

Technology Observer

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Quantum Computing May Be Small Now: Long-Term Horizon Required to Invest in This Emerging Area

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Executive Summary

Quantum computing is an emerging area that is likely to have a profound impact on the compute function as it offers potential performance advantages over traditional computers. It seems likely that quantum computers will be able to perform calculations that are simply not possible using even the most powerful classical computers in the world today. With headline-stealing promise like that, money has been pouring into the field for some time, and several publicly traded quantum pure-plays have seen their market caps balloon in 2025.

The technology is nothing short of bleeding edge, but unfortunately, quantum computing is not ready for mass-market adoption. Investors should take notice that the technology is real, even if experimental, and is being used in real-world trial situations. The hardware lags where it needs to be to drive commercialization and we see the ecosystem, including software, as being underdeveloped and scattered. We think in the next five to 10 years we will begin to see commercial deployments of limited capability systems for specific use cases. We think use cases will initially be limited, as the technology remains in its infancy. However, the floodgates should open eventually, giving way to broad quantum computer availability solving all manner of problems with broader applicability.

Companies Mentioned

Name/Ticker	Economic Moat	Currency	Fair Value Estimate	Current Price	Uncertainty Rating	Morningstar Rating	Market Cap (Bil)
Amazon (AMZN)	Wide	USD	260.00	230.00	Medium	★★★★	2447.00
Alphabet (GOOGL)	Wide	USD	340.00	322.00	Medium	★★★	3888.00
IBM (IBM)	Narrow	USD	264.00	308.00	Medium	★★	287.00
Microsoft (MSFT)	Wide	USD	600.00	483.00	Medium	★★★★	3582.00
Nvidia (NVDA)	Wide	USD	240.00	182.00	Very High	★★★★	4441.00

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Dan Romanoff, CPA
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivyaa Vaidya
Associate Equity Analyst
+1 872-371-4154
jivyaa.vaidya@morningstar.com

Key Takeaways

Quantum Computing Is Coming

- ▶ Quantum computing is real and promising, as it offers exponential speed advantages in some use cases, but the applicability is quite limited for now. Primary initial use cases are likely to be in pharmaceuticals, materials science, and cybersecurity. We believe this powerful technology will warrant research and development budgets for firms operating in these fields to shift more toward quantum over time.
- ▶ The investment follows the opportunity, and we believe the market for quantum computing can be enormous. The market can be \$200 billion annually at maturity, which we believe could be up to 30 years from now, and will be driven by fundamental performance advantages, new use cases for problems that cannot be addressed by computers today, and mass-market adoption.

Early Commercialization Is at Least Five Years Away

- ▶ Quantum computing is not ready for widespread adoption and probably will not be ready for even the earliest adopters in the initial commercialization stage for five to 10 years. We see market commercialization for general-use quantum computers beginning in about 20 years, with market maturity in approximately 30 years.
- ▶ Quantum computing must develop along three vectors to make the technology viable: improved hardware (including more quantum bits in fault-tolerant systems), new software, and a more developed ecosystem. We see progress on all three fronts from a wide variety of industry participants and believe that we are on a path to eventual full commercialization.

The Platform Model Will Likely Prevail in a Crowded Field Led by IBM

- ▶ We see the cloud service providers as best-positioned for the long term, given the established cloud platforms, established quantum platforms, financial resources, and ongoing R&D. Quantum computing will likely become another menu item within the public cloud suite.
- ▶ The field is already crowded with startups, large-cap vendors with quantum divisions, and government or academic research projects, which we do not think is viable over the long term.
- ▶ IBM is the clear leader in quantum computing today. We see Alphabet as already well-positioned and Microsoft emerging as a strong player that has been building a portfolio of quantum technology specifically around chemistry use cases, where we think it has already built a roster of users. We also see Amazon and Nvidia as offering call optionality for quantum exposure.

