecast an upcoming wave of consolidation in the quantum space, driven by the need to accelerate business development and customer acquisition, co-design next-generation hardware and software products for specific markets, and combine resources for more economies of scale and best-in-class talent.

We also see greater maturity in the quantum computing industry's participants. Fernweh has developed a maturity index to describe industry players based on the state of their technology, the maturity of quantum players, the engagement of large ecosystem players (e.g., tech giants like Amazon, Google, IBM, and Microsoft), and the level of investor support. According to the index, maturity has been increasing, a trend expected to continue during this decade. Already qubits have scaled up to 100, and they are expected to reach 1,000 or more by 2025 and a million or more by 2030. We expect to see more pure-play quantum computing companies receive higher funding and even go public and greater involvement of enterprises and investors.

However, for quantum computing to achieve widespread adoption, the industry will require much more enterprise engagement.

Only a few Fortune 500 companies have committed spending on projects with quantum computing providers. Companies are more willing to provide internal resources for collaborative research with IP development as the primary objective, rather than developing useful applications. In addition, very few enterprises are looking to invest in developing internal expertise and quantum talent, which is likely to hinder their understanding of which parts of their businesses can benefit from quantum technologies. More robust engagement will be necessary to set off a wave of growth and observe a domino effect.

For quantum computing to become a widespread phenomenon with commercial applications across a broad range of sectors, multiple stakeholders will need to influence the shaping of the market. Quantum computing providers must be more oriented to end users and adopt a full-stack strategy with more hardware-software collaboration to develop compelling apps for practical use cases. Enterprises must commit much more spending to R&D projects with providers and invest in development of quantum skills. Governments need to facilitate establishment of international supply chains for components and invest in start-ups, not just in academia. Investors should become long-term partners to start-ups and engage in technology development.



Chapter 1

Quantum Technologies Overview

Quantum Technologies Overview

Quantum technologies are those that use concepts of quantum physics—that is, the effects of the wave properties observed in tiny particles such as electrons, photons, and quarks. The world we perceive every day is governed by certainty; for example, things can be in only one place at a given time. But the world of quantum physics is based on uncertainty and chance, so quantum physics uses mathematics to predict how the particles will act and interact.

This chapter offers basic background on the various quantum technologies. It begins by describing the major product categories and the underlying technology that is expected to make such products feasible. Next, we describe some potential applications that are already being pursued. Since quantum computing is a key growth area in the larger sphere of quantum technologies, later chapters will narrow the focus to that specific application of quantum technology.

PRODUCT CATEGORIES

In academia, researchers learned to exploit these characteristics of quantum physics in light and materials, resulting in the invention of the laser and transistor; these developments, known as the "first quantum revolution," went on to become the basis for today's information technology. Until recently, it was largely regarded as impossible to control individual quantum systems such as atoms, electrons, or photons. But now that this is occurring in laboratories, the door is open to a second quantum revolution, offering entirely new possibilities.

Products now being developed fall into three major categories: quantum computing, quantum communications, and quantum sensing. These offer the potential of faster and more secure computing and more precise measurement.

Quantum Computing

Quantum computing harnesses the phenomena of quantum mechanics to deliver higher computational power than classical supercomputers. The basic building block and unit of information in a quantum computer is a quantum bit or qubit. In a classical computer, the information is encoded in bits, where each bit can have the value 1 or 0. A qubit can be in the state 1 or 0 or unlike a classical bit in a linear combination of both states.

Once the technology is fully mature and developed, quantum computing is expected to perform any task faster and more accurately compared to a classical computer.

For example, quantum computing is expected to be useful in tasks such as breaking cryptographic algorithms and simulating new materials. In general, it is expected to be well suited for processes that tax the limits of classical computing, like warehouse management and transportation logistics.

At this time, however, state-of-the-art quantum computing devices are limited by noise and lack error correction. Therefore, no commercial applications have yet been deployed.

Quantum Communications

Quantum communication applies to data transmission. Since the laws of physics allow qubits to represent multiple combinations of zero and one simultaneously, the large number of possible combinations offers great bandwidth potential for communication. Moreover, and measurement of qubits irreversibly changes them, endowing them with inherent security. For example, if a message is transmitted with a key that is 128 bits long, there are 2^{128} possibilities of the key used. As a result, quantum-based channels could become capable of helping companies share more information with greater security. In systems that use single photons (light quanta) as information carriers, cryptographic keys can be distributed between distinct users, and the laws of quantum physics guarantee the security of the keys. Such systems can be used for refreshing cryptographic keys in encryption systems without using vulnerable classical solutions or manual changes of keys.

Quantum Sensing

Quantum sensing utilizes quantum states for more precise measurements of various parameters, such as magnetic field, time, and temperature. It capitalizes on the fact that quantum states are extremely sensitive to disturbances. This also means that they have the potential to become extraordinarily sensitive measuring instruments. Measurement devices that leverage quantum properties have been around for a while, for example, atomic clocks, laser distance meters and magnetic resonance imaging (MRI) used for medical diagnosis. For MRI, the newest advancements in quantum systems enhance the sensitivity and improve accuracy, giving physicians a clearer picture of the patient's body. The technology extracts information from individual atoms, which can be much more precise than just measuring a group of atoms.

UNDERLYING TECHNOLOGY: QUANTUM PHYSICS

The underlying technology of quantum technologies is quantum physics, as mentioned at the beginning of the chapter. The technology applies four phenomena of quantum physics: superposition, entanglement, squeezed states, and decoherence (Exhibit 1).[1]

Exhibit 1

Phenomena underlying quantum technologies

QUANTUM PHENOMENA	KEY APPLICATIONS
Superposition: Condition of a particle being in more than one state (e.g., position) at a given time	Storing vast amounts of information
Entanglement: Superposition of multiple particles that results in strong correlations between them, even though the individual particles can be random	Processing vast amounts of information for computing; creating extremely secure communication systems
Squeezed state: Condition in which a quantum state has been manipulated so a particle's position or velocity is relatively certain	Designing highly sensitive measuring instruments
Decoherence: Process in which disturbances to a system cause superposition to diminish and finally collapse	A major challenge to overcome; no key applications

Source: "The Central Phenomena of Quantum Technology," Chalmers University Wallenberg Centre for Quantum Technology, Nov. 27, 2017, https://www.chalmers.se.; SIT & Jacobs University Insights in Technology 2021.

[1] "The Central Phenomena of Quantum Technology," Chalmers University Wallenberg Centre for Quantum Technology, November 27, 2017, https://www.chalmers.se.

Superposition

Throughout the day, we consciously or unconsciously observe that physical objects, whether our computers or our own bodies, can exist in only one state of existence at one time. While this seems obvious, quantum physics has found that simple particles can be in more than one state at a given time. Electrons spinning around an atom's nucleus can be both here and there, and a light particle, or photon, can travel along two different paths at the same time. Such composite conditions are called *superpositions*.

When a measurement is made, the particle is forced into one of the possible alternatives. Chance determines which alternative, so the mathematics of probability comes into play. Employing this knowledge, scientists see superposition as a means of enabling the storage and processing of vast quantities of information.

Entanglement

Superposition involving two or more different particles becomes a condition scientists call *entanglement*. Two particles are said to be entangled when one of them cannot be perfectly described without including all the information about the other one. The "connection" between the two particles is this condition in which they are not independent of one another.

Quantum entanglement is at the heart of the nascent fields of quantum computing and quantum communications. It could be used as the basis of extremely secure networks.

In particular, measuring the amount of correlation between entangled objects in a communication system can provide proof that the system is safe from eavesdropping.

Squeezed States

A cornerstone of quantum physics is Heisenberg's uncertainty principle, which states that there is a limit to the precision with which, say, the position and velocity of a particle can be known at the same time. Normally, the uncertainty is split equally between the two variables of position and velocity. However, scientists can manipulate the quantum system to ensure that the uncertainty mainly affects just one of the variables, a condition called a *squeezed state.*

In a squeezed state, it becomes possible to measure the second variable with extremely high precision. This ability can be used for designing highly sensitive measuring instruments.

Decoherence

States of superposition are very sensitive to disturbances, which can cause the superposition to diminish and finally collapse. Scientists call this process *decoherence*. In decoherence, the quantum characteristics used for quantum technologies disappear.

Decoherence presents one of the greatest challenges in developing and deploying quantum technologies. The technologies require manipulating a system, but manipulation conflicts with isolating the system to avoid decoherence. The larger the system, the greater the problems with decoherence.

POTENTIAL APPLICATIONS

Once quantum technologies have further matured, as described in the next chapter, they have potential for a wide variety of real-world applications in diverse industry sectors. The most applications have been identified for quantum computing, and quantum sensing is still at the stage where research is more speculative.

In quantum computing, companies engaged in chemistry and life sciences may use the technology to improve the efficiency of drug discovery, thanks to more accurate simulation of atoms and molecules, delivering a better understanding of the body's reactions. In cryptography, quantum computing may make it feasible to break encryption codes[2] that use very large prime-number factorization (300 or more integers), which could result in much stronger protection of digital lives—people's online activities and histories—and digital assets such as databases and documents.

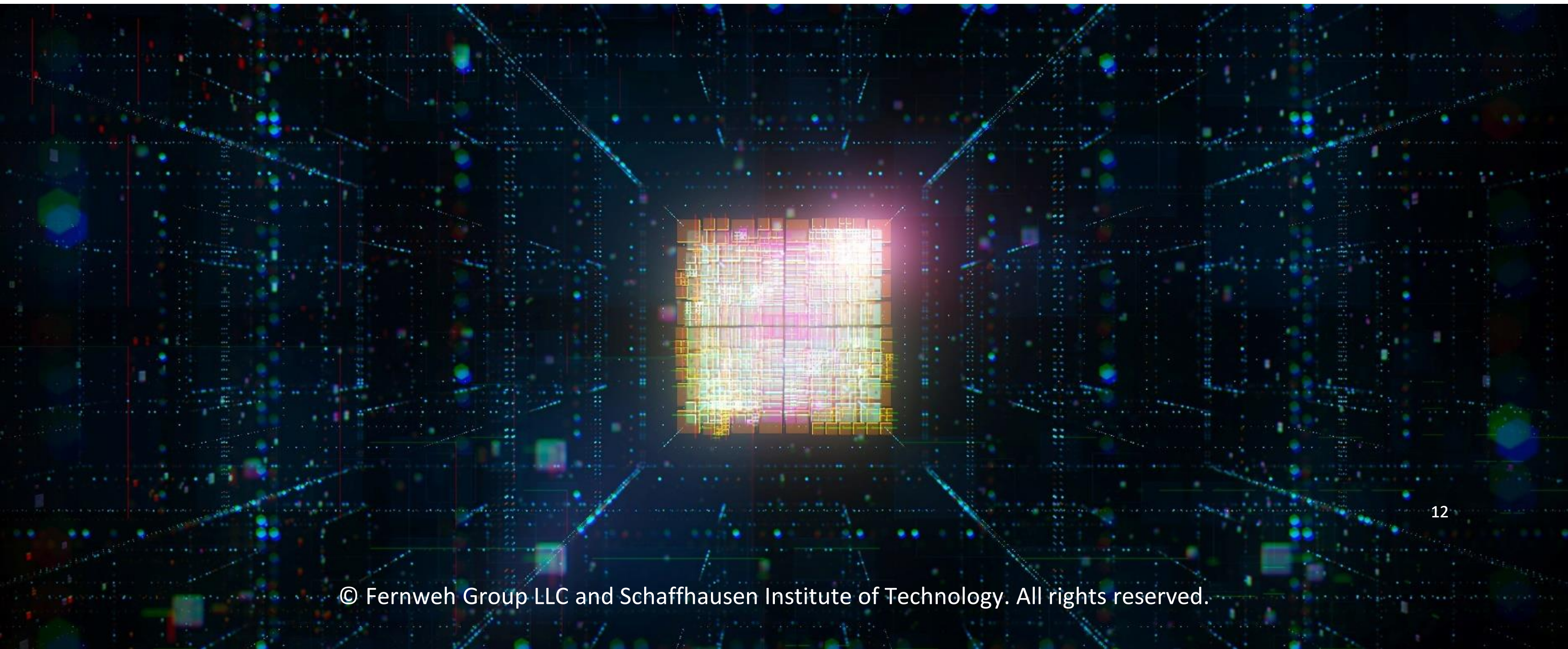
Further applications of quantum computing are in manufacturing, logistics, and financial services. In manufacturing, quantum computing is drawing interest from big players thinking about industrial design. For instance, for someone like Airbus, a quantum computer could filter through countless variables to help determine the most efficient wing design for an airplane. In financial services, quantum computing could use large and complex data sets on market movement to optimize pricing of derivatives. And logistics companies could use quantum computing to improve data analysis and modeling, using robust models to optimize schedules and work flows for supply chain management.

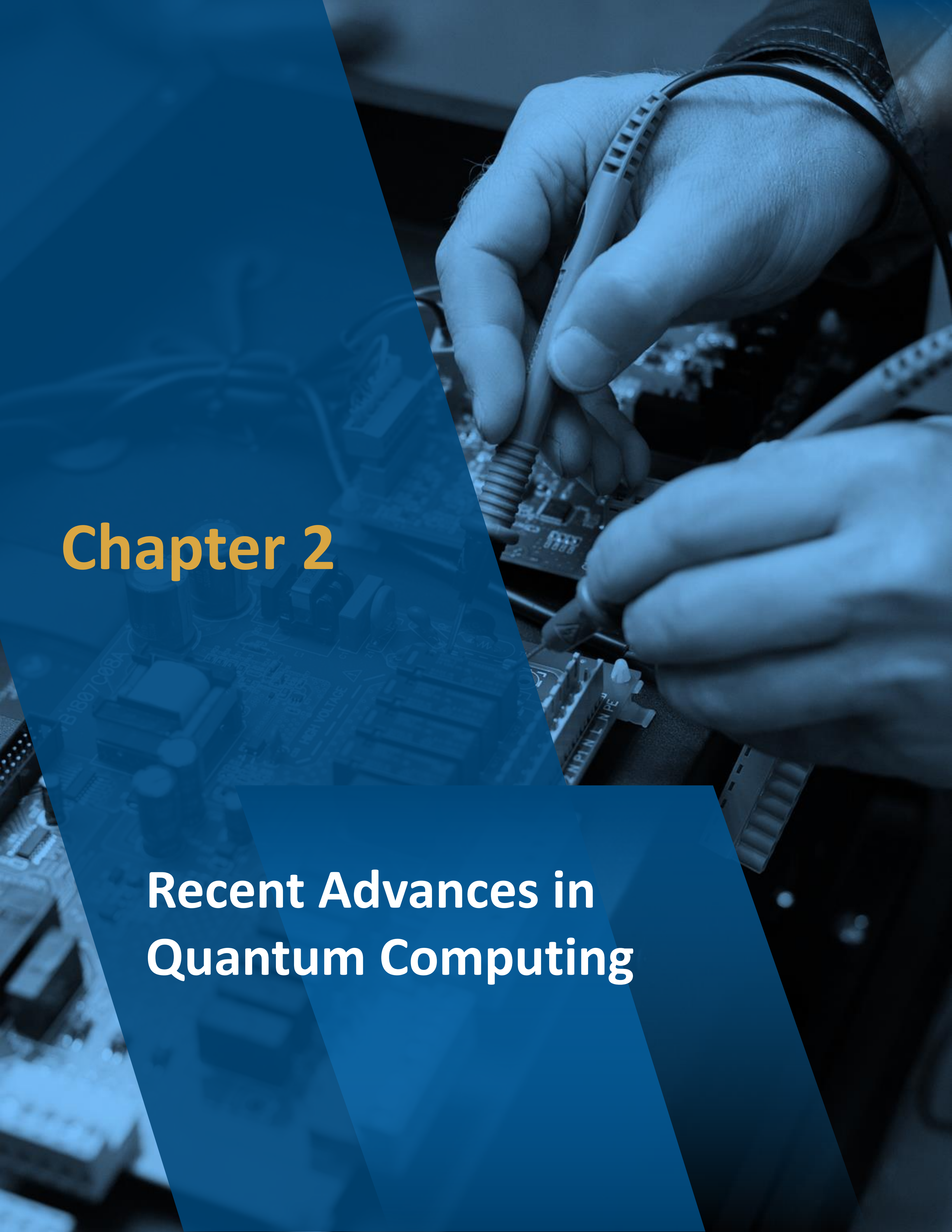
Quantum communications applications may first be used in financial services and in government and defense organizations. For financial services, work is already under way to develop high-security networks and encryption keys to safeguard critical business data, such as credit-card information. Financial-services companies may also use quantum communications to leverage quantum random-number generators that generate keys for security and cryptological applications, such as authentication, digital signatures, and secure access control. For government and defense, quantum communications may enable protection of classified data against cyberattacks through unbreakable quantum key exchange.

[2] Craig Gidney and Martin Ekera, "How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits", May 23, 2019, *Quantum Physics, Cornell University,* https://arxiv.org/abs/1905.09749.

For quantum sensing, the earliest applications could apply to food safety and life sciences. Food safety applications are relevant across the supply chain: detection of contaminants, including pathogens, pesticides, toxic elements, antibiotics, and metals. Life sciences applications involve the early authentic detection of analytes related to medical diagnoses—for example, cancer markers, heart attack markers, allergy markers, blood clotting, antibodies, and hormones.

While the science of quantum physics happens at a level invisible to the human eye, visionaries who have studied the behavior of subatomic particles find potential to use their knowledge for solving extremely complex problems. As the next chapter describes regarding quantum computing, we are witnessing the first steps toward moving these insights from university laboratories into a wide variety of businesses.





Chapter 2

Recent Advances in Quantum Computing

Recent Advances in Quantum Computing

In recent years, quantum computing has swiftly spread from being squarely located within academia to a technology at the heart of many business plans that are now seeking—and often receiving—funds from investors. This chapter provides an overview of progress made in academia and then examines recent trends in investment and the status of industry entrants through the end of 2021.