Investors Must Focus on the Long Term for Quantum Computing

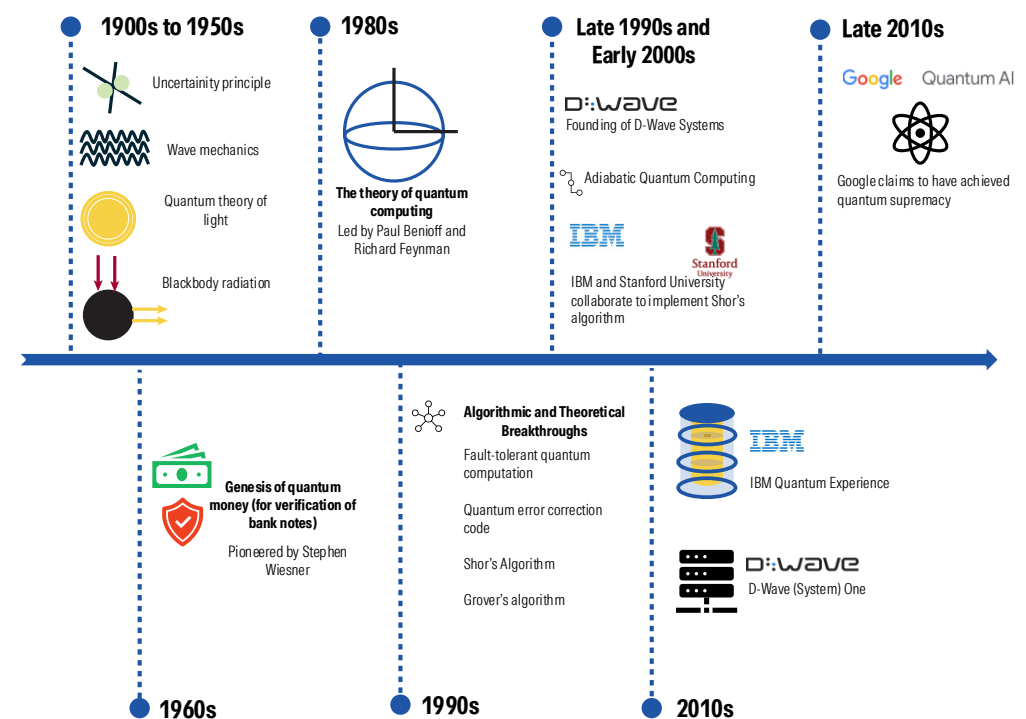
- ▶ We think investors seeking a rapid fundamentals-based return are fishing in the wrong pond, given the likely timeline to even initial commercialization.
- ▶ Our top picks for quantum computing are Microsoft and Alphabet, as they are the only stocks that currently offer attractive upside to our fair value estimates. Realistically, we think investors are yet to ascribe value to their quantum efforts, so we view quantum as offering future upside. We also think it will take years for quantum-related value to be realized by investors.

While we do not cover the four publicly traded quantum computing companies, we are cautious about them in general given extreme valuations, limited revenue, negative cash flow, and the likely need for capital infusions to stay afloat as they develop their technologies

Quantum Computing Is in Its Infancy, but Can Grow to Be a Significant Opportunity

Quantum computing is an emerging technology area that is not quite ready for prime time. It has been a slow rolling development over a century that is founded in theoretical physics by the intellectual giants of that era, including Albert Einstein. Along the way, academics reconciled experimental oddities with theoretical foundations and the field has slowly been pushed forward. In the last 20 years, tens of billions of dollars have been plowed into research and development programs surrounding quantum computing. Pilot programs and test case usage are underway. While we think the technology is still years away from mass adoption, we think it is reaching critical mass and can move from the experimental phase to the early adopters perhaps as soon as five years from now.

Exhibit 1 The Road to Quantum Computing Has Been Long Indeed



Source: BTQ, Morningstar.

While the timing may be somewhat of a moving target, quantum computing should ultimately represent a massive market opportunity. We think it will open up new computing possibilities and can possibly pick up where Moore's law eventually leaves off and drives the entire compute function forward. Overall, we find ourselves at odds with the consensus opinion on quantum technology mainly on the timeline to commercialization and the ultimate market size. Further, given that the technology is still emerging, the market's view seems to be somewhat scattered.

Exhibit 2 We Have Developed a More Holistic View of the Quantum Computing Market

Topic	 Morningstar View	 Market View
Technology	Quantum computers are proven technology that work today on a limited basis but need to be improved along many vectors.	The combined market capitalization for the publicly traded pure plays is in excess of \$50 billion (Oct. 21, 2025) despite having very little revenue so either the market believes the technology is ready or commercialization will happen in the near future.
Market Opportunity	The market is very limited today based on the fact that the technology is not mature, but the opportunity will eventually be substantial. We think the market can reach \$200 billion annually at maturity.	Some well-known consulting organizations have pegged a market that can reach \$1 trillion in a couple decades.
Timing	Quantum technology remains a minimum of five years away from commercialization, as more development is needed within hardware, software, and the overall ecosystem.	The combined market capitalization for the publicly traded pure plays is in excess of \$50 billion (Oct. 21, 2025) despite having very little revenue so either the market believes the technology is ready or commercialization will happen in the near future.
Leadership	IBM is clearly the leader in 2025. We think the industry develops to include multiple winners, including IBM and the large cloud service providers.	Given more than \$40 million in revenue last year and the largest market cap of the publicly traded quantum computing companies, the market sees IonQ as the leader.

Source: Morningstar.

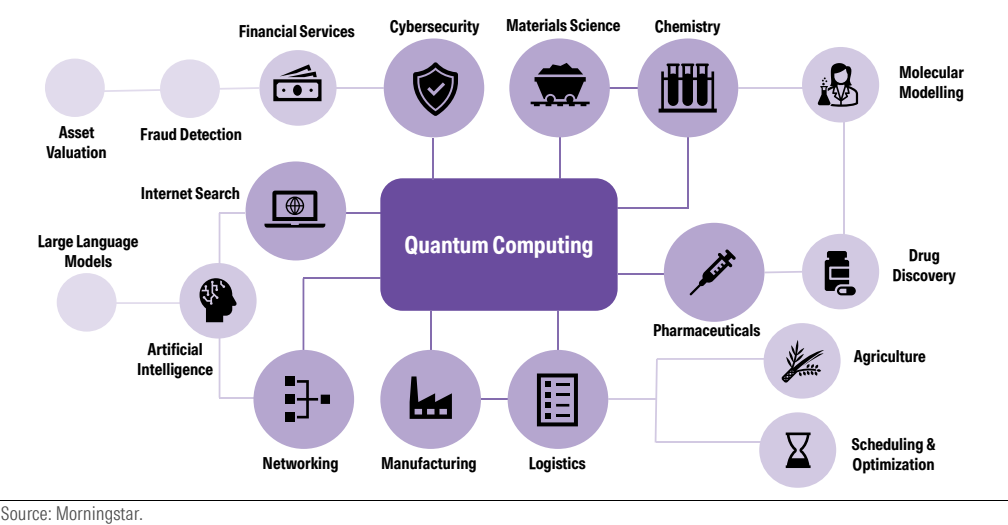
Challenges remain—primarily driving costs down, scaling systems up, and reducing error rates. The technology itself is advancing rapidly along many vectors. There are various approaches to the underlying architecture of quantum processors, including the creation, usage, and measurement of states of quantum particles along variables such as spin and charge. The particle building blocks of these processors are being stretched to perform calculations faster, and have longer periods of coherence or usability while producing fewer errors. New materials are being explored and new types of qubits are being created. The cost of most of these systems is inherently rolled into the technical challenges. We liken it to the early days of the transistor or mainframe computers. We see impactful advancements happening on a weekly basis throughout the quantum technology research chain. In the last 12 months we have seen breakthrough quantum processor announcements made by Alphabet (Willow), Amazon (Ocelot), and Microsoft (Majorana One).

With so many companies funding projects or being formed in dedication to quantum computing, we are impressed and think it is simply a matter of time. There are publicly traded companies, such as D-Wave Quantum (QBSTS), major cloud service providers such as Microsoft, industrial conglomerates such as Fujitsu, and venture capital-funded startups like Xanadu—all of which we discuss in some detail in this report. These companies are pushing different technology nodes for qubits, different parts of the quantum value chain (quantum computing as a service versus stand-alone on-premises systems), consulting, and software. Quantum computing, for example, is Microsoft’s single longest-running R&D project, at nearly 20 years.

Nearly as important to the hardware element, we see different aspects of the quantum computing ecosystem beginning to coalesce. There are dozens of primary quantum algorithms, with major cloud service providers and IBM all offering their own quantum platforms for algorithm writing, simulating, and testing. Leading global consultancies such as Accenture and Deloitte have already established practices around quantum technologies. We see the ecosystem as real and ready to grow as technological experimentation continues.