EIGHT DECADES OF RESEARCH

The concept of a quantum computer germinated from almost 80 years of fundamental academic research[3] on quantum mechanics, going back at least to Albert Einstein's explanation of the photoelectric effect in 1905. Einstein put forth the idea that light consists of quantum particles or photons.

The science of quantum mechanics accelerated in the 1920s. In 1925, physicists Werner Heisenberg, Max Born, and Pascual Jordan formulated matrix mechanics, the first conceptually autonomous and logically consistent formulation of quantum mechanics. Around the same time, Niels Bohr and Werner Heisenberg developed the Copenhagen interpretation, which became the earliest and most widely taught interpretation of quantum mechanics. Their thinking was incorporated in Paul Dirac's book *The Principles of Quantum Mechanics*, a standard reference that is still used today.

Two landmarks in 1935 addressed the quantum phenomenon of superposition. Einstein, Boris Podolsky, and Nathan Rosen published a paper on the counterintuitive nature of quantum superpositions. And Erwin Schrödinger, following discussions of quantum superposition with Einstein, developed the thought experiment today known as Schrödinger's cat.

It was Schrödinger who coined the term quantum entanglement.

In 1959, while a professor at the California Institute of Technology, physicist Richard Feynman described the possibility of using quantum effects for computation. It was a visionary idea that would take decades to demonstrate.

In 1976, Roman Stanisław Ingarden of the Nicolaus Copernicus University in Toruń, Poland, published one of the first attempts at a quantum information theory. Four years later in 1980, mathematician Yuri Manin mentioned in the introduction of his book Computable and Uncomputable the idea of a quantum automaton that used superposition and entanglement. In the same year, Paul Benioff of the Argonne National Laboratory published a paper describing a quantum mechanical model of a computer. In 1981, more than 20 years after expressing his vision of quantum computing, Feynman wrote a paper arguing that a quantum computer had the potential to simulate physical phenomena that a classical computer could not. He proposed a basic model for a quantum computer that would be capable of such simulations and urged the scientist community to build one.

[3] Gil Press, "27 Milestones in the History of Quantum Computing" *Forbes article*, May 18 2021, https://www.forbes.com/sites/gilpress/2021/05/18/27-milestones-in-the-history-of-quantum-computing/?sh=1ffc4b7c7b23

Nature isn't classical, and if you want to make a simulation of nature, you'd better make it quantum mechanical.[4]

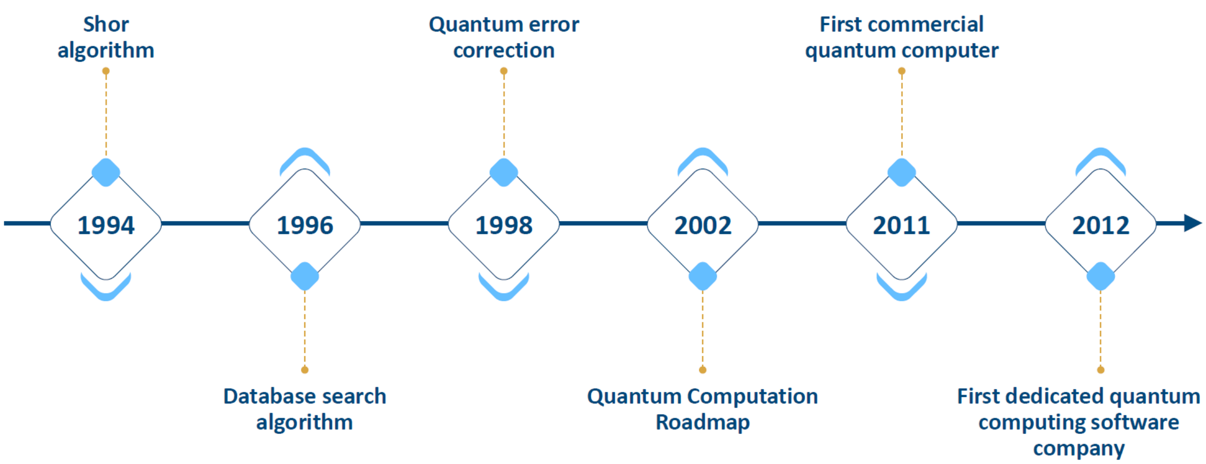
- Richard Feynman

FROM THEORY TO APPLICATION

The move from academia to industry began with research at Bell Laboratories, where Peter Shor in 1994 developed a quantum algorithm to efficiently factor large integers. Shor's algorithm worked exponentially faster than the best algorithms running on classical machines, which would require millions of years to factor a 300-digit number. Theoretically, the Shor algorithm can break many of the cryptosystems used today. For example, it has the potential to decrypt RSA-encrypted communications, a widely used method for securing data transmissions.

The possibility of using quantum computers to break crypto systems in hours rather than millions of years ignited industry interest in quantum computing and its applications (Exhibit 2). In 1996, Lov Grover, a computer scientist at Bell Labs, invented a quantum database search algorithm.

Exhibit 2 Two decades of progress ignited industry interest in quantum computing.



Source: Rebecca Krauthamer, "History of Quantum Computing—a Timeline," Quantum Thought, June 29, 2020, https://www.quthought.com; Markus C Braun, "A Brief History of Quantum Computing," Medium, June 25, 2018, https://medium.com.

Two years later came the first proposition of quantum error correction by Peter Shor. He formulated a quantum error correcting code by storing the information of one qubit onto a highly entangled state of nine qubits.

[4] Richard P. Feynman, "Simulating Physics with Computers," keynote talk, Conference on Physics and Computation," Massachusetts Institute of Technology, 1981, in International Journal of Theoretical Physics 21 (1982): 467–88.

The Quantum Computation Roadmap was first published in 2002. The purpose of the document is to help facilitate the progress of quantum computation research. This is a living document which is updated at least annually.

The next decade brought new entries to the industry side of quantum computing. In 2011, D-Wave Systems announced D-Wave One, described as "the world's first commercially available quantum computer", operating on a 128-qubit chipset using quantum annealing. 1QB Information Technologies became the first dedicated quantum computing software company, founded in 2012.

A SURGE IN INVESTMENTS

Investors have been interested in quantum technology opportunities since at least 2012, with most of the funds flowing to quantum computing, as we will show later in this section.

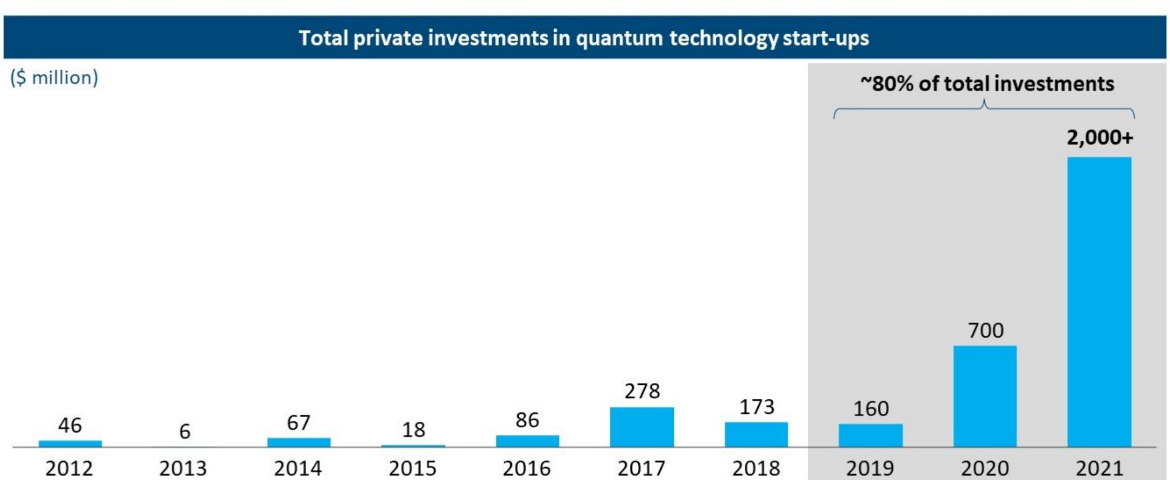
> ***Annual private investments in quantum technology start-ups have surpassed $100 million every year starting in 2017.***

Nearly half of the funding came from venture capitalists, with private investors and corporate investments making up most of the remainder.

Investments surged in 2020 and 2021 (Exhibit 3). In fact, about 80 percent of total private investments in quantum technology start-ups happened in just three years, 2019–21.

Exhibit 3

About 80 percent of private investment in quantum technology start-ups occurred in the past three years.

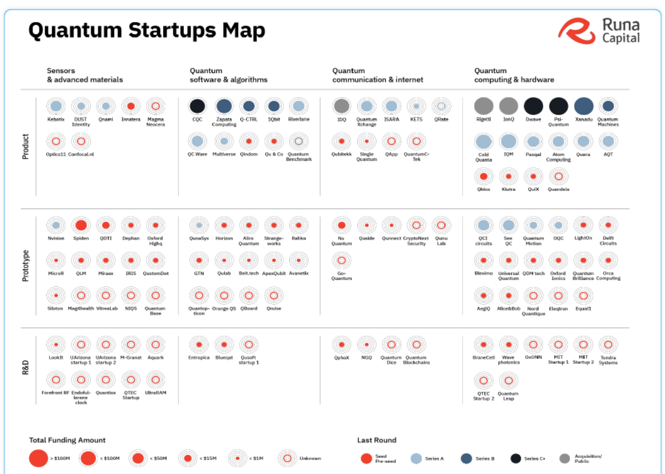


Source: PitchBook; Crunchbase.

ENTRANTS INTO THE INDUSTRY

With the increasing support of private funding, start-ups seeking to apply quantum technologies have proliferated. Of 119 start-ups identified by Runa Capital, more than one-third (35 percent) already have an operational product (Exhibit 4).[5] In October 2021, IonQ became the first publicly traded pure-play quantum computing company, based on a business combination with SPAC entity dMY Technology Group III. Recently, Rigetti Computing also became a public company through a SPAC deal valuing the company at over $1.0 billion. In addition, three start-ups have funding in excess of $100 million.

Exhibit 4 Backed by private funding, start-ups have proliferated; more than a third have at least one operational product.



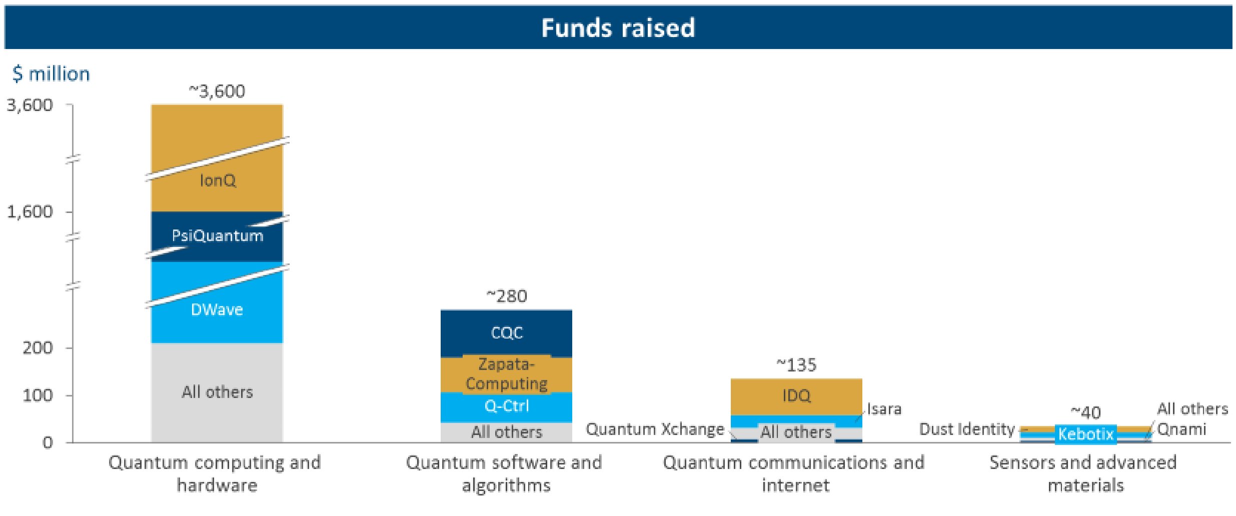
Number of Start-Ups
42 (35%)
52 (44%)
25 (21%)
119

Source: Maria Lepskaya, Igor Kotua, and Ivan Khrapach, "Venture Capital Trends in Quantum Technologies," *Quantum Computing Report*, Jan. 26, 2022, https://quantumcomputingreport.com.

Looking just at the start-ups with operational products, they have raised more than $4 billion since their founding (Exhibit 5). The lion's share of the funds—$3.6 billion—went to start-ups in quantum computing and hardware. The dominant leader in fund-raising is IonQ, which has raised about $2 billion in total funding as of October 2021 including $650 million in SPAC IPO proceeds, followed by PsiQuantum ($665 million) and D-Wave ($210 million).

[5] Maria Lepskaya, Igor Kotua, and Ivan Khrapach, "Venture Capital Trends in Quantum Technologies," *Quantum Computing Report*, January 26, 2022, https://quantumcomputingreport.com.

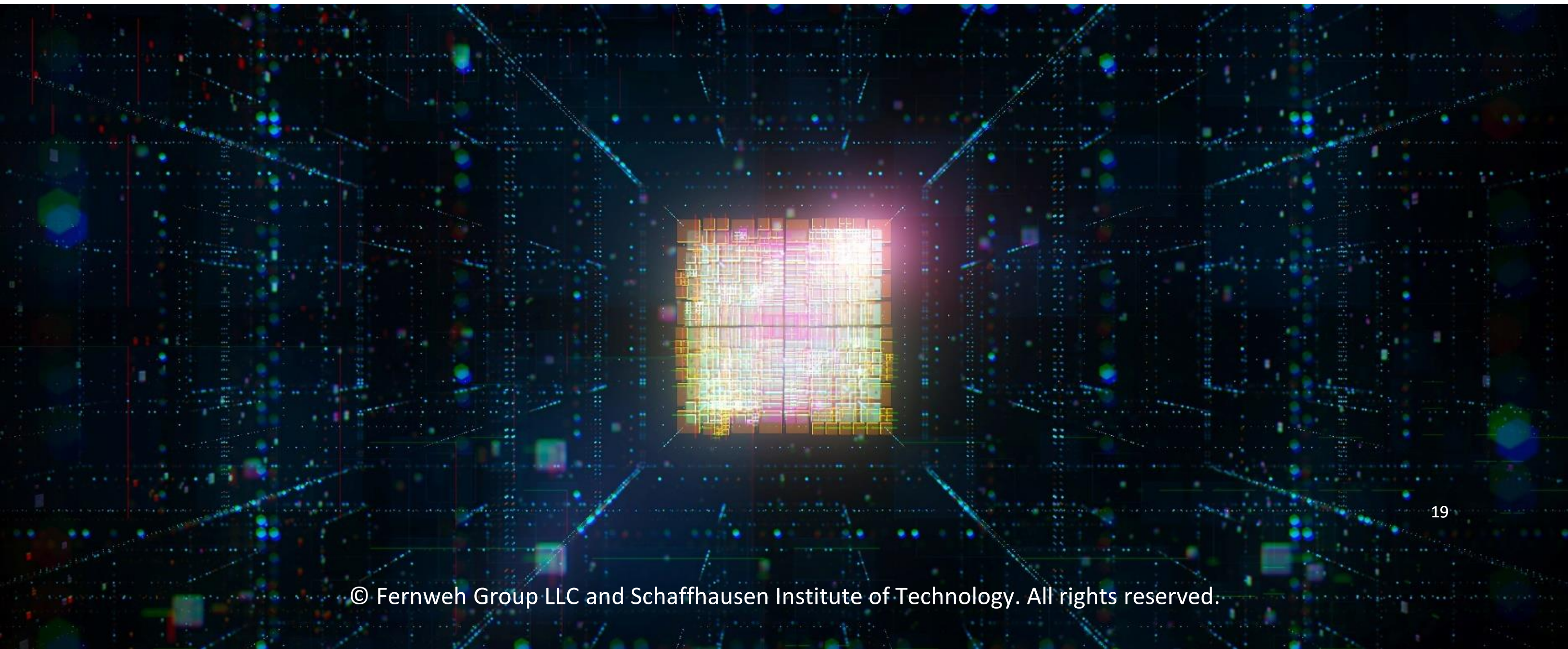
Exhibit 5 Start-ups with operational products have raised $4 billion since their founding, with the lion's share to quantum computing.

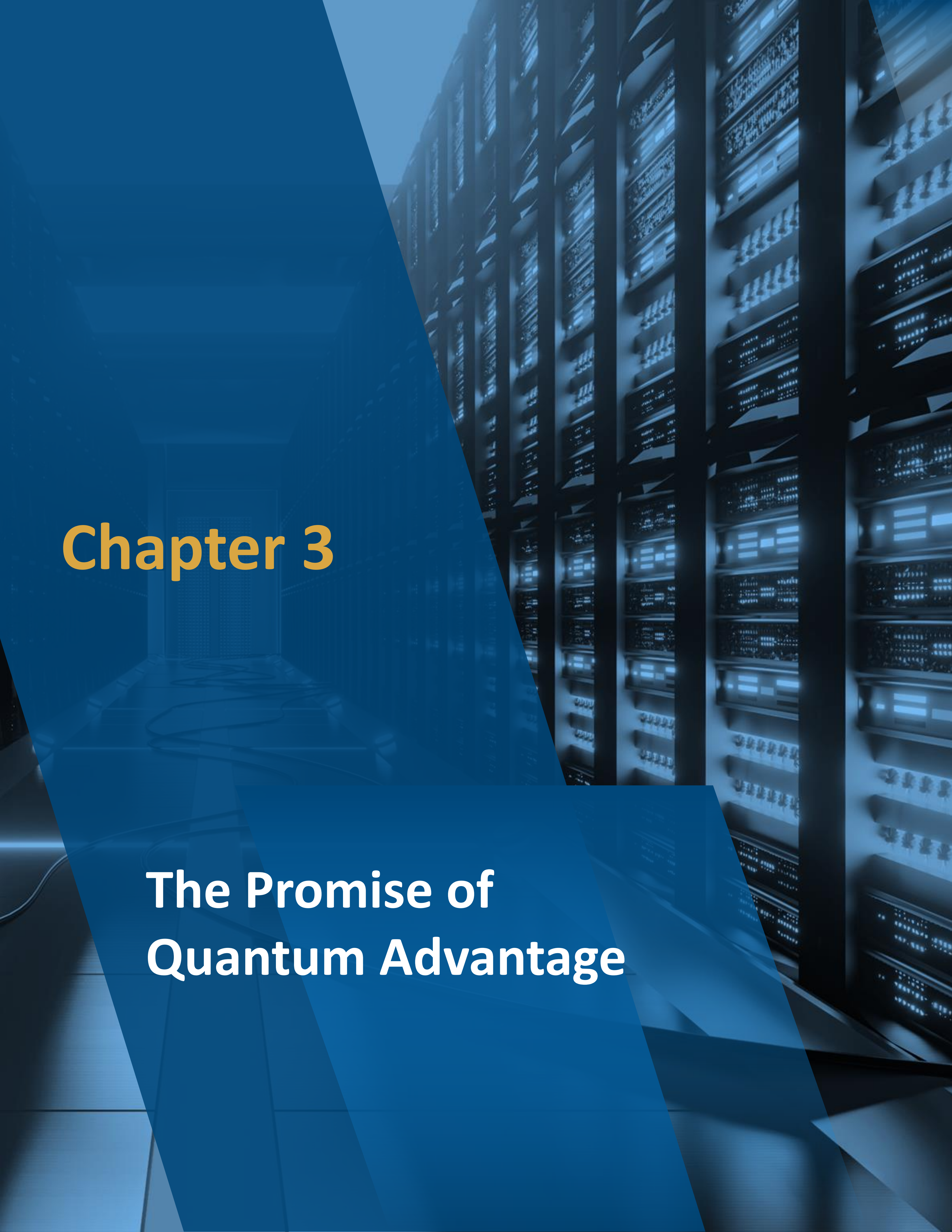


Source: PitchBook; Crunchbase.

Most of the companies with funding of more than $70 million are in series C or higher. For most companies in the seed and pre-seed phase, we lack data on the amount of funding and made a conservative estimate to arrive at a total.

After 80 years of academic research by physicists, computer scientists began to develop the idea that quantum mechanics could be applied to computing. In a few decades, researchers were beginning to demonstrate the potential of the technology, and entrepreneurs began to form start-ups. As interest in quantum computing grows, most of the hardware and software companies are pressing toward the goal of achieving "quantum advantage," the topic of the next chapter.





Chapter 3

The Promise of Quantum Advantage

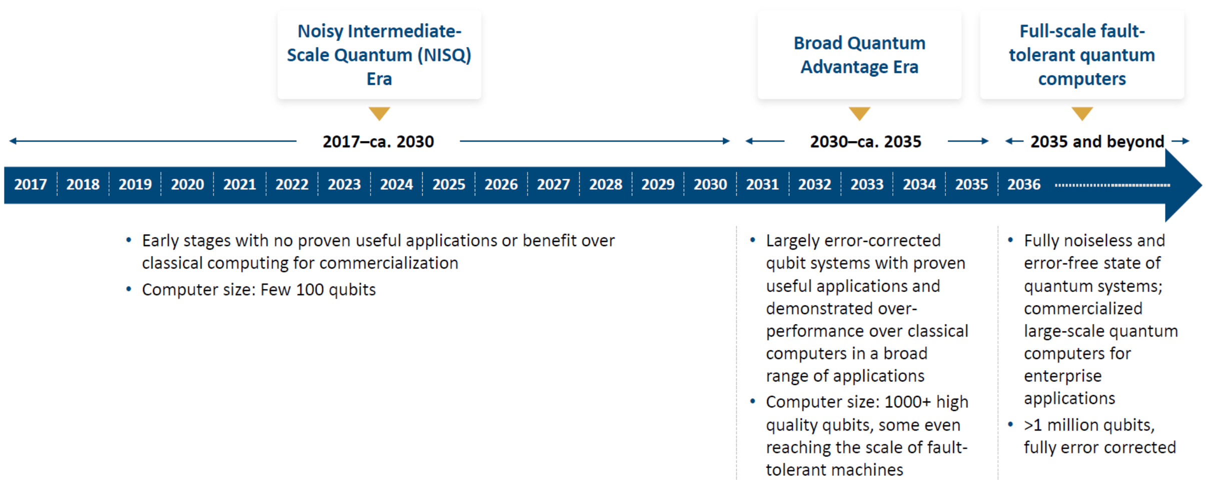
The Promise of Quantum Advantage

With quantum computing being the quantum technology application receiving most investor attention, this is where we focus our discussion of the technology's maturity. This chapter provides a timeline of the expected evolution of quantum computing through the 2030s and beyond. We then look at investors' perspective on the state of quantum computing, followed by overviews of promising hardware technologies and approaches developers are taking to platforms, software, and algorithms.

EXPECTED EVOLUTION OF QUANTUM COMPUTING

Industry experts—including quantum computing companies, academics, scientists, and researchers—see quantum computing evolving from its present state to one with error-free, fault-tolerant systems in a little more than a decade, with limited useful applications already available (Exhibit 6). "Quantum advantage," where quantum computers outperform classical computers in speed and accuracy, is expected to become broad during the 2030s.

Exhibit 6 Quantum computing is currently in the NISQ era and is expected to demonstrate quantum advantage by 2030.



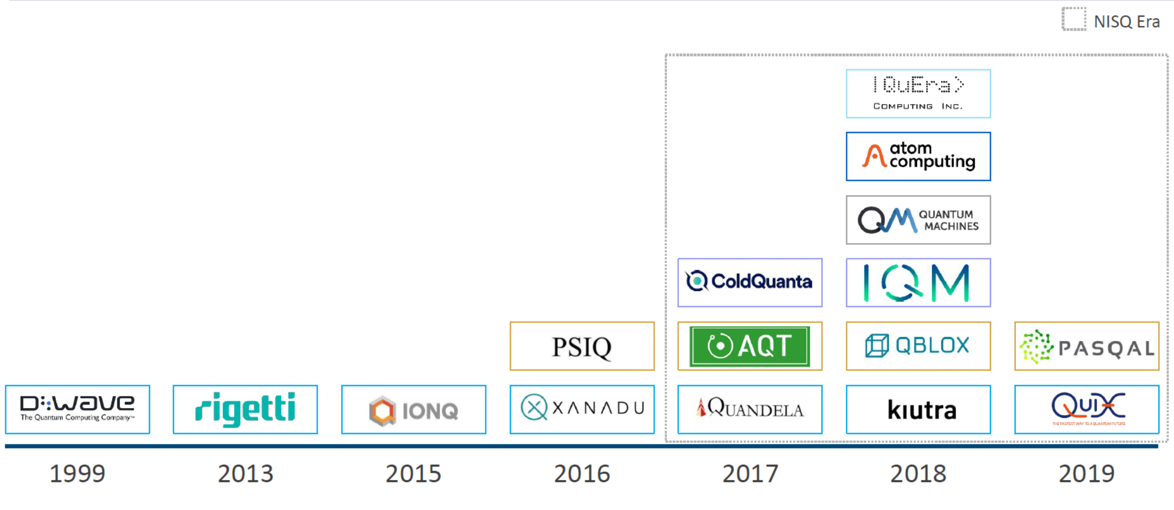
Source: Industry interviews.

NISQ ERA (2017–2030)

Beginning around 2017, the pace of quantum computing start-ups accelerated (Exhibit 7), and the world entered what has been called the Noisy Intermediate-Scale Quantum (NISQ) Era. In the NISQ Era, researchers expect to soon reach quantum advantage for some narrow applications.

In these early stages of quantum computing, systems are small at few 100 qubits. Already, Google, IBM, IonQ, and Rigetti have created processors ranging from 31 to 127 qubits.

Exhibit 7 Most quantum computing hardware companies with operational product were founded during the NISQ Era.



Source: Tracxn; Crunchbase.

In the NISQ Era, quantum computing has not yet demonstrated a benefit over classical computing in commercial applications.

However, progress suggests that narrow quantum advantage could be demonstrated in about two or three years.

"Narrow" quantum advantage means quantum computers outperform some classic computational methods on accuracy and speed.

NISQ Era breakthroughs are expected to offer applications for finance, life sciences, and logistics. The first applications are expected to be in a few key areas: logistics and manufacturing process optimization, supercharging machine learning, and financial modeling (specifically, Monte Carlo simulation).

BROAD QUANTUM ADVANTAGE ERA (2030–2035)

Around the end of the 2020s or beginning of the next decade, quantum computing is expected to move into the Broad Quantum Advantage Era. Computers of this era would have largely error-corrected qubit systems with proven useful applications. They would demonstrate superiority to classical computers in speed and accuracy for a broad range of applications, while classical computing is likely to reach its limits for those applications. These quantum computers would be somewhat larger, at 1,000 or more high-quality qubits and some even reaching the scale of fault-tolerant machines (which can run as high as millions of qubits for some technologies).

In this model of quantum computing evolution, there is some trade-off between advances in error correction and advances toward quantum advantage.

To achieve broad quantum advantage, system developers will create error correction that is just enough for the system to not fall apart for a stipulated computation time.

Applications of the Broad Quantum Advantage Era will extend to optimization problems in logistics, manufacturing, finance, and aviation (see sidebar "IonQ's Chris Monroe on the Potential of Quantum Computing"). In addition, forecasters expect progress toward quantum advantage in drug discovery, chemistry simulation, and random-number generation.

IonQ's Chris Monroe on the Potential of Quantum Computing

Professor Christopher Monroe is the cofounder and chief scientist at IonQ, a start-up that made headlines by becoming the first pure-play quantum computing company to go public, which happened in October 2021. He is also a professor of Electrical and Computer Engineering (ECE) and physics at Duke University. He is an atomic physicist and quantum engineer specializing in the isolation of individual atoms for applications in quantum information science. The following edited transcript is from his recent conversation with Nidhi Arora, Vice-President at Fernweh.

Nidhi Arora:
Which industries do you think will benefit the most across the different types of applications?

Chris Monroe:
We don't know exactly what the first killer application will be in quantum computing, but we have very strong hints. We're where we look for problems that conventional computers are not very good at—problems that require lots of configurations.

An example I like to use is a famous math problem called the traveling salesman problem. This is a logistics problem. Imagine having to go to all of the state capitals in the United States in the lower 48 states exactly once, and you want to minimize the total path traveled. There are a lot of possible combinations. Forty-eight is still on the borderline of being interesting, but when you get to a hundred cities, you can't store all those configurations, even in all of the computers in the world. Optimization problems like that, where you have lots of configurations but one output, are very likely amenable to quantum computing.

Another example is modeling the weather. We have models of climate that are very complicated. We can't solve them. Quantum computers might give us the ability to take better guesses at the models that are behind something like the upper atmospheric chemistry.

Financial models are another one actually at IonQ. Financial models are very complicated because they have many variables—thousands of financial indicators throughout the world that can drive the price of an index. If we had a model that could at least predict more accurately, it would be very useful, and quantum computers might be able to do that. Nobody thinks the quantum computer can find the optimal solution, but it still might be better than what we could do using conventional computers.

One final example, which doesn't sound like an optimization, comes from physics and chemistry. When you take a complex molecule, there are many electrons on that molecule, and those electrons actually do their own optimization, automatically. The electrons find out where they need to be. They minimize their energies, what they're doing. We sort of understand the models of how that works, but we can't solve those models because, once again, there are too many configurations. Quantum computers have already been put to the task of simulating very small molecules. Unfortunately, these molecules are so small that we already know the answer. Quantum computers will be able to solve bigger molecules, and that's very promising. Of course, that hits the oil and gas sector, and the big pharmaceuticals, from drug delivery to drug design phase, are very interested in molecular simulation.

Quantum is not adding value yet but solving a problem in a different way like this will allow us when we scale our systems to be bigger.

Nidhi Arora:
We are seeing in the quantum space an emergence of multiple full-stack players. Why are players increasingly looking to become full stack?

Chris Monroe:
Building the hardware for quantum computing is very expensive, very difficult. There are many different technologies right now. Most of the companies in quantum computing have been, not hardware, but more on the algorithms, applications, and software side, which is good to have, but in these early stages of quantum computing, a software company really needs to codesign the hardware based on their software. The software and hardware can't be separate.

We're not used to that in conventional computing, where totally different hardware can run the same software. The hardware is a commodity, and entire software companies don't really have to care about the hardware. We're not there in quantum computing. It's going to take a long time to get there. So right now, I think the more adept software companies are starting to latch onto hardware.

Full stack means the software application layer, the software layer, then the controls layer, and then the quantum hardware layer. A successful full-stack company will allow the users at the very top of the stack to not create. The way we use cell phones today, you could know what's inside, but nobody cares. You don't have to, and that's a good thing. So having a full-stack approach is a good thing. In these early stages, it's very important to be able to codesign the hardware to the software and the other way around, take the hardware to write better software. You need to look on the native expression that the hardware can do. There are quantum gate sets that certain hardware has and other hardware doesn't, and you should write your software around that to compress it, make it run better, run larger problems that will allow us to get to quantum advantage sooner.

Nidhi Arora:
A lot of enterprises may have the budget to invest in quantum technologies, but they're still taking a wait-and-watch approach. In your view, how should these enterprises be thinking about adoption, which could also help the commercial efforts quantum computing?

Chris Monroe:
We need these people. If they have problems that are, that are vexing, that are very hard, we need them to somehow reach out. Now, maybe they don't have to make a large in-house investment. They certainly don't have to build a machine. They can certainly consult with maybe a quantum software company or use small computers that are available on the cloud. You can actually get access to IonQ, computers and other quantum computers. They're small, but you can start to think about running very small versions of these programs, but even that's a big investment.

It really takes a full timer to start thinking about applying quantum computing to your problem, so I think the first step would be for these companies to reach out to other companies and do some exploration. Nothing is going to be free. There will be some amount of investment, but I don't think you have to make a big jump like $10 million per year. Right now, waiting and seeing is a little bit passive.

FULL-SCALE, FAULT-TOLERANT QUANTUM COMPUTERS (2035 and beyond)

In the mid-2030s, quantum computing is expected to reach the level of full-scale, fault-tolerant quantum computers. Such systems would be fully noiseless and error free. Producers would offer commercialized large-scale quantum computers for enterprise applications. The systems would have tens of thousands to over a million qubits, including the qubits needed to correct errors produced by noise. These qubits will be fully error corrected for the computation to last forever.

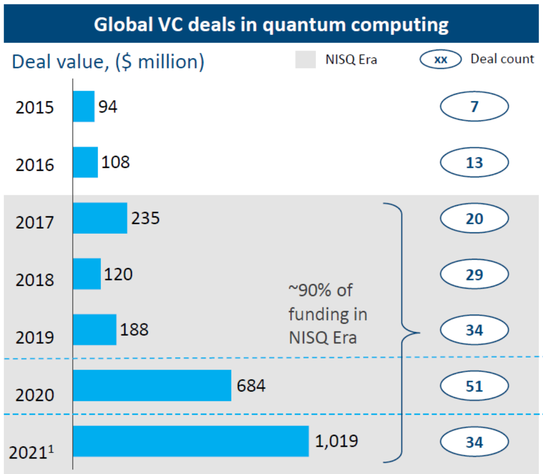
Applications for these computers include cryptography for breaking encryptions. Ultimately, users could obtain a universal quantum computer that performs all the tasks a classical computer is capable of and more.

Already, companies including PsiQuantum and Xanadu are focusing solely on the development of full-scale, fault-tolerant quantum processors.

INVESTOR CONFIDENCE

Although quantum computing is still in its nascent stage, venture capitalists are demonstrating growing confidence in the technology. Globally, VC deals accelerated rapidly in the last 2 years, with such notable deals as PsiQ ($450 million), Xanadu ($100 million), and Rigetti ($79 million) (Exhibit 8).

Exhibit 8 Venture capitalists' confidence in quantum computing has recently accelerated.



Notable deals

Start-Up Name	Deal Size ($ million)	Select Investors
IONQ	62	Airbus Ventures, Amazon Web Services, Mubadala
rigetti	79	Andreessen Horowitz, Battery Ventures, Bessemer Venture Partners, DCVC
QM Quantum Machines	50	Battery Ventures, Red Dot Capital Partners, Samsung NEXT Ventures, Valor Equity Partners
XANADU	100	Bessemer Venture Partners, Georgian, Tiger Global
PsiQ	450	Baillie Gifford, BlackRock, M12, Temasek

[1]As of Sept. 2021.
Source: Marina Temkin, "Investors Bet on the Technologically Unproven Field of Quantum Computing," PitchBook, Sept. 13, 2021, https://pitchbook.com.

Governments also are heavily investing in quantum computing (Exhibit 9). Examples that made the news include China's announcement it had budgeted $10 billion to support quantum computing research. Germany, Canada, and France each announced spending of more than $2 billion for similar programs. Other major players investing at least $1 billion include the United Kingdom, United States, and India.

Exhibit 9 Governments also are heavily investing in quantum computing.