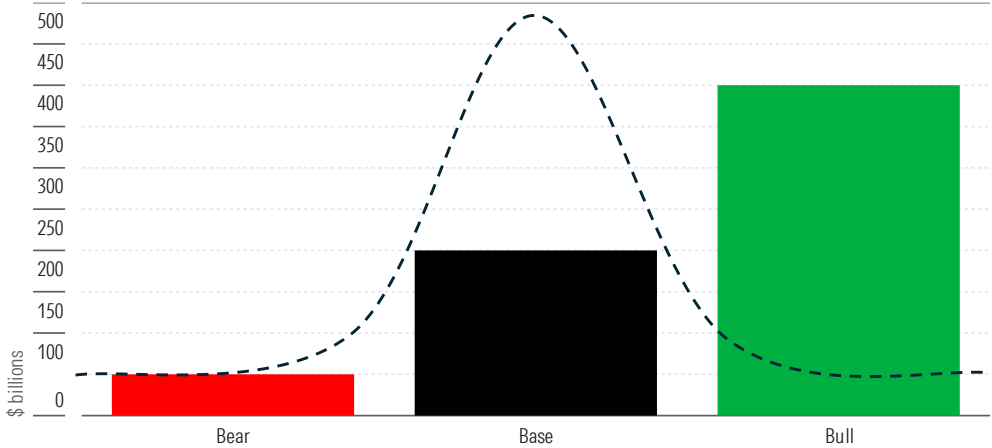
Figuring out exactly what to do with powerful technology is an important process also. Progress is being made here, but again, it is very early in the development cycle. The use cases then are going to be highly specialized and perhaps for areas where even powerful public cloud muscle is not enough to tackle certain kinds of problems. Chemical molecule analysis, for example, is likely to be an area where quantum computing shines, and we can easily see complex molecule and large protein analysis in drug discovery happening in ways that simply are not possible on today's computers even with powerful server arrays.

Exhibit 3 While Initial Use Cases May Be Limited, This Should Expand Over Time as the Technology Improves



A unique angle of quantum computing is that classical computers are going to perform most workloads in a much more efficient manner, at least through the early adopter phase, or in other words at least the next 10 years. That said, we expect the market for quantum computing to eventually be substantial, even if it takes years to get there. We think the market could reach \$200 billion annually in approximately 30 years.

Exhibit 4 We See a \$200 Billion Market, Even if It Takes 30 Years to Realize and Has Fat-Tailed Possibilities



Source: Morningstar.

In short, quantum computing is a very exciting area with potential to have significant impacts on large swaths of the economy. The technology and surrounding ecosystem are growing and evolving on a monthly basis. Change has been rapid, and we expect it to remain so over the next several years, even as quantum computing has already come such a long way.

While we discuss many companies throughout this report—including both firms we cover and firms we do not—the primary companies covered include Amazon, Alphabet, IBM, Microsoft, and Nvidia. We think these firms ultimately use their financial and engineering heft along with leadership positions. Specifically, we see IBM as the clear leader in quantum computing today. We also believe quantum computing will quickly evolve to be the same as public cloud is today, where Microsoft, Alphabet, and Amazon dominate. Given their investments in quantum computing, substantial financial resources, and leadership in public cloud, we expect they will lead in the coming quantum computing market. Lastly, while Nvidia is behind today, we view it as an innovative powerhouse with enormous financial and engineering capabilities that should be able to rapidly muscle its way into the quantum industry.

Exhibit 5 We View IBM as the Clear Leader in Quantum Computing Today

Company	Star Rating	Fair Value Estimate	Stock Price	Upside to FVE	Moat Rating	Uncertainty Rating
Amazon	★★★★	\$260	\$230	13%	Wide	Medium
Alphabet	★★★	\$340	\$322	6%	Wide	Medium
IBM	★★	\$264	\$308	-14%	Narrow	Medium
Microsoft	★★★★	\$600	\$483	24%	Wide	Medium
Nvidia	★★★★	\$240	\$182	32%	Wide	Very High

Source: Morningstar Direct. Data as of Dec. 8, 2025.

Because this report is lengthy and deals with highly technical material, we have provided a high-level roadmap below, with the basic concepts discussed in each section:

1. Technology overview
2. The path to commercialization
3. Market opportunity and competitive landscape
4. Investment conclusions and best ideas
5. Appendix with additional technical details

Quantum Computers Offer a Significant Speed Advantage

Dan Romanoff
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivya Vaidya
Associate Equity Analyst
+1 872-371-4154
jivya.vaidya@morningstar.com

Key Takeaways

- ▶ Quantum computers take advantage of superposition and entanglement to create a technology paradigm that differs in profound ways from classical computers and offers a massive performance advantage.
- ▶ Quantum computing is in its infancy and not ready for broad commercialization. Many technology vectors are under development with no clear indication of what the "best" technology is likely to be. Beyond the hardware, we find the software and ecosystem are also underdeveloped.

Primer on Quantum Mechanics: Everything You Thought You Knew About Reality Is Wrong

Before we dive into quantum computers, we think it will be helpful to be familiar with some of the basic tenets of quantum mechanics. We think the four key principles of quantum mechanics that are particularly important for a better but still rudimentary understanding of quantum computing are as follows: 1) probabilistic rather than deterministic, 2) wave-particle duality, 3) superposition, and 4) entanglement. While the first two may be higher-level things to keep in mind, the second two, superposition and entanglement, are the driving forces behind quantum computing from a more practical standpoint.

Uncertainty Principle

Quantum mechanics is probabilistic in nature. In other words, if you know a particle's position then you cannot be certain about its momentum, and vice versa. Classical mechanics is deterministic in nature and dictates that if you know a particle's speed and position, you can perfectly predict the state of the particle in physical space.

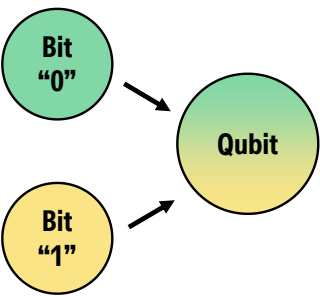
Wave-Particle Duality

Energy and matter are both particles and waves. More precisely, they are probabilistic waves until you observe them. As soon as a particle is observed, the probability wave collapses, and it becomes a particle.

Superposition

Unlike in classical systems where objects can be defined in one state or another, such as a light switch being on or off, superposition refers to the ability of a quantum system, such as an electron, to exist in multiple states simultaneously. In the case of the light switch, it could be both on and off at the same time.

Exhibit 6 The Qubit . . . Is It a One or a Zero? Yes

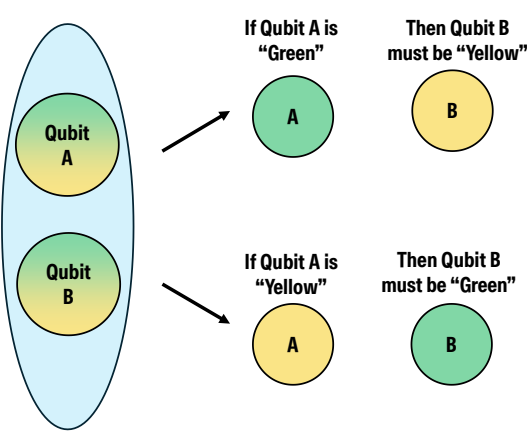


Source: Morningstar.

Entanglement

Quantum entanglement is the phenomenon that the quantum state of any particle in a system cannot be defined independently of the quantum state of other particles within the system. In practical terms that means that once you observe a quantum particle, you know the state of the entangled particle as well, regardless of where that particle is.

Exhibit 7 Einstein Referred to Entanglement as “Spooky Action at a Distance”



Source: Morningstar.

While the uncertainty principle and wave particle duality are helpful background to build a more robust understanding, superposition and entanglement are the two properties of quantum mechanics that ultimately will give quantum computers significant advantages over classical computers. For more details on the underlying properties of quantum mechanics, please refer to Note 1 within the appendix.