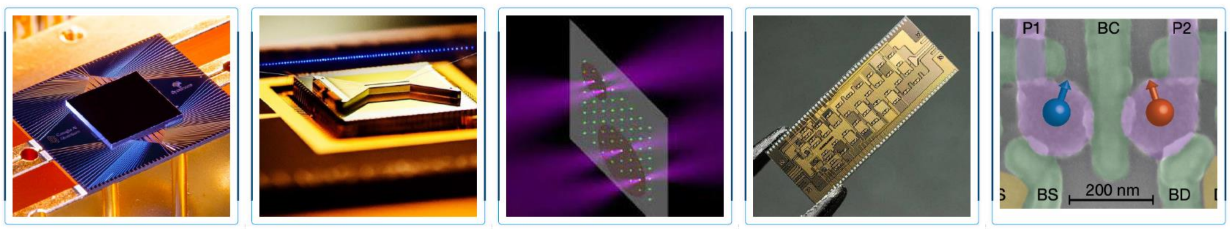
Country	Disclosed investment ($ billion)	Initiatives
China	10.0	• Budgeted for the Chinese Academy of Sciences Center for Excellence in Quantum Information and Quantum Physics, the Quantum Experiments at Space Scale, National Quantum Laboratory, and the Beijing-Shanghai Quantum Secure Communication Backbone
Germany	2.4	• Collaboration with research institutions, industry, government agencies, and the community – Ten leading German corporations are co-founding the Quantum Technology and Application Consortium to develop the fundamentals of quantum computing into use cases
Canada	2.2	• Support for establishment of the Quantum Algorithms Institute to increase innovation and be one of the top countries in quantum technology
France	2.2	• 5-year investment plan announced in January 2021 with the goal of putting France in the world's top 3 in quantum technologies
United Kingdom	1.3	• Investments in 2 phases to establish 4 hubs for quantum technologies involving ~30 universities; hubs specialize in imaging, ultraprecise sensors, secure communications, and new concepts for quantum computing • Establishment of a National Quantum Computing Center to help the UK evaluate, design, develop, and build a practical quantum computer
United States	1.2	• Under the National Quantum Initiative Act, funds allocated to establish 12 quantum research centers to boost the productivity of quantum computing and 5 quantum computing centers under the Department of Energy
India	1.0	• Establishment of a National Mission on Quantum Technologies and Applications with a 5-year budget

Source: "Overview on Quantum Initiatives Worldwide—Update Mid-2021," Qureca, July 19, 2021, https://qureca.com; "Top Government's Budget for Quantum Computing in 2022," *Analytics Insight*, Mar. 2, 2022, https://www.analyticsinsight.net.

PROMISING HARDWARE TECHNOLOGIES

In hardware, five promising hardware approaches already have emerged: superconducting qubits, trapped ions, neutral ion arrays, silicon photonics, and spin-based quantum dots (Exhibit 10). Each of these has its own promises and unique set of challenges.

Exhibit 10 Five promising hardware approaches have emerged.

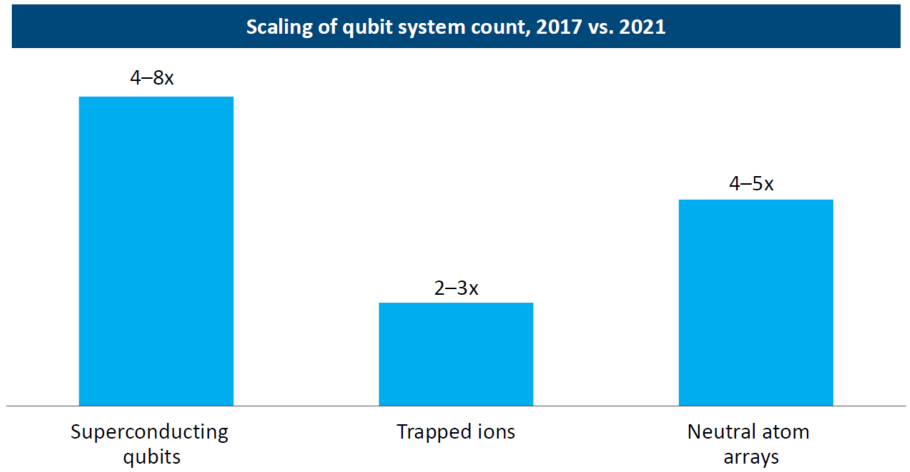


Superconducting qubits	Trapped ions	Neutral atom arrays	Silicon photonics	Spin-based quantum dots
Qubits given by the state of small superconducting circuits	Qubits implemented by the internal state of trapped ions	Qubits implemented by internal states of neutral atoms trapped in an optical lattice	Qubits implemented by units of light (photons) on a silicon chip	Qubits given by spin states of trapped electrons
rigetti, IBM, Google, D-Wave	IONQ, Honeywell Quantum Solutions, AQT	QuEra, PASQAL, ATOM Computing, ColdQuanta	XANADU, ORCA Computing, PsiQuantum	intel, HRL Laboratories

Source: SIT & Jacobs University Insights in Technology 2021.

Already in the NISQ era, these hardware technologies have made significant strides in qubit scaling (Exhibit 11). It should be noted however, that raw qubit number is not necessarily relevant to quantum computer performance, and most of these high-qubit systems effectively use just a few for computation. Examples in the market include IBM, which already had a 65-qubit system early in 2021 and unveiled its 127-qubit Eagle in Nov 2021, and QuEra, which demonstrated a 51-qubit system in 2017 and a 256-qubit system in 2021. In addition, researchers have reached some influential technology milestones over the last few years (see sidebar "Milestones in Hardware Technology"). These advances have enabled several providers, including D-Wave, IBM, IonQ, Rigetti, and Xanadu, making qubit systems available on cloud service platforms.

Exhibit 11 Hardware technologies have made significant strides on qubit scaling in the NISQ Era.



Source: Rigetti investor presentation 2021; IonQ Investor Presentation 2021; Siobhan Roberts, "This New Startup Has Built a Record-Breaking 256-Qubit Quantum Computer," *MIT Technology Review*, Nov. 17, 2021, https://www.technologyreview.com; "IBM's Roadmap for Scaling Quantum Technology," IBM blog, Sept. 15, 2020, https://research.ibm.com; "IBM Announces Advances to IBM Quantum Systems & Ecosystem," news release, Nov. 10, 2017, https://newsroom.ibm.com.

Milestones in Hardware Technology

The following advances have influenced the development of quantum computing hardware:

- **Quantum supremacy.** In October 2019, Google announced that its 54-qubit processor called Sycamore had completed a calculation in less than 4 minutes, which was 158 million times faster than the world's fastest supercomputer. However, Google's claim to quantum supremacy have been challenged thereafter when a team of scientists from China said that their non-quantum classical computer completed the sampling task "in about 15 hours" with higher estimated accuracy than Google'S Sycamore
- **5,000-qubit advantage.** In September 2020, D-Wave Systems launched a next-gen quantum computing platform called Advantage with 5,000 qubits, capable of handling problems with a million variables. It uses the company's new Pegasus chip with 15 connections per qubit and was implemented on specialized quantum annealing.
- **Highest quantum volume.** In July 2021, Honeywell's 10-qubit System Model H1 achieved a quantum volume of 1,024—the highest measured to date. The H1 quantum system pioneers the use of QCCD, an advanced trapped-ion architecture that allows for arbitrary movement of ions and parallel gate operations across multiple zones.
- **256-qubit breakthrough**. In July 2021, a team of physicists from the Harvard–MIT Center for Ultracold Atoms developed a quantum simulator operating with 256 qubits. Unprecedented size and programmability puts it at the cutting edge of the race for a quantum simulator.
- **Most powerful quantum system.** In February 2022, IonQ announced that its latest quantum computer Aria had achieved a record 20 algorithmic qubits (#AQ), furthering its lead as the most powerful quantum computer in the industry. IonQ Aria is able to run hundreds of accurate quantum gates in a single algorithm, whereas previous quantum computers were only capable of running dozens of gates at a time.

Superconducting Qubits[6]

With superconducting qubits, each qubit consists of a nonlinear Josephson inductance in parallel with an ultra-low-loss capacitor to create a resonant structure in the range of three to six gigahertz. The qubits are coupled to a linear superconducting resonator for readout. Single-qubit and multiqubit logic operations are implemented by applying microwave or direct-current pulses.

Promises of superconducting qubit technology include 127-qubit chips developed already, reaching 1,121 qubits in about a year and perhaps a million qubits further in the future.

Two-qubit fidelity is expected to reach 99.5 percent, and the fastest gate operation time is expected to be 10 to 50 nanoseconds. In four years, the measurable speed on lithium-hydrogen molecule simulation could increase by 120 times.

Error correction has been demonstrated, and the path toward fault-tolerant computing is known.

This hardware technology is most mature when compared to other hardware platforms driven by the world's IT giants (IBM, Google). IBM, Google and Rigetti's qubit systems are also available in the cloud.

Many challenges remain. First is the low coherence times, which are about 10^4 gate times which complicates error correction.

While an isolated qubit maybe very coherent, but this coherence can be destroyed by the connections with the outside (classical) world that are needed to control and measure the qubit.

The second challenge is the relatively high qubit frequencies (on a scale of a few gigahertz) which then requires expensive control electronics and complicates the wiring between these electronics and cryostat, where the quantum computing chip is located. Third, the capacitor involved in the transmon construction must be 100 femtofarads, which implies sizes of the scale of hundreds of nanometers, that requires packing more than a few hundred of the on a few-mm chip. Fourth, nanofabricated transmons come with slightly different resonant frequencies and require special efforts to tune in resonance with each other.

Trapped Ions[6]

The use of trapped ions begins with laser-cooling ions to nearly at rest in a vacuum chamber.. The cooled ions are then trapped in electromagnetic (radio frequency) traps. Hyperfine or ground-excited states are used to encode quantum information and qubits. Radiofrequency / optical gates are implemented using a common mode of the trap and Coulomb interaction. The architecture within a trap is mainly one-dimensional.

Promises for the trapped-ion approach include the progress to date: 20 to 30 algorithmic qubits are realized, and plans are in place for 10^3 to 10^6 qubits using modular architecture. Developers have achieved record quality of operations—99.9 percent for two-qubit gates—and 99.999 percent is possible. There is a long coherence time, 10 minutes.

[6] A.K. Fedorov, N. Gisin, S.M. Beloussov, and A.I. Lvovsky, "Quantum computing at the quantum advantage threshold: a down-to-business review", February 7, 2022

This hardware offers all-to-all connectivity within the trap, as well as quantum algorithms (chemistry and machine learning have been demonstrated). It is accessible in the cloud. IonQ, a user of trapped-ion technology, is the first publicly traded company in quantum computing. Qudit quantum processors are realized.

Among the challenges with trapped ions is scalability within a single trap: currently, there are no more than 30 to 50 good qubits or 50 to 100 ions for simulation. Companies need modular architecture or two-dimensional traps. Also, operations are slow, at one microsecond. The systems require photonic interconnections with high efficiency of transporting entanglement. Heating rates increase with the numbers of qubits. Advanced materials for traps are required, as well as new lasers for fast and stable operations.

Neutral Atom Arrays[6]

The technology for neutral atom arrays involves cooling Rydberg atoms (atoms in a very excited state) in a vacuum chamber to microkelvins. Then they are trapped in optical tweezers using lasers and acousto-optical deflection (AOD). Qubits are made using atomic states to encode quantum information. Rearrange positions of traps into one, two, and three dimensions. Rydberg states of atoms are used to make the atoms interact for gates.

One promising characteristic of neutral atom arrays is their high scalability: it is easy to add more atoms.

Already arrays have 256 atoms now, and they will have 10 million in 2030. This technology also offers high coherence, because neutral atoms are very stable, with coherence length ranging from 10 seconds to about 100 seconds. In addition, native gate times are fast, having been reduced from about 200 nanoseconds to 20 nanoseconds. The systems are cooled by laser, so they don't require a dilution refrigerator and expensive helium-3. They are controlled by light, so they do not need wires and waveguides for each qubit. Devices can be shipped to customers. Finally, they have many scientific applications, such as a highly programmable simulator, and native applications, such as maximal independent set (MIS) optimization and machine learning.

Challenges include the ability to control individual atoms, including confining them while running high-performance quantum operations, and the need to develop transportable entanglement for scaling.. Another need is for photonic integrated circuits for these wavelengths, which requires developing fast (in the range of nanoseconds) electronic control and fast, scalable, phase-coherent emitter arrays. Finally, optics alignment still needs to be automated, and the architecture of elements (optics) should be improved for miniaturization.

[6] A.K. Fedorov, N. Gisin, S.M. Beloussov, and A.I. Lvovsky, "Quantum computing at the quantum advantage threshold: a down-to-business review", February 7, 2022

Photonics[6]

Developing photonics requires first getting a source of three-photon entangled states. Each photon needs to pass through a small, constant number of components, interfering with at most two other spatially nearby photons. Current photonics chip engineering performance allows the creation of tens of thousands of photons entangled in a state universal for quantum computation.

Photonics promises high scalability, at least in principle—one million qubits by 2025. In addition, there is no decoherence in the usual sense, although photon loss and component performance can be debilitating. The systems do not require expensive cooling, and they offer many ways to encode quantum information. And an arsenal of quantum optical tools exist.

Several challenges remain. One is that optical losses occur in the medium. Also, there is a lack of good sources of three-photon entangled states. The process requires challenging manipulation and measurements for quantum optical states. Developers need better single-photon sources and detectors, as well as interferometric stability, especially communicating between chips. Finally, they need better and scalable electronics to control the large number of active optical chip components.

[6] A.K. Fedorov, N. Gisin, S.M. Beloussov, and A.I. Lvovsky, "Quantum computing at the quantum advantage threshold: a down-to-business review", February 7, 2022

Spin-Based Quantum Dots[6]

To use spin-based quantum dots, the hardware must trap a single electron in a transistor, typically using a quantum dot beneath the gate electrode. Then the system applies a magnetic field using a superconducting magnet in a refrigerator. The spin state of the electron is the value of the qubit. A second single-electron transistor in proximity can interact with good precision to form a two-qubit gate.

Promises of spin-based quantum dots include practically unlimited scalability, reusing existing semiconductor technologies.

Speed and fidelity are potentially very good. The technology is ready for mass production (CMOS-compatible). Two teams (UNSW Australia and TU Delft) have independently published articles in *Nature* on helium-4-cooled qubits. Three teams in 2022 independently reported two-qubit gates with silicon quantum dots with fidelities over 99%, which is sufficient to enable surface-code error correction. Finally, the coherence time is few microseconds.

One challenge to overcome is that silicon purity affects coherence when transistors are working on a single-electron level. As a result, developers need better purity silicon. In addition, low temperatures require expensive He-3 dilution refrigerators and days of start-up time to reach micro-Kelvin temperatures.

Which Will Dominate?

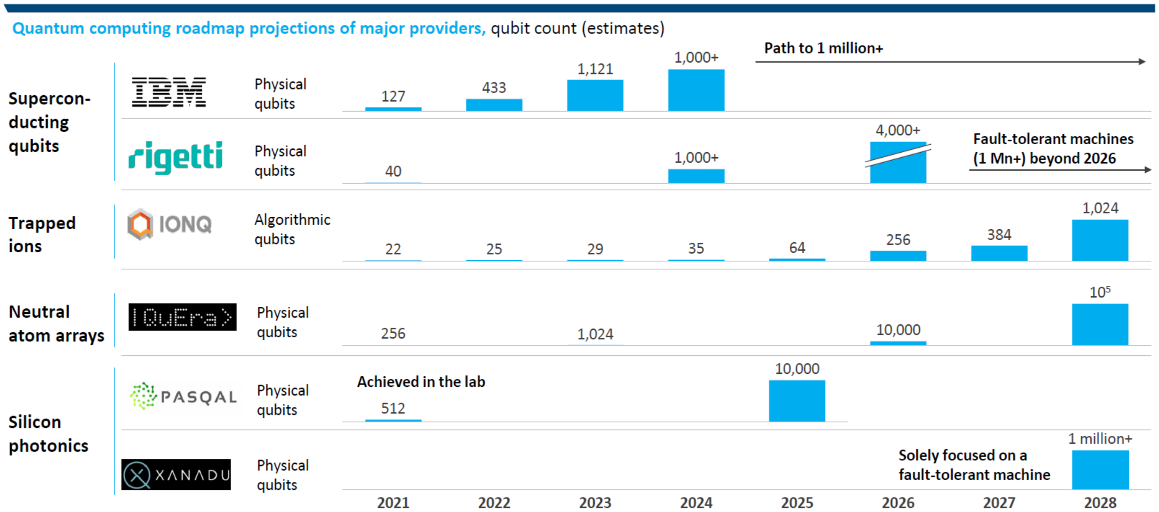
The jury is still out as to which technology will win the race in quantum computing hardware. Whichever comes out ahead, the industry is ambitious.

> *Hardware providers have issued robust projections. These public statements are a sign of management confidence and thus an indicator that the industry is making progress.*

Several companies have announced planned breakthroughs in hardware. ColdQuanta's Hilbert cloud-based quantum computer, based on neutral atoms, is expected to deliver 100 qubits in early 2022, with the team targeting more than 1,000 qubits by 2024.

[6] A.K. Fedorov, N. Gisin, S.M. Beloussov, and A.I. Lvovsky, "Quantum computing at the quantum advantage threshold: a down-to-business review", February 7, 2022

Exhibit 12 Hardware providers across the board have made robust projections of technological advances.



Source: IonQ Investor Presentation 2021; Rigetti Investor Presentation 2021; "IBM's Roadmap for Scaling Quantum Technology," IBM blog, Sept. 15, 2020, https://research.ibm.com; industry interviews.