Qubits Are Critical to Quantum Computing

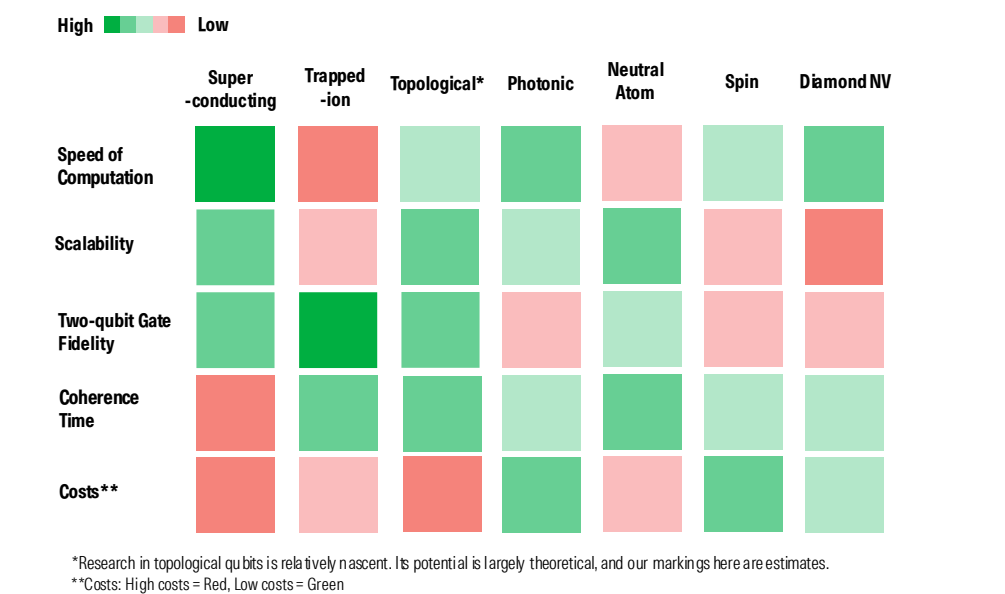
Quantum computing uses particles such as electrons, photons, and trapped ions, which are referred to as quantum bits, or qubits for short. Qubits are the core building blocks of information processing that are needed to have a framework to build quantum computing.

Qubits in quantum computing are analogous to bits in classical computing. Jumping to fundamental particles that can be in two states at the same time seems counterintuitive, to say the least, but it accurately reflects physical reality and we must accept this before diving deeper into the fascinating technology underpinnings.

We see a variety of qubit types employed in the early days of quantum computing, with the early lead showing up in superconducting, trapped ion, and photonic approaches. We stress these are the early days of R&D efforts within quantum computing and the pace of innovation along each vector is impressive. There is no standard approach to creating, manipulating, and observing qubits. Some qubit types are easier to produce, some are easier to measure, some offer the lowest error rates, some have longer coherence times, and some perform calculations faster than others. Decoherence is particularly important because qubits are often in existence for a fraction of a second before factors such as temperature, vibration, and electromagnetic pulse cause the quantum state to change; and qubits are highly sensitive to external interference.

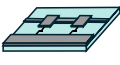
In our view, there is no clear “best” technology approach. The combination of accuracy, reliability, coherence times, cost, and scalability will ultimately settle the qubit race. Different technological approaches are likely to be best suited for different use cases. Technology like superconducting qubits is well understood but extremely difficult to work with, while trapped-ion approaches produce the lowest error rates. The best error rates for superconducting circuits are 2-3 times worse for trapped ions. Regardless of the qubit technology employed, the leading error rates are not yet good enough for mass adoption. We think these rates must improve to 1 in a million or 1 in a billion, from 1 in a thousand today, to make quantum computers applicable to more commercial applications.

Exhibit 8 There Are No Perfect Qubits



The industry is still trying to figure out which approach to quantum computers is best. Currently, different companies are championing different qubit approaches to chart the roadmap to a scalable, fault-tolerant computer. We discuss the technological approaches different competitors are using in more detail later in this report. For a more detailed discussion of qubit technology, please see Note 2 in the appendix.

Exhibit 9 Quantum Technology Can Make Your Head Spin

(Non-exhaustive)						
Qubit Technology						
	Superconducting	Trapped-Ion	Photonic	Neutral Atom	Cat	Majorana
	Comprised of nano-scale circuits, typically Josephson junctions, and use microwave pulses to manipulate the current	Isolated ions, or charged atoms, that are trapped in electromagnetic fields	Occupation of a photonic waveguide	Atoms are trapped using lasers and then further manipulated with lasers to change the excited state of the atoms	A specific kind of superconducting qubit created by using microwave oscillators and a Josephson junction	Entangled Majorana fermions "remember" information contained in their counterpart antiparticles
Physical Qubit Count	• IBM: 1,121 • Chinese Academy of Sciences: 504 • Fujitsu: 256 • Google: 105 • Rigetti: 84	• IonQ: 36 • Alpine Quantum Technologies: 20	• Xanadu: 216	• Infleqtion: 1,600 • Atom Computing: ~1,200 • QuEra Computing: 280	• Alice & Bob: 16 • Amazon: 9	• Microsoft: 8

Source: Company releases, Morningstar.