IBM, applying superconducting cubits, expects to release in 2023 a 1,000-qubit quantum computer that achieves prebuilt quantum runtimes (integrated with circuit libraries) for algorithm developers. In the same year, IonQ says it will deploy modular quantum computers based on trapped ions; the company says these computers are "small enough to be networked together in a datacenter."[7] Applying silicon photonics, PsiQuantum intends to commercialize a million-qubit system with a single photon-based setup in 2025. Rigetti and Google have announced plans involving superconducting qubits. Rigetti is planning a 4,000-qubit D-2 system available as "quantum computing as a service" in 2026. And Google is aiming to develop error correction for a million-qubit superconducting system by 2029. In all of these proclamations, it should be kept in mind that raw qubit number does not necessarily correspond to quantum computer power. More qubits demand ever-longer coherence and ever-more operation. As qubits are added, they must therefore either maintain or even improve their level of performance.

[7] Peter Chapman, "Scaling IonQ's Quantum Computers: The Roadmap," IonQ blog, December 9, 2020, https://ionq.com.

TWO APPROACHES TO PLATFORMS, SOFTWARE, AND ALGORITHMS

While hardware producers work on five different types of platforms, companies that develop software and algorithms are taking two different approaches to their endeavors. Some are developing hardware-agnostic software for quantum computing, while others build software for both classical and quantum computing.

Hardware-Agnostic Software for Quantum Computing

The value proposition of hardware-agnostic software is that it simplifies quantum computing programming by eliminating the need-to-know, gate-level details. It also enables algorithms to be employed on different quantum computing platforms.

Finally, hardware-agnostic software makes quantum computing easily accessible for near-term quantum computing hardware at a low cost to enterprises.

Companies that are applying this approach include Multiverse Computing, Q-Ctrl, QC Ware, and Riverlane. For example, Multiverse Computing, a leader in quantum computing for the financial industry, builds algorithms that run on all possible quantum hardware platforms (superconducting, photonics, ion traps, neutral atoms). Its flagship product, Singularity, allows financial professionals to leverage quantum computing with common software tools. Similarly, Riverlane, has developed software technology across a range of quantum hardware platforms (superconducting qubits, trapped ions, silicon qubits, photonic qubits) that can address the barrier of error correction at higher qubits. Its Deltaflow operating system for quantum computers was inspired by heterogeneous architectures (all computing elements in the stack accessible, including the CPU, FPGAs, and qubits) and empowers quantum programmers to implement fast operations at the right level in the stack. Deltaflow increases performance by several orders of magnitude, accelerating material discovery by 30 times and reducing error rate by a factor of 1,000.

Software for Both Classical and Quantum Computing

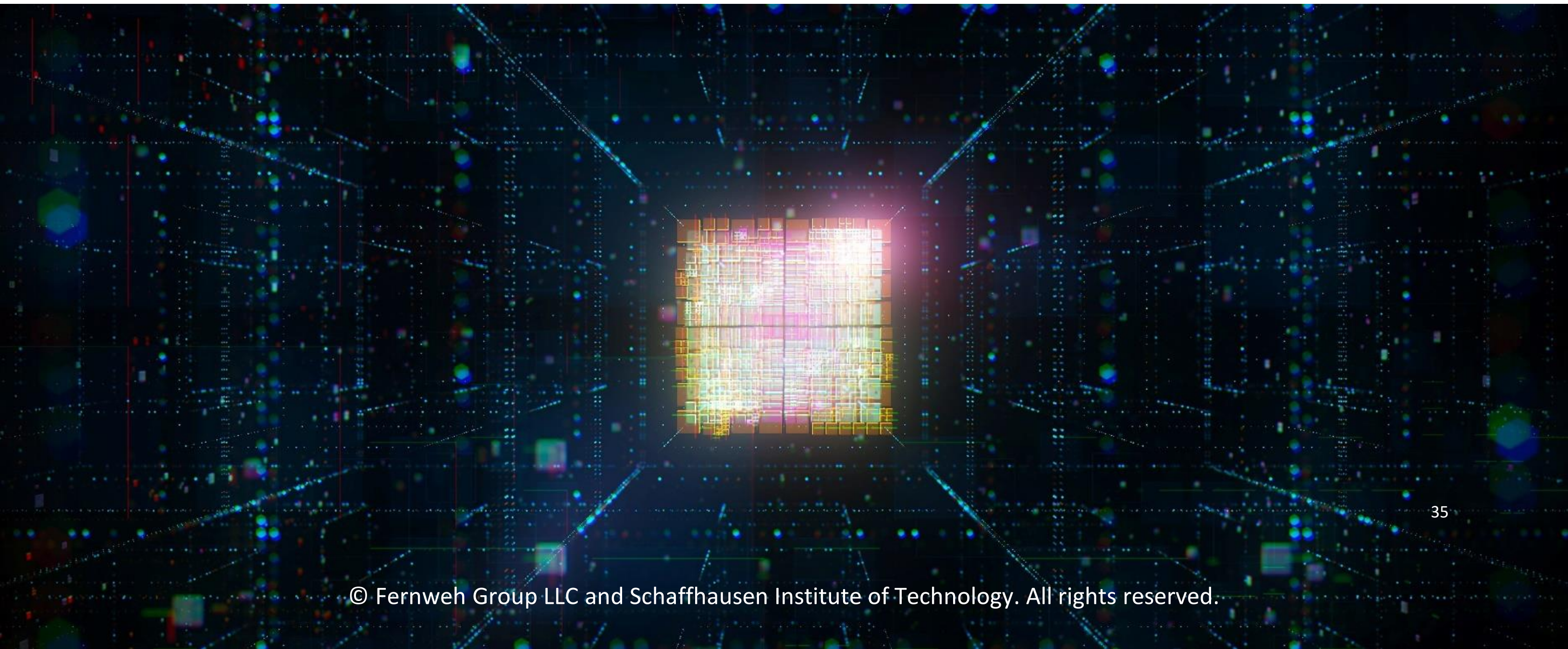
The approach of developing software for both kinds of computing has a different value proposition. It enables enterprises to obtain quantum capabilities without making big investments in quantum computing technology. It also makes the switch to quantum worthwhile for many applications because it takes the existing computer infrastructure necessary for large-scale enterprise applications and blends in a small amount of quantum enhancement to make those systems run well enough.

Enterprises also can bring improved applications to life sooner by leveraging advances in quantum and classical hardware simultaneously.

Key players in developing software for both classical and quantum computing include Horizon Quantum Computing, 1Qbit, and Zapata.

Horizon writes programs in classical languages that can be compiled and run on conventional or quantum computers without any knowledge of quantum computing. At the core of their technology is a process (compiler) that automatically constructs quantum algorithms based on programs written in classical languages. The mission of 1QBit is to solve the industry's most demanding computational challenges by building software that allows applications to continually benefit from advances in both quantum and classical hardware. The company has built a hardware-agnostic platform and partners with Fortune 500 clients and leading hardware providers to solve industry problems in the areas of optimization, simulation, and machine learning. Zapata's Oquestra platform combines a software platform and quantum algorithm libraries to deliver real-world advances in computational power for applications, particularly in chemistry, machine learning, and optimization. Orquestra enables users to compose quantum workflows and orchestrate their execution across classical and quantum technologies.

A technology becomes transformative when it begins to accomplish something that previously had been impossible. For quantum computing, this point is the "quantum advantage," the ability of a quantum computer to arrive at solutions to problems that classical computers cannot solve within a meaningful time frame. Indicators suggest that we may reach quantum advantage for a broad spectrum of tasks by the end of this decade. Already, players in the quantum computing ecosystem are preparing for this new era.



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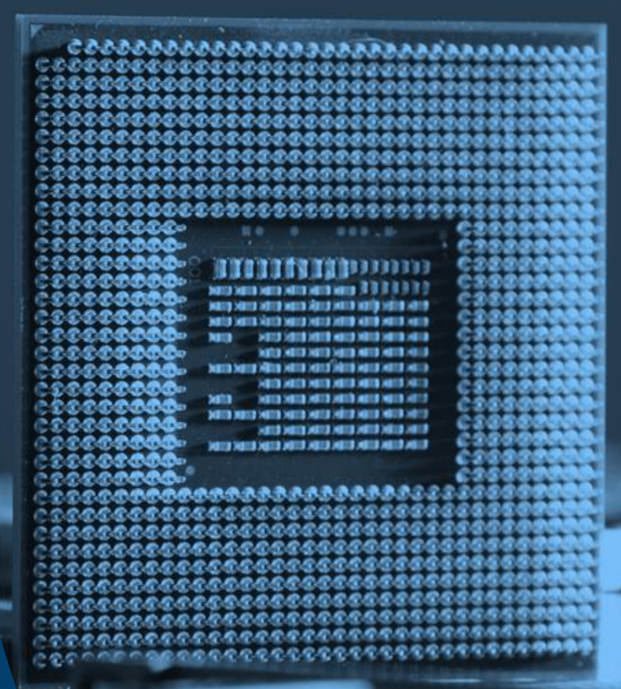
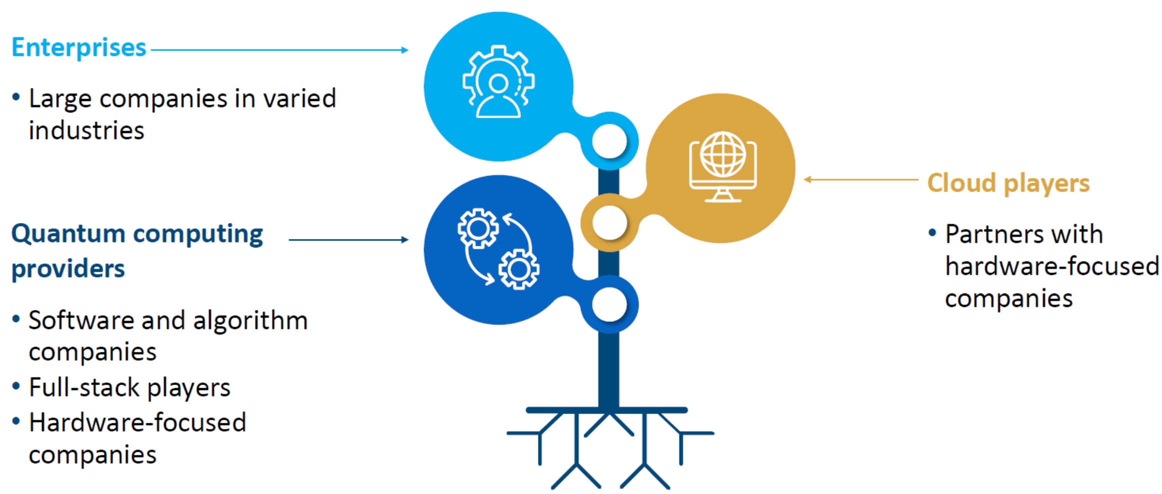


Competitive Landscape

Competitive Landscape

As the technology develops, players in the quantum computing ecosystem are paving the path for commercialization. These major players include quantum computing providers, enterprises that see relevant applications for quantum computing, and cloud players offering qubit systems (Exhibit 13).

Exhibit 13 Players in the ecosystem include three types of computing providers.



Source: Industry interviews

QUANTUM COMPUTING PROVIDERS

Quantum computing providers may focus on hardware or software, or they may be full-stack players developing both hardware and software at the same time.

Software and Algorithm Companies

Software-focused computing providers are collaborating with enterprises to explore quantum algorithms. The goal is to ensure rapid adoption when quantum hardware technology is ready for commercial use. In some cases, software and algorithm companies are forming joint research teams and multiyear partnerships.

The following software- and algorithm-focused companies are notable examples of companies working closely with end users on applications and use cases:

- *QC Ware* is collaborating with three end users—Goldman Sachs[8], Total[9], and Aisin[10]—on separate projects. Researchers at QC Ware and Goldman have designed new, robust quantum algorithms that outperform

8 . QC Ware news, "Goldman Sachs and QC Ware Collaboration Brings New Way to Price Risky Assets within Reach of Quantum Computers," April 29, 2021
9. QC Ware news, "QC Ware Teams up with Total to Advance Energy Resource Optimization," November 10, 2020
10. QC Ware news, "Japan's Global AISIN Group Enlists QC Ware for Joint Quantum Computing Research to Advance Digital Transformation," June 3, 2020

state-of-the-art classical algorithms for Monte Carlo simulations and can be used on quantum hardware expected to be available in 5 to 10 years. With Total, QC Ware is leveraging its Forge cloud service to explore modeling of continuous variables to run optimization use cases that are critical to Total's operations. And QC Ware and Aisin are collaborating on research that explores the impact of quantum optimization and quantum machine-learning algorithms on automotive applications. Their focus is on solving challenges involving the design of auto parts—for example, quality assurance in automatic-transmission software.

- *1QBit* has been collaborating with Dow[11] and Biogen[12]. The 1Qbit effort involves developing quantum computing tools for chemicals and materials science. The aim is to augment Dow's discovery process by building a stronger fundamental understanding of new chemicals and materials. The collaboration with Biogen, which also involves support from Accenture, led to the development in 2017 of a first-of-its-kind application for quantum enabled molecular comparison. This is expected to significantly improve advanced molecular design to speed up drug discovery for complex neurological conditions such as multiple sclerosis, Alzheimer's disease, Parkinson's disease, and Lou Gehrig's disease.
- *Multiverse Computing* and BBVA[13] formed a joint research team that evaluated and benchmarked several quantum and traditional technologies to improve the process of using market data to dynamically optimize investment portfolios.
- *CQC* and Roche[14] have engaged in a multiyear collaboration to design and implement NISQ algorithms for early-stage drug discovery and development.

Full-Stack Players

Multiple full-stack quantum companies are accelerating commercial efforts by working closely with enterprises on applications as they also develop the hardware.

In promising signs of early success and investor confidence with two companies, IonQ and Rigetti have gone public.

Several quantum computing companies have organically evolved into full-stack players to accelerate commercialization:

- *D-Wave Systems*, founded in 1999, covers the whole gamut of the development and delivery of quantum computing systems, software, and services. Quantum computers already availed by multinationals like Google and Lockheed Martin and by government labs such as NASA Ames, Oak Ridge National Laboratory, and Los Alamos National Laboratory.
- *Rigetti*, a Berkeley based start-up founded in 2013, is working on a one–two combo: a fab lab for speedy creation of better quantum circuits with superconducting qubits and a cloud service that provides early hands-on

11 . Dow news, "Dow and 1QBit Announce Collaboration Agreement on Quantum Computing," June 17, 2021.
12. Accenture newsroom, "Accenture Labs and 1QBit Work with Biogen to Apply Quantum Computing to Accelerate Drug Discovery," June 14, 2017.
13. BBVA news, "BBVA announces partnership with Multiverse," August 2020.
14. BioPharm International Editors, "Roche and Cambridge Quantum Computing Use Algorithms for Early Alzheimer's Drug Research," March 2, 2021, https://www.biopharminternational.com/.

experience with writing and testing software. With an IP portfolio of more than a hundred patents across software, algorithms, hardware, and chip design and fabrication, Rigetti in 2020, was also named as the core industry partner at the new Superconducting Quantum Materials and Systems Center (SQMS) led by the U.S. Department of Energy's Fermilab.

- *IonQ* in October 2021 became the first pure-play, full-stack quantum computing company to go public. Founded in 2015, it was the first company to focus on trapped-ion technology and is the only company to have made its quantum systems available through both the Amazon Braket and Microsoft Azure clouds, as well as through direct API access. IonQ has been working directly with many financial giants (for example, Goldman Sachs and Fidelity) to use its advanced quantum hardware architecture and machine-learning algorithms for complex financial modeling.

- *Xanadu*, launched in 2016, provides hardware and software based on quantum photonic semiconductors, as well as a cloud service. The company offers three open-source software products: Penny Lane, a machine-learning platform for quantum computers; Strawberry Fields, a full-stack Python library that enables users to design, simulate, and optimize quantum optical circuits; and a quantum programming language called Blackbird. Xanadu also offers open-source tools for quantum machine learning, quantum computing, and quantum chemistry.

  The company already has built seven photonics-based quantum computers, which are used by national labs and research institutions.

Hardware-Focused Companies

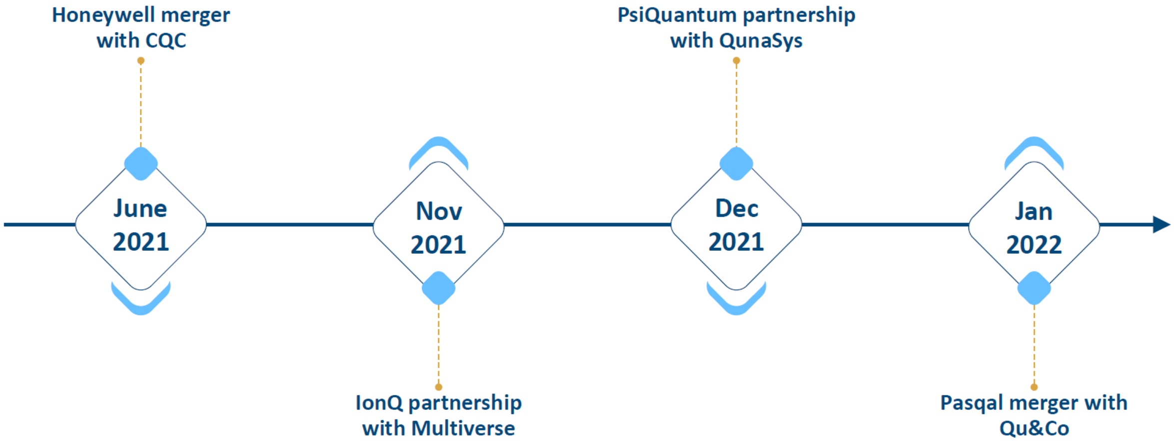
As hardware-focused companies seek close access to end customers, the industry has seen increased merger activity and the formation of partnerships between hardware and software companies (Exhibit 14). These deals allow software companies to test the viability of their products on a particular quantum hardware, so their efforts aren't thinly spread across multiple hardware platforms.

> *Hardware-focused companies are forming partnerships or merging with software companies to better understand end-customer needs.*

Two partnerships involving hardware and software companies are of particular note:

- *IonQ*, which creates hardware based on trapped-ion technology, and Multiverse, which creates algorithms for the financial industry, announced their partnership in November 2021. It combines IonQ's Quantum Cloud platform with Multiverse's financial solution named Singularity. The integrated system is intended to allow financial institutions to model financial problems—for example, fair price calculations, portfolio creation and optimization, exchange-traded fund replication, and risk valuation—with unprecedented speed and accuracy.

Exhibit 14 Hardware-focused companies are forming partnerships or merging with software providers.



Source: "Honeywell (HON) to Combine Quantum Solutions Unit with CQC," Nasdaq, June 9, 2021, https://www.nasdaq.com; "Quantum Startups Pasqal and Qu&Co Announce Merger to Leverage Complementary Solutions for Global Market," Pasqal, Jan. 11, 2022, https://pasqal.io/; "Multiverse Computing Partners with IonQ to Unlock the Power of Quantum Computing for Global Financial Companies," Business Wire, Nov. 11, 2021, https://www.businesswire.com; "PsiQuantum and QunaSys Partner to Advance Industrial Chemistry and Materials Science through Quantum Computing," Dec. 8, 2021, https://www.businesswire.com.

- *PsiQuantum*, producer of silicon photonics-based hardware and quantum architecture, and QunaSys, which develops innovative algorithms in chemistry, announced their partnership in December 2021. It aims to assess how well fault-tolerant quantum computing for industrial chemistry calculations could accelerate the development of sustainable materials. JSR Corporation joined as alpha customer to evaluate quantum computing for advancements in the manufacture of photoresists, elastomers, plastics, and reagents.

Promising mergers include the following:

- *Pasqal*, which focuses on neutral-atom hardware technology, announced a merger with Qu&Co, creator of algorithms for finance, fluid dynamics, and chemistry, in January 2022. The deal is intended to enable a full-stack, neutral atom solution to achieve near-term commercial benefit. It gives Pasqal access to Qu&Co's prestigious list of end customers (Airbus, BMW, Covestro, Johnson & Johnson, and LG) to accelerate commercialization efforts.

- *Honeywell Quantum Solutions,* developer of trapped-ion-based hardware, and CQC, which focuses on quantum chemistry, quantum machine learning, and quantum cybersecurity, announced their merger in June 2021. The merged entity hopes to offer the world's highest performing quantum computer and a full suite of quantum software that will better support customer needs for improved computation in cybersecurity, drug discovery and delivery, materials science, finance, and optimization across all major industrial markets.

ENTERPRISES

Multiple large industrial companies in sectors spanning life sciences and chemistry, financial services, energy, and automotive are working with quantum providers to explore applications for meeting business challenges. The following use cases are still under development as of this writing.

In life sciences and chemistry, Roche[15] is working with the quantum provider CQC on early-stage drug discovery and development. Meanwhile, Boehringer Ingelheim[16] is collaborating with Google on accurately simulating and predicting the behavior of large numbers of atoms during the R&D phase of drug discovery.

In financial services, Goldman Sachs[17] is working with Rigetti on quantum computing that can aid the pricing of derivative contracts by simulating market movements. Crédit Agricole CIB[18] is involved with Pasqal and Multiverse in exploring how quantum computing can support investment optimization to improve asset allocation and management.

In the energy sector, ExxonMobil[19] has teamed up with IBM to explore the optimization of ocean fleet routing. The European utilities company E.ON[20] is working with IBM to advance the integration of vehicle-to-grid technologies to the distribution grid, focusing on the coordination and control of widespread smaller systems.

And in automotive, Daimler has joined with Google and IBM to employ quantum computing for designing longer lasting and more efficient batteries for electric cars. Volkswagen has at least three applications in the works. It is working with D-Wave on how to accurately simulate and predict traffic conditions on congested road networks. Volkswagen is working with Pasqal and Qu&Co on optimizing schedules for electric vehicles' charging across multiple stations. With the same two quantum providers, Volkswagen also is exploring how to optimize the schedule for electric vehicles' charging across multiple stations.

15. . Rick Mullin, "Roche Partners to Apply Quantum Computing to Drug Discovery," *Chemical & Engineering News*, February 6, 2021, https://cen.acs.org.
16. "Quantum Computing: Boehringer Ingelheim Pioneers with Google for Pharma R&D," Boehringer Ingelheim, n.d., https://www.boehringer-ingelheim.com, accessed March 11, 2022.
17. Ram Sagar, "IBM & Goldman Sachs Make A 'Quantum' Leap Into The Markets," *Analytics India Magazine,* December 23, 2020, https://analyticsindiamag.com/.
18. "Crédit Agricole CIB: Partnership with Pasqal and Multiverse Computing in Quantum Computing," Multiverse Computing, June 2021, https://www.multiversecomputing.com.
19. "ExxonMobil Strives to Solve Complex Energy Challenges," IBM case study, n.d., https://www.ibm.com, accessed March 11, 2022.
20. Christian Drepper, "E.ON Allies with IBM Quantum to Advance Energy Transition Goals," E.ON, September 2, 2021, https://www.eon.com.

CLOUD PLAYERS

All major cloud players have entered the quantum computing ecosystem by partnering with quantum computing hardware companies and offering qubit systems via cloud services.

Braket is a fully managed offering from Amazon Web Services that gives customers access to quantum computing on the internet. AWS partners with D-Wave, IonQ, and Rigetti, which offer their existing quantum computers to run simulations. Microsoft's Azure Quantum service is a full-stack computing ecosystem that includes a cloud-based service and development kit for students, developers, and researchers working on quantum computing solutions. Its partners include Honeywell, IonQ, Quantum Circuits, and Rigetti. Google Cloud Marketplace offers quantum computing hardware including IonQ's 11-qubit system on Google's Cloud Quantum Service. Plans are under way to add IonQ's latest 32-qubit system sometime in 2022.

ALLIANCES AND NETWORKS ENTER THE RACE

Multiple alliances and networks involving quantum providers, research institutes, and enterprises are being formed in a healthy race to achieve quantum advantage.

IBM Quantum Network

Launched in December 2017, the IBM Quantum Network enables start-ups to run experiments and algorithms on IBM quantum computers via cloud-based access. In addition, the network offers an opportunity to collaborate with IBM researchers and technical subject-matter experts on potential applications, as well as other IBM Quantum Network organizations. Participating start-ups include Zapata, 1Qbit, Q-Ctrl, CQC, and QC Ware, among others.

Quantum Intermediate Representation (QIR)

Formed in 2021, Quantum Intermediate Representation (QIR) facilitates interoperability between new languages and new hardware capabilities within the quantum ecosystem.

Open technical development will enable the community to experiment with and develop optimizations and code transformations that work in a variety of use cases, even as software development kits for quantum development and languages rapidly appear and evolve.

QIR players include Honeywell, Microsoft, the Oak Ridge National Laboratory, QCI, and Rigetti.

Alliance for Quantum Technologies

The Alliance for Quantum Technologies is the result of a collaboration between the AT&T Foundry innovation center and Caltech. These two players joined forces in 2017 to bring industry, government, and academia together to speed quantum technology development and emerging practical applications. The collaboration also involves a new research and development program named INQNET, for Intelligent Quantum Networks and Technologies. The program will focus on the need for capacity and security in communications through future quantum networking technologies.

Quantum Technology and Application Consortium (QUTAC)

BMW, Bosch, and Volkswagen formed Quantum Technology and Application Consortium (QUTAC) to bring industry-relevant applications to market in the technology, chemical and pharmaceutical, insurance, and automotive industries. QUTAC's mission is to create the basis for successful industrialization of quantum computing in Germany and the rest of Europe.

M&A ACTION

Despite its nascent stage of development, the quantum ecosystem has seen three high-profile M&A deals in a short span (Exhibit 15):

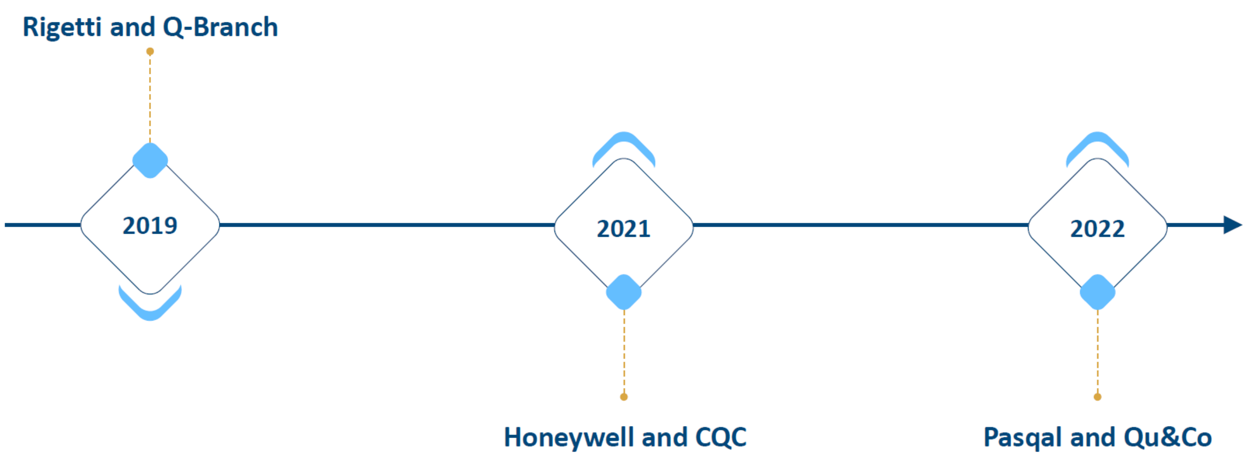
- Rigetti acquired QxBranch, a start-up in quantum computing and data analytics software, in 2019. The deal enabled Rigetti to expand its full-stack capabilities and build on its ability to deliver quantum solutions, algorithms, and services.
- Honeywell Quantum Solutions spun off its HQS unit to combine it with CQC, maintaining a 54 percent stake in the new company. This deal, which closed in 2021, created a full-stack quantum computing company. It give Honeywell access to more capital as the company looks to increase qubits on its quantum systems.
- Two start-ups in quantum computing, Pasqal and Qu&Co, merged in 2022. A key objective of the deal is to integrate Qu&Co's quantum algorithm routines with Pasqal's neutral-atom-based quantum hardware. The merged company, operating under the name Pasqal, also intends to address new markets for quantum solutions, especially in chemistry and life sciences.

Viewed together, these deals share several categories of objectives. One is that they aim to accelerate business development and customer acquisition.

Deal partners also seek greater ability to integrate hardware and software technologies, thereby improving the performance of quantum systems.

In addition, quantum players pursue greater ability to codesign next-generation quantum hardware and software products for specific markets. Finally, the deals seek to combine resources and best-in-class quantum talent.

Exhibit 15 Three high-profile M&A deals in the quantum ecosystem were closed in short span.



Source: Quantum Computing Report.

EXPECTATIONS OF CONSOLIDATION

Players in the space expect the quantum ecosystem to continue undergoing consolidation. For example, the general manager of EMEA region at Quantum Brilliance notes that the significant investments in quantum computing create a situation in which the pressure to become profitable has increased. Executives at Pascal and ColdQuanta, D-Wave, and ColdQuanta note the advantages of having expertise in both hardware and software. M&A is a fundamental strategy for achieving goals such as these (see sidebar "Case Study: Pasqal and Qu&Co's Merger").

Case Study: Pasqal and Qu&Co's Merger

The announcement of the merger of quantum computing start-ups Pasqal and Qu&Co predicted that the combined entity would become one of the leaders in quantum computing, especially because of the combined companies' full-stack capabilities (exhibit).

Exhibit

The case for full-stack capabilities

"Working with NISQ hardware is tough; there is no standard system. There is so much noise, so for any quantum advantage, we need to know if algorithms are working or not on a particular hardware. This is one of the reasons for Qu&Co to merge with Pasqal."

Former CEO of Qu&Co before merger with Pasqal

"Qu&Co has strong knowledge of applications and use cases with end customers. It's important for Pasqal to have those types of people and knowledge on board. We have developed the hardware, and now we are trying to find applications. "

Former CTO of Pasqal before merger with Qu&Co

Executives defined three rationales for the merger. First, the merger would integrate Qu&Co's rich algorithm portfolio with Pasqal's neutral-atom hardware to strengthen the combined organization's full-stack capabilities. Second, the combined company will be able to offer end-to-end quantum solutions to key customers, including Airbus, BMW, Crédit Agricole, EDF Thales, Johnson & Johnson, LG, and MBDA. Finally, the merger would combine best-in-class talent, including Qu&Co's team winners of the BMW–Amazon quantum computing challenge.

The merged company, operating under the name Pasqal, is small, but its ambitions are lofty. The newly merged company has 60 employees and operates in seven countries. It plans to target quantum solutions to a broad range of sectors, including aerospace, automotive, chemistry, defense, electronics, finance, life sciences, and utilities. It aims to deliver a 1,000-qubit quantum solution in 2023 and to become the European leader in quantum computing.

Industry players expect two types of mergers going forward. Most common will likely be those combining software and hardware players. Other deals will involve only hardware companies.

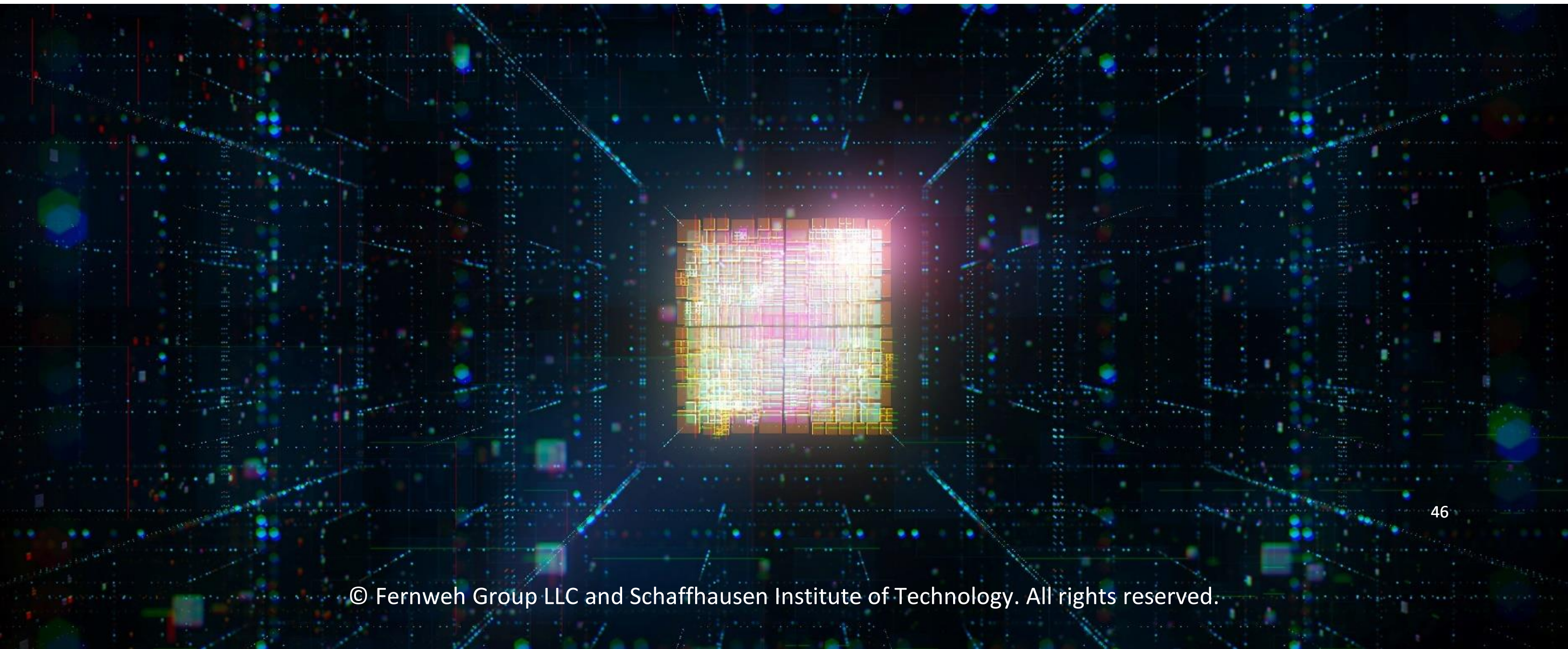
Deals bringing together hardware and software companies are likely to result from quantum computing companies' efforts to accelerate the pace of bringing quantum computing solutions to the market. These deals meet software companies' need to codesign algorithms with hardware companies, as well as hardware companies' need to get closer to end users and prove that their system works for users with specific algorithms. At this stage of quantum computing development, software and hardware cannot operate separately as they do in conventional computing, where, for example, Microsoft writes software that can run on systems designed by Dell or Lenovo using chips developed by Intel or Motorola.

Although deals between hardware players are likely to be less prevalent, the crowded nature of the space suggests they will become more frequent.

As many hardware players push on the different technology platforms, we can expect consolidation in the industry.

Some players will take the lead, and funding for others could dry up as investors back the leaders.

Quantum computing providers, enterprises interested in quantum technology applications, and cloud players are already engaging in the development and use of quantum technology. With the technology evolving quickly, industry consolidation is inevitable, and well-informed investors are critical to help move the ecosystem toward widespread adoption of viable applications.