In the coming years, companies will likely take potshots at one another’s technologies, which we believe will be counterproductive to industry progress. Unfortunately, it is easy to see a focus on qubit count for the next decade, which we do not think will be helpful. This thinking resembles comparing the clock speeds of AMD and Intel PC processors during the internet bubble—interesting from a technical perspective, but ultimately not important. Different technological approaches will inevitably succeed in different ways while failing in others.

Quantum Computers Function Differently and Can Offer a Significant Speed Advantage

The superposition of multiple states allows a quantum system to run many operations in parallel simultaneously, and this parallelism provides a massive speed advantage over classical computers. While a traditional processor relies on the principles of classical physics, a quantum computer relies on the principles of quantum mechanics. In a classical system, electrons either flow through a circuit or they do not. The gate is open or closed—voltage is flowing or it is not—1 or 0. However a quantum computer uses superposition, the principle that a quantum system can be in any number of states at the same time. The electron is not a 1 or a 0—it exists in a superposition of both 1 and 0. Realistically, the electron falls along a probability distribution between 1 and 0, where it is not just 1 and 0, but it is also any other state between 1 and 0.

We see an obvious parallel with the emergence of quantum computers within the broader evolution of computing paradigms over the last 75 years since the first commercial mainframe, the Univac I, was put into service by the US Census Bureau. Mainframes then proliferated and enjoyed a series of advancements on both the hardware and software sides through the 1970s. In 1975, the first commercial personal computer, the Altair 8800, was launched, while in 1978, the x86 server was introduced. These two milestone achievements had one thing in common—they decentralized workloads away from a monolithic mainframe setup. Please see Note 4 in the appendix for more detail around traditional semiconductors.

The coincidental rise of the x86 server is notable in that any one unit was far less powerful than a mainframe, but by deploying thousands of vanilla x86 servers, complex tasks could be broken apart and distributed over many processors running in parallel, thus shortening the processing time required to complete a task. This arrangement was both more cost-effective and more productive from a computing standpoint. As x86 servers were reaching their zenith, Nvidia (and others) recognized that the same approach could work with an Intel Xeon processor in a typical x86 server. That is, discrete graphics chips that Nvidia was already producing for the sole purpose of playing video games already had multiple cores, and each core could process in parallel alongside all the other cores. Therefore, replacing a single core processor with multicore chips could multiply parallel processing power in server arrays. This architecture represents another step up in processing power. To be fair, others, including Intel, AMD, and Arm were also advancing multicore technology, just not as aggressively. Quantum computers are the next logical step then, as superposition allows qubits to account for all possible outcomes simultaneously.

To illustrate this concept, classical computing efforts would use a brute force approach to discovering a four-digit pass code. That is, it would try all combinations until the code was broken. A mainframe would go through each combination serially, starting with 0000, which might take a while. Two x86 servers could each try a combination discretely, so the time to crack the code would be cut in half. If each server had a dual core processor, four attempts could be made simultaneously, thus cutting the time required to crack the code in half again.

Now imagine a few qubits come strolling in, use their superposition and entanglement advantages to check all combinations at the same time in a single pass. Quantum architecture exponentially reduces the time it takes to crack the code in our simple illustration. These two quantum properties allow for exponential performance gains in a variety of use cases. Quantum computers will potentially also allow users to execute calculations that are simply impossible with today's technology. The potential new applications then are enticing and seemingly justify the money and time being spent on quantum computing.

Exhibit 10 Parallel Processing Allows for Many Simultaneous Attempts to Crack the Code



Source: Morningstar.

For context, in 2023, Microsoft estimated it would take a classical computer one billion years to break a 2048-bit RSA encryption, whereas a quantum computer with just 4,000 qubits could factor enough prime numbers to break the encryption in a mere 100 seconds. The estimate for the number of qubits and time needed to perform the calculations on a quantum system needed to break RSA encryption continues to decline as the technology is honed. As we discuss later in this report, cryptography is likely to be a major use case for quantum technology and companies are already working to prepare for post-quantum cryptography, or PQC.