Chapter 5

Paths to Widespread Adoption

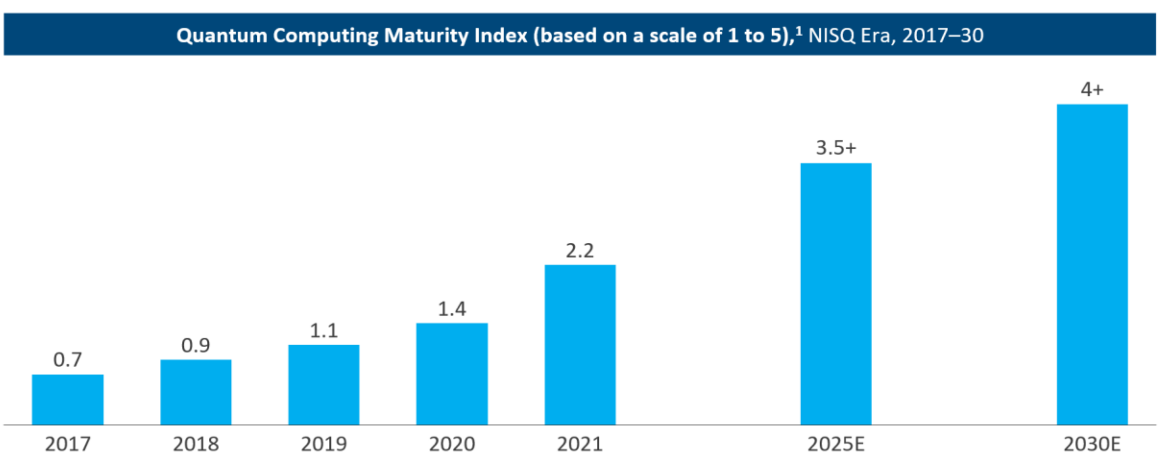
Paths to Widespread Adoption

For investors, the promise of quantum computing comes true when the technology achieves widespread adoption. Wide usage is, of course, also the dream of scientists and entrepreneurs in the ecosystem. For investors, the promise of quantum computing comes true when the technology achieves widespread adoption. Wide usage is, of course, also the dream of scientists and entrepreneurs in the ecosystem. To measure progress, Fernweh has developed a maturity index for quantum computing, based on four factors related to technological capabilities, investments, and industry participants. Applying the index, we find that quantum computing maturity has been increasing and is expected to accelerate during this decade. However, challenges lie in the way of widespread adoption. For the industry to meet these challenges, the various players need to meet the imperatives we describe in this chapter.

A Rapidly Maturing Industry

The quantum computing industry has been steadily maturing during the NISQ Era, a trend we expect to continue through the remainder of this decade (Exhibit 16). This conclusion is based on Fernweh's Quantum Computing Maturity Index (QCMI) which weights four factors: technology maturity, quantum players' maturity, the engagement of large ecosystem players, and investor activity (see sidebar "About the Quantum Computing Maturity Index").

Exhibit 16 Quantum computing maturity has been rising during the NISQ Era, with advances expected to accelerate over this decade.



[1]Fernweh's Quantum Computing Maturity Index measures industry maturity relative to, based on state of technology, clarity of industry participants' road maps, level of investor funding, and engagement of large players in the ecosystem. Based on a scale of 1 to 5

About the Quantum Computing Maturity Index

To develop the Quantum Computing Maturity Index (QCMI), Fernweh began by identifying four relevant factors and defining a metric for assessing each:

1. Technology maturity is measured as algorithmic qubit scale, that is, the number of algorithmic qubits achieved in quantum computing at the given time.
2. Maturity of quantum players is a count of the pure-play public companies existing at the given time.
3. Large ecosystem player engagement is a count of the number of large technology companies (e.g., Amazon, IBM, Google, ETC.) involved in the sector at the given time.
4. Investor activity is defined as the level of funding in the industry, expressed in millions of dollars.

We collected data for these, measured for each year between 2017 and 2021. We also estimated values for 2025 and 2030 based on technology road map projections of quantum players and analysis of trends and forces in the quantum computing ecosystem.. Based on the ranges of values, we rated each measure of maturity from 0 (not at all mature) to 5 (fully mature). The exhibit shows the values associated with these ratings.

	Rating Scale					
Factor	**0**	**1**	**2**	**3**	**4**	**5**
Technology maturity, scale in algorithm qubits	0	<5	5–10	10–50	50–100	>100
Quantum player maturity, number of companies	0	1–2	3–5	5–10	10–20	>20
Large ecosystem player engagement, number of companies	0	1–2	3	4	5	>5
Investor activity, $ million	0	<500	500–1,000	1,000–2,000	2,000–5,000	>5,000

Then we assigned weights to each measure and weighted technology maturity and maturity of quantum players by 30 percent each, and we weighted large ecosystem player engagement and investor activity by 20 percent each.

To calculate the index, we found the sum of the weighted values. The sum of the weighted values across the four factors in a year is the QCMI for that year.

3. Engagement of large players ecosystem, a count of the number of engaged technology giants (20 percent)
4. Investor activity, measured as the total level of funding that has flowed into quantum computing projects (20 percent)

Several milestones have contributed to the increase in maturity up to 2021. In technology, four players—ColdQuanta, IBM, QuEra, and Rigetti—have reached a scale of about 100 qubits. In maturity of quantum players, IonQ and Rigetti went public. In engagement, we have seen Amazon, Google, IBM, and Microsoft become deeply engaged in quantum computing. And investor funding reached $1 billion in 2021.

Looking ahead to 2025, we see further developments. Road maps of key quantum players suggest scaling could reach the level of 1,000 or more qubits. We expect two or three more pure-play quantum computing companies to go public. Technology giants, including Apple and Facebook, are expected to make announcements in the quantum computing space. And there is much potential for additional investor funding. Only five companies have received funding of at least $100 million as of this writing, and more will likely attract investments at this level.

By 2030, with qubits expected to scale to a million or more, pure-play quantum computing companies will become larger, attracting more funding.

More will go public, and technology giants will continue to play major roles as intermediaries in the quantum computing ecosystem.

CHALLENGES TO WIDESPREAD ADOPTION

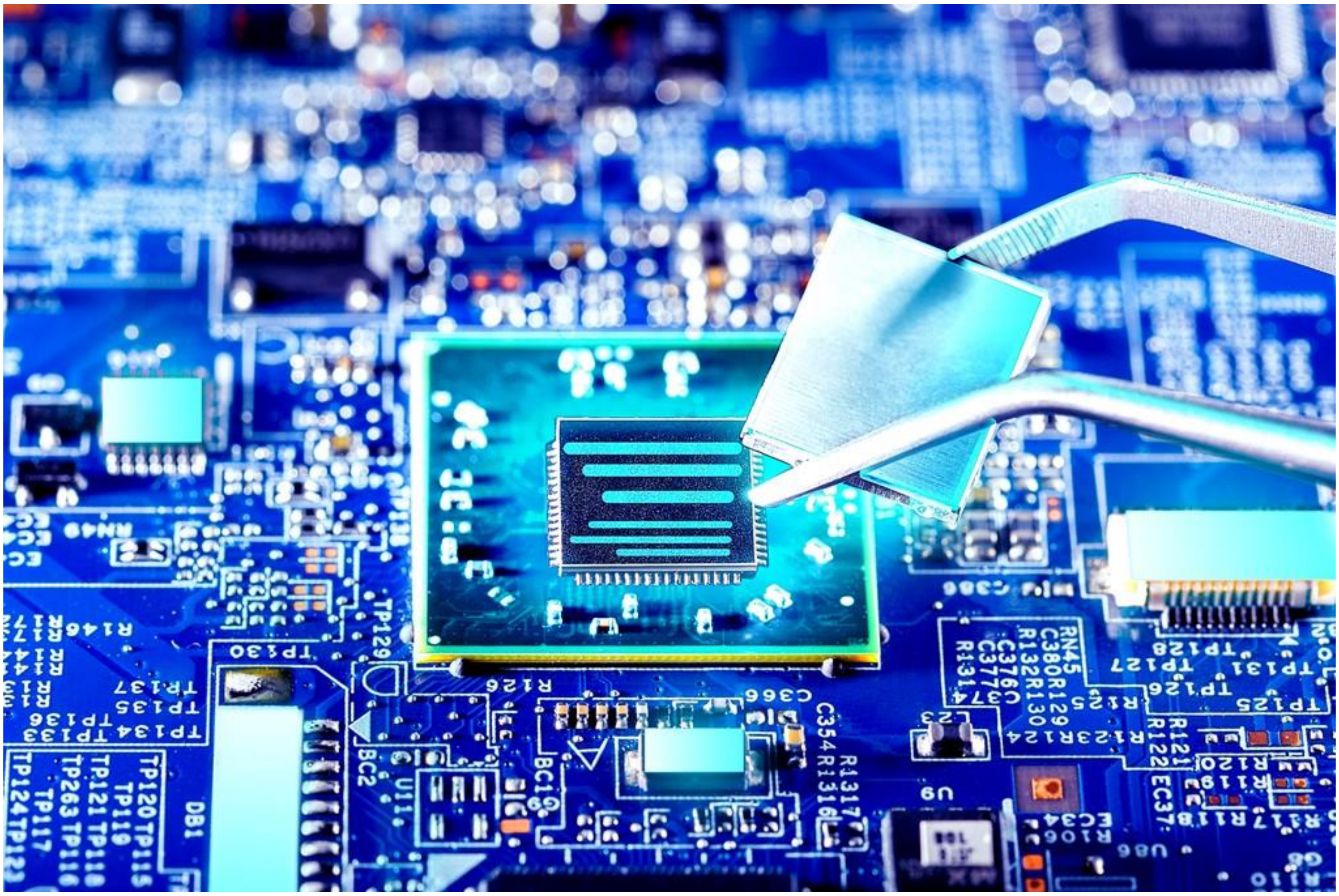
As quantum computing providers try to follow their road maps toward widespread adoption, several major challenges complicate their path: the limited engagement of enterprises so far, the lack of compelling apps available at the early stages of this technology, and a shortage of expertise among those with an interest in the technology.

Limited Enterprise Engagement

So far, enterprise engagement in quantum technology has been confined to a few Fortune 500 companies with limited spending on projects. Enterprises typically provide internal resources during collaborations with quantum computing providers, and their key objective is development of intellectual property, rather than promoting commercial applications (for examples, see sidebar "Early Movers in Quantum Computing").

Early Movers in Quantum Computing

So far, efforts to build internal quantum computing teams and engage with start-ups has been limited to a few early movers, such as Airbus, BMW, and J.P. Morgan.



Airbus set up a Quantum Technology Application Centre in Newport, Wales, in collaboration with Endeavr. The center focuses on exploring space, aerospace, and defense applications with external partners such as Cardiff University. In 2019, the company launched the Airbus Quantum Computing Challenge to promote innovation across the full aircraft life cycle and shift the context of science from laboratory to industry. In 2021, Airbus signed a collaboration agreement with Qu&Co for research, development, and testing of quantum computational methods for flight physics simulations relevant to the European aerospace and defense sector.

BMW has established two quantum technology teams—one in the development department and the other in IT—firmly implanting quantum computing into its strategy. The company launched a quantum computing challenge in 2021 in collaboration with Amazon Braket. The competition invites start-ups and academics to provide quantum solutions for specified problems. The same year, BMW announced that it had been making progress in designing quantum algorithms for supply-chain management; these have been successfully tested on Honeywell's 10-qubit system.

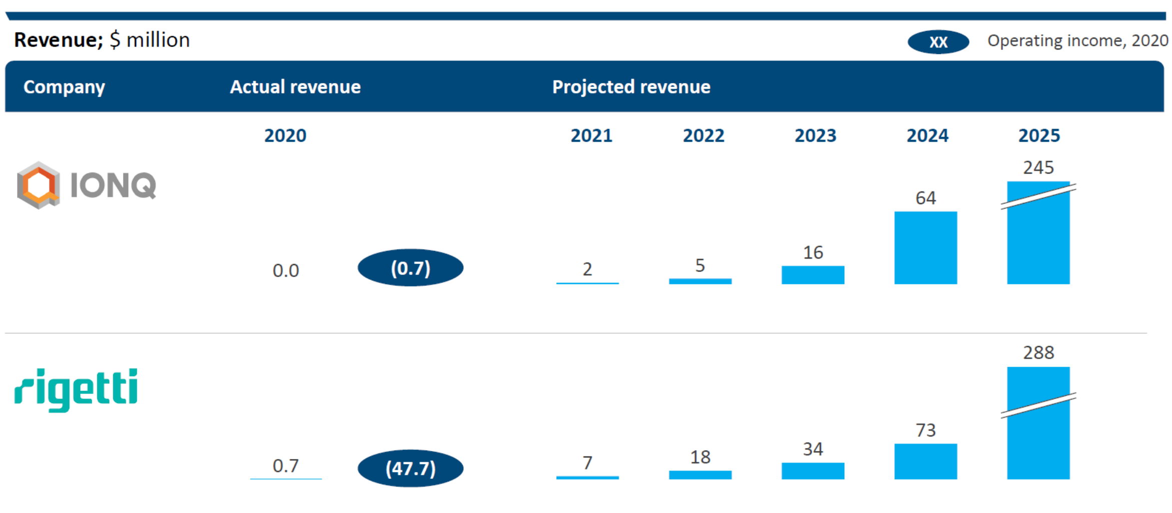
J.P. Morgan has set up a quantum engineering team, headed by Marco Pistoia, who was hired from IBM to be head of applied research and engineering. The company also set up an internship program for quantum computing talent. In 2019, J.P. Morgan's quantitative research team and IBM researchers coauthored a paper on a methodology for pricing option contracts using a quantum computer. The following year, J.P. Morgan partnered with the Chicago Quantum Exchange, a quantum technology hub working on post-quantum cryptography.

The low level of committed project spending from enterprises constrains investments by quantum technology companies, ultimately providing a drag on revenue growth. At companies that have gone public, revenues have been small to date (Exhibit 17). With even the investor-backed start-ups still lacking a proven stream of revenues, the quantum computing ecosystem is still waiting for a success story to draw significant funding.

Solving the enterprise engagement challenge is the key;

one sizable investment in the right company could set off a chain reaction that leads to widespread adoption of quantum technology.

Exhibit 17 Limited enterprise spending on quantum technology projects has suppressed revenue growth at select quantum computing companies.



Source: IonQ investor presentation 2021; Rigetti investor presentation 2021; Sentieo Financial Tool.

How Enterprises Can Engage

Some Fortune 500 companies, including Airbus, BMW, Citigroup, and Goldman Sachs, are actively engaged in quantum computing via investments in start-ups, encouragement of experimentation by sponsoring quantum computing challenges, and convening of industry events (Exhibit 18). In a survey of 300 corporate leaders, 28 percent reported having quantum computing budgets larger than $1 million.[5]

A 2021 survey by International Data Corporation (IDC) found that

the number of organizations allocating more than 17% of their annual IT budgets to quantum computing is expected to rise from 7 percent in 2021 to an estimated 19 percent by 2023.[6]

Exhibit 18 Enterprises that are engaged in the quantum space do so in several ways.

01 Increasing quantum budgets

02 Investing in quantum start-ups

03 Providing a launchpad for experimentation

04 Convening events

Enterprises also are investing in start-ups by providing seed capital. Citigroup, for example, has invested in 1Qbit and QC Ware, and Airbus is leading the series B funding of Q-Ctrl. In some cases, organizations have their own venture capital arms to carry out this type of investing.

Companies with an eye on the future may want to bridge the gap between academia and industry. One way of doing this is to sponsor a quantum computing challenge, such as the BMW-IBM Computing Challenge and the Airbus Computing Challenge. This provides a launchpad for quantum start-ups to work on real industrial use cases.

Another way to support the advancement of quantum technology is to convene events where researchers, businesspeople, and thought leaders can learn from one another. For example, the Dutch Payments Association—whose members include ABN AMRO, ING Group, and Rabobank—organized a quantum symposium in March 2021. The symposium was organized in collaboration with Quantum. Amsterdam, the innovation hub for quantum software, technologies, and applications.

[5] The First Annual Report on Enterprise Quantum Computing Adoption, Zapata Computing, December 2021, https://www.zapatacomputing.com.

[6] Heather West, IDC Enterprise IT Infrastructure Survey, 1Q21: Insights on End-User 2021 IT Compute Infrastructure Priorities and Adoption of Quantum Computing, IDC, April 2021, https://www.idc.com.

The event gave a brief update on developments related to quantum computing, explores opportunities, prepares for the advent of the quantum computer, and aims to strengthen the dialogue between the academic and industry community.

IMPERATIVES FOR STAKEHOLDERS

For quantum advantage to become a widespread phenomenon, each category of stakeholders in the quantum technology ecosystem needs to recognize and meet its own set of imperatives (see sidebar "Qu&Co's Benno Broer on Overcoming Obstacles").

Qu&Co's Benno Broer on Overcoming Obstacles

Following Qu&Co's merger with Pasqal, former CEO Benno Broer, became the chief commercial officer of the merged entity that will keep the name Pasqal. The following edited transcript is from his recent conversation with Fernweh's Nidhi Arora about the challenges facing widespread adoption of quantum technologies.

Nidhi Arora:

As the technology for quantum computing continues to develop, what remaining challenges could prevent commercialization of quantum computing?

Benno Broer:

We have to get people to adopt the technology. There may be a lack of killer apps in the beginning, but first narrow and then broad quantum advantage should trigger a huge amount of interest. Then we will have some use cases that can be used to make the killer apps.

In the beginning, we need turnkey solutions from full-stack players. If we want a high level of adoption in the beginning, we want people who know this to develop easy turnkey solutions for end users to plug in and play. Full-stack players are best positioned to offer turnkey solutions for quantum advantage.

This will have to be delivered as part of a broader classical software tool, which is why Qu&Co have been focusing on this with Qubec. Users who do not want to get trained in quantum computing for 2 years have already been investing in classical computing workflows, so they would like to just alter a step or two and reap the benefits of quantum offered through a cloud service or a local HPC [high-performance computing] center and potentially also the ability to install this hardware on premises.

Finally, the whole thing has to become a part of a trusted ecosystem with hardware. Companies should be willing to get this hardware from players like Pasqal plus infrastructure from large players like AWS, Microsoft, and Google. You need that to increase the adoption rate.

Nidhi Arora:

Could talent or supply of components be a limiting factor for scalability?

Benno Broer:

Workforce should not be an issue. The first wave of consolidation has already happened, and in a few years, we will have 10 large-scale, full-stack players. Each of these would have 500 to 1,000 people, which is not a lot. At some point, in fact, we might have an oversupply of talent. Look at any workforce report.

But it will be difficult for small players and end users to find interesting talent. There won't be small software players that have five or 10 people to build software, because this is a specialist space. Large players will be the ones that will survive and attract talent.

In the supply chain, one of the forces could be geopolitical trends—for example, if some part cannot be exported. We have seen that already for some parts of superconducting qubits. This could be a risk for scaling.

Nidhi Arora:

How good has engagement and adoption been from end users? What role do they need to play to shape this space?

Benno Broer:

Part of the market is just talking about it and not investing enough in it. It is the same names again and again in conferences. People will say there is an interest group, but they do not do much about it. But there are companies that have longer-term engagements.

On one end, they should be putting in domain experts to understand where they are running into limits of their use cases. The other thing is that we need some private funding from these companies, the willingness to spend $100,000 to $200,000 on R&D and collaborative efforts. They will put internal resources, but ultimately some of the start-ups need to show revenue to have traction and get funding.

Companies should not be in it to capture IP [intellectual property] from these engagements. They should be open to procuring. They should support the growth of the sector. This will help the start-ups get going, and then VC [venture capital] funding will take over.

We need companies that realize the technology could become something for them. They want to be innovative and tell the world that they are doing it but let the quantum sector develop as a sector of its own. We want end users to engage with start-ups and big players, so they should not force end users to overstate the results.

Nidhi Arora:

What role do investors and governments need to play for quantum computing to make its mark in the real world?

Benno Broer:

Investors and governments are very important. This sector has little money coming out of actual projects. Until tangible benefits are shown, investors and governments will need to support the quantum sector until quantum advantage is reached. Then with narrow advantage, government funding can go away. A couple of years later, spending from companies can also take over from venture capital.

Governments currently play a good role in supporting investments, but they should also take responsibility for thinking about international trade and setting up supply chains. There is a lot of geopolitical stuff happening right now. We need less of that.

Quantum Computing Providers

Hardware companies must adopt a strategy that is more oriented to the end customer. For people deeply engaged in science and technology, it is tempting to assume that "if we build, they will come" and make a purchase. However, to attract interest and the accompanying investments, companies must identify and meet customer needs.

Enterprises

Given that most enterprises have not yet invested in understanding quantum technology and its potential, the primary imperative is to start preparing for quantum advantage.

When that era arrives, the companies that are ready to apply the technology will swiftly pull ahead of those that are unprepared. Preparation involves a structured approach (Exhibit 19):

Extending this customer focus, a second imperative for technology providers is for hardware and software companies to collaborate on developing compelling apps that can integrate seamlessly into enterprises' existing high-performance computing (HPC) infrastructure until they are ready to make investments in quantum infrastructure.

1. **Education.** Companies need to understand the technology's implications for business. This requires identifying and prioritizing business problems that can be addressed with quantum applications such as optimization, simulation, and machine learning. A helpful tactic is to prepare business cases for each quantum computing use case affecting the various parts of the organization based on the potential value to be delivered.
2. **Blueprinting.** Develop a five-year road map for the adoption of quantum computing, including data and IT readiness, onboarding of providers, and rollout of use cases. Map out the gap between the company's existing and required data and IT infrastructure. Identify algorithms that would be useful and potential software and hardware providers. Sequence the prioritized use cases.
3. **Experimentation**. Evaluate providers and start exploring applications. Begin by identifying all providers in the quantum ecosystem, including hardware and software quantum companies, academic institutions, research labs, and cloud-based providers. Then prioritize the right companies to partner with and engage via short-term commitments, such as pay-per-use models for cloud quantum services and project-based collaboration, for initial experimentation. Based on the results of experimentation, seek longer term commitments with providers.

Exhibit 19 Companies need to start preparing today for the era of quantum advantage.

Education
- Understand technology's implications for business

Blueprinting
- Develop a road map for adoption of quantum computing

Experimentation
- Evaluate providers
- Start exploring applications

Investment
- Develop in-house quantum skills and infrastructure

Source: Industry interviews; Marc Carrel-Billiard, "Five Years until Enterprise Quantum, but Your Prep Begins Now," *VentureBeat*, July 10, 2021, https://venturebeat.com; Owen Hughes, "Quantum Computing in the Enterprise: Four Factors to Consider," *ZDNet*, Nov. 1, 2021, https://www.zdnet.com; Kalyan Kumar, "Rebooting the Future with Quantum Computing," *Reworked*, Dec. 9, 2020, https://www.reworked.co.

4. **Investment**. Develop quantum technology skills and infrastructure in-house. Build an in-house quantum workforce with a broad spectrum of skills—academic (quantum physics scientists and researchers, data scientists), developers and engineers (software coders to build algorithms and enterprise applications or product interfaces), and subject-matter experts at the interaction of quantum and business. Finally, develop the data and IT systems' architecture required to implement quantum applications and use cases.

In addition, take steps now to begin investing in quantum technology, even if you must start slowly and build up gradually. Set aside and commit spending on R&D and collaboration projects with quantum computing companies. Start with as little as $100,000 or $200,000 per project. As the practicality of applications emerges, you will be ready to scale up.

Governments

Governments that want to equip their economies for the future of technology also will need to educate themselves and direct investments wisely. Investing in start-ups can encourage development of commercial applications. Another possible role for governments is to facilitate the building of international supply chains for the various hardware components used in quantum technologies—for example, lasers, fabricated chips, controls, and cooling devices.

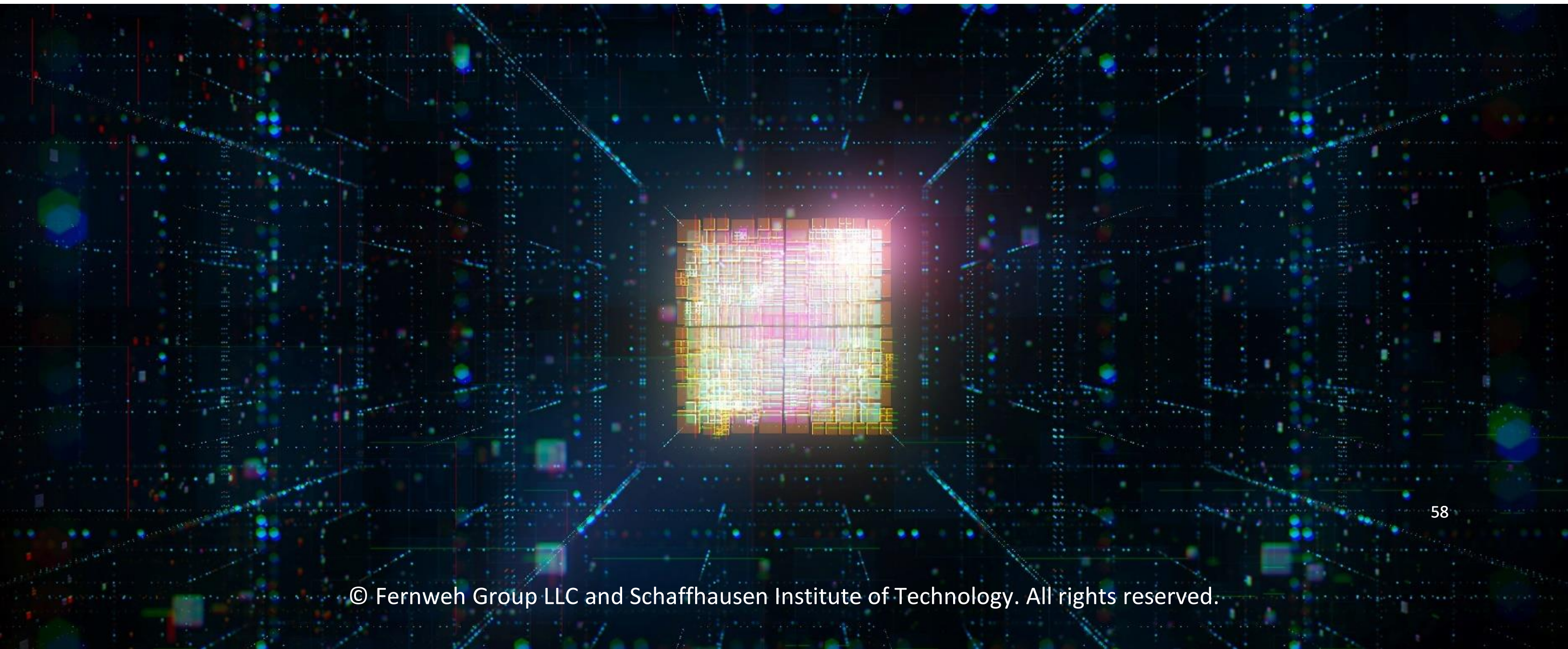
Private Investors

In the private sector, investors should establish a long-term horizon for investment in quantum start-ups, keeping in view technology road maps such as those described in this report and those that update the present information.

Investors can benefit greatly from developing deep relationships as tech partners of start-ups.

One way to cultivate mutually beneficial relationships is to engage with them in solving problems associated with potentially useful applications.

Widespread adoption of quantum technology will arrive, but the pace and effectiveness of change will depend on the actions of stakeholders in all categories. Quantum computing providers can hasten adoption by working with end users to develop practical use cases. Enterprises should develop their understanding of the technology and plan to scale up their investments strategically and with eyes wide open. Governments can prepare their economies by investing in supply chains and entrepreneurship. Investors can direct their funds wisely by researching their moves and becoming long-term partners with high-potential start-ups.



Conclusion

As quantum technology moves out of university research labs and into businesses, investments in quantum technology are surging. More than 100 start-ups are operating; a significant share of them with a working product.

True, quantum computing devices are small in scale and not yet practical for business uses, but with early breakthroughs on the horizon for applications such as financial modeling and optimization of decisions in logistics and manufacturing, the time to act is now. Quantum computing may outperform all forms of classical computing in a broad range of applications by the 2030s.

For developers and investors, we see the strongest potential for companies set up as or evolving into full-stack providers. Hardware-focused companies are getting a few steps closer to end-users by forging partnerships or merging with software and algorithm companies that already have a prestigious list of enterprise customer relationships. Multiple large enterprises are engaged in developing use cases with providers for identified business problems. The major cloud players are partnering with hardware providers to offer existing qubit systems via their cloud services.

As quantum providers are forming alliances with enterprises and institutes to speed up development of a scalable commercial quantum computer, industry experts and providers forecast an upcoming wave of consolidation, driven by the need to accelerate business development and customer acquisition, co-design next-generation hardware and software products for specific markets, and combine resources for more economies of scale and best-in-class talent.

Success in this space will require overcoming significant challenges impeding widespread adoption. Most significantly, enterprise engagement remains limited, as reflected in slow revenue growth and quantum start-ups. Also, some providers have yet to take a customer-focused approach to strategy. For quantum advantage to become a widespread phenomenon with commercial applications across a broad range of sectors, all stakeholders will need to influence the shaping of the market. Quantum computing providers should consider a full-stack strategy with more hardware-software collaboration to develop compelling apps for practical use cases. Enterprises must educate themselves, scale up investments in R&D projects with providers, and focus talent strategy more on internal quantum skills. Governments need to facilitate establishment of international supply chains for components and invest in start-ups, not just in academia. Investors should consider becoming long-term partners to the start-ups.

The technology is complex, and therefore the path forward may seem daunting. But for investors and business leaders willing to explore the frontiers of innovation, these are exciting times indeed.

Glossary

TITLE	DEFINITION
Algorithmic qubits	• Largest number of effectively perfect qubits that can be deployed for a quantum program • Takes error correction into account and represents the number of “useful” encoded qubits
Copenhagen interpretation	• A collection of views about the meaning of quantum mechanics principally attributed to Niels Bohr and Werner Heisenberg • One of the oldest of numerous proposed interpretations of quantum mechanics and still one of the most taught
Decoherence	• In quantum computing, a qubit’s interactions with its environment • Causes disturbances and leads to errors in quantum information
Fault-tolerant (FT) quantum computers	• A computer that captures and corrects errors and limits the ways in which errors can spread throughout the system
Physical qubits	• A physical device that behaves as a two-state quantum system (qubit), used as a component of a computer system
Quantum advantage	• Demonstrated and measured success in processing a real-world problem faster on a quantum computer than on a classic computer
Quantum annealing	• A type of quantum computing used mainly for optimization problems • An optimization process for finding the global minimum of a given objective function over a given set of candidate solutions
Quantum error correction (QEC)	• A set of methods to protect quantum information—that is, quantum states—from unwanted environmental interactions (decoherence) and other forms of noise • The information is stored in a quantum error-correcting code, designed so that the most common errors move the state into an error space orthogonal to the original code space while preserving the information in the state

TITLE	DEFINITION
Quantum entanglement	• The occurrence of two atoms becoming enmeshed or entangled despite being separated by space • Changes in one of these atoms instantly changes the properties of the entangled partner atom.
Quantum mechanics	• The branch of physics that deals with the behavior of matter and light on a subatomic and atomic level • It attempts to explain the properties of atoms and molecules and their fundamental particles like protons, neutrons, electrons, gluons, and quarks.
Quantum superposition	• A physics theory that subatomic particles can exist in multiple states at once • Unlike classical binary digits — the 1 and 0, which form the basis of traditional computing—qubits can exist as both 1 and 0 at the same time or as a linear combination of 1 and 0.
Quantum supremacy	• The demonstrated and measured ability to process a problem (any problem, not necessarily a real-world problem) faster on a quantum computer than on a classical computer
Qubit	• The basic unit of quantum information; the quantum mechanical analogue of a classical bit • While each bit can have the value 0 or 1, a qubit can be in state 0 or 1 or in a linear combination of both states.
Squeezed state	• A quantum state for which one of a pair of conjugate variables, which cannot simultaneously possess definite values according to the Heisenberg uncertainty principle, is specified more accurately than in the vacuum state, at the expense of increasing the uncertainty in the value of the other variable

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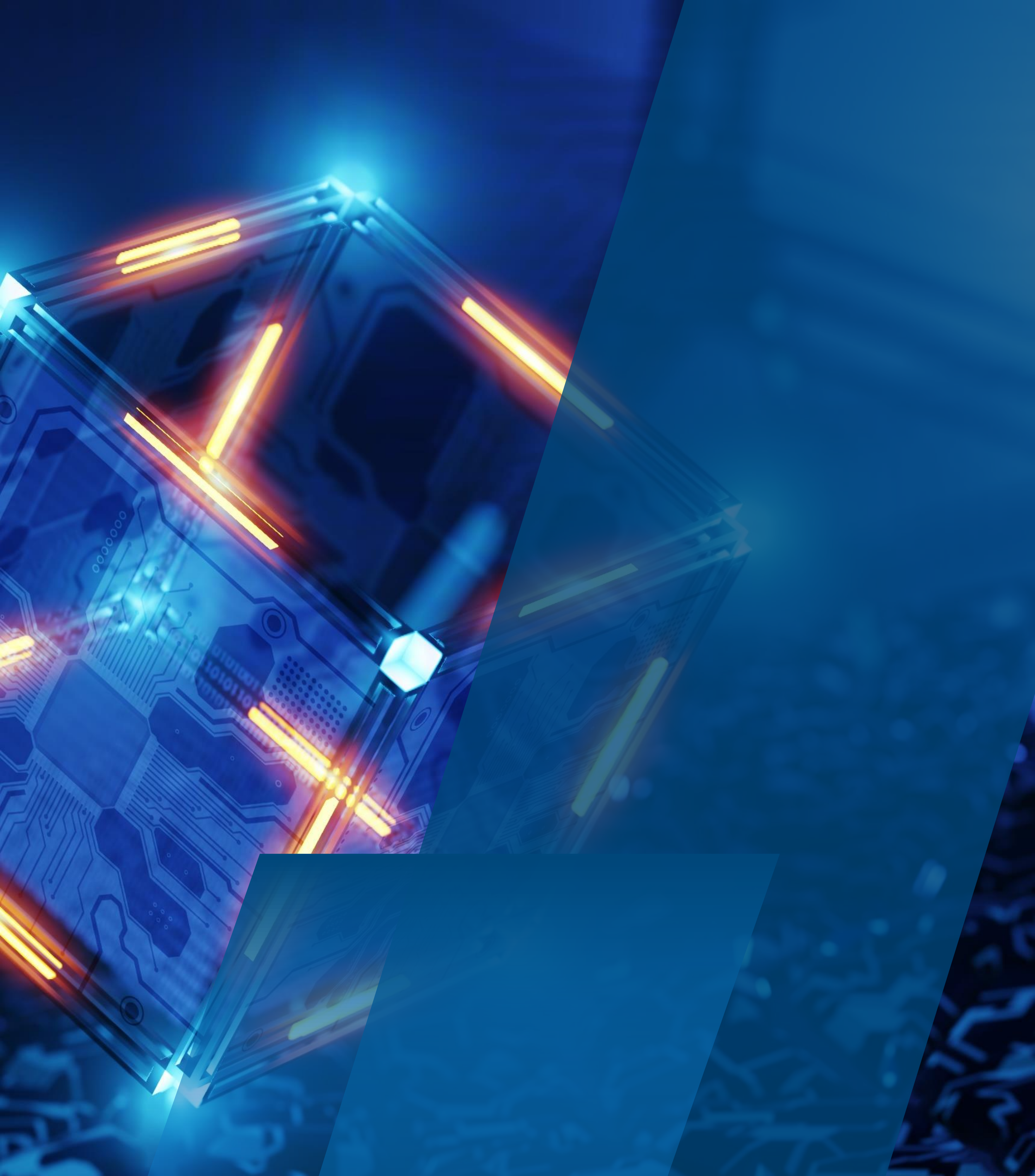

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