Researchers continue to push for quantum supremacy, which is the theoretical point at which a quantum computer can perform calculations that a classical computer cannot perform within any reasonable timeframe. In 2019, Alphabet first claimed quantum supremacy over classical computers when its Sycamore chip performed an operation in 200 seconds that would have taken the most powerful classical computer 10,000 years. Since then, a variety of other teams—including Xanadu, D-Wave Quantum, and the University of Science and Technology of China—have announced quantum supremacy. With its 2025 Willow chip, Alphabet employed more qubits so the set of possible quantum gates was much larger. Willow completed this same operation in about five minutes, compared with an estimated 10 septillion years to complete on the most powerful classical computer in existence today.

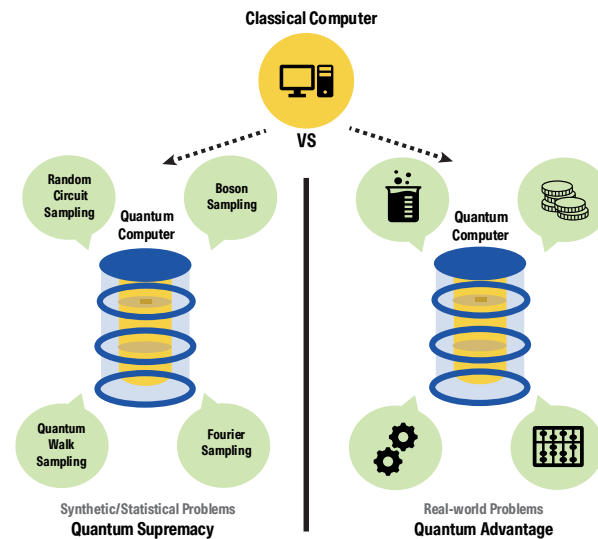
While there is a speed advantage, which is a combination of theoretical and real, the technology behind quantum computers must be refined in order to fully realize the potential speedup.

Exhibit 11 Quantum Computers Trail Classical Computers for Now

Status Quo			
Criteria	Quantum Computing	VS	Classical Computing
Error Correction	Minimal to none	<	Built in
Performance	Slower	<	Faster
Scalability	Very limited	<	Cloud-scale
Cost/Accessibility	Expensive, mostly cloud-based	<	Cheap and ubiquitous
Ecosystem Development	Tools are mostly stand-alone, early-stage and experimental	<	Mature and fully integrated
Potential Future Baseline (Fault-Tolerant Era)			
Criteria	Quantum Computing	VS	Classical Computing
Error Correction	Quantum error correction (QEC) protected	≥	Still highly reliable
Performance	Faster for more complex problems	>	Likely still better for general operations
Scalability	High	>	Limited by Moore's law/transistor scaling
Cost/Accessibility	Affordable (via cloud)	≤	Continued affordability
Ecosystem Development	More developed architectures and integrated stacks	>	Growth will likely plateau

Source: Morningstar.

While we do not view the random circuit sampling test as particularly practical or relevant as a testament to utility, researchers are also pushing for what is known as quantum advantage, which focuses both on speed and practicality. We substitute “commercialization” in place of practical because this is clearly the ultimate endgame. Quantum advantage is the demonstration that a quantum computer can solve a real-world problem faster, more cost effectively, or more accurately than a classical computer, thus making commercialization of the technology possible.

Exhibit 12 Quantum Advantage Is More Meaningful Than Quantum Supremacy

Source: Morningstar.

While we think quantum computing can offer a tremendous speed advantage for some use cases, we recognize that the technology is not fully developed. As such, quantum computers are not as good relative to classical computers for most workloads today, like sending an email or writing a report. For now, quantum computers are more prone to errors, are not as scalable, and are more expensive than their classical counterparts. We explore the specific challenges in more detail later in this report.

Over time, quantum computing can potentially serve as a workaround for Moore's law, which is coming under increased stress as geometries shrink on traditional semiconductors. There is a theoretical limit to Moore's law. We believe that at some point, the circuitry will become the diameter of an atom, which is typically 0.1 to 0.5 nanometers, compared with current leading-edge 5 nanometers. Realistically, 5 nanometers is the smallest theoretical size that can reliably be fabricated on that chip. At the current trajectory, within 15 years the features etched on chips will be approximately the size of atoms. At that scale, quantum properties, such as tunneling, may prevent further advancements. Once we reach the point where the feature sizes on a chip can no longer be practically reduced, quantum computers may be the only option to improve computing power.

Quantum Algorithms Have Been Proven and Are Proliferating

While creating, sustaining, and manipulating qubits is a monumental engineering task, in order to make a quantum computer process information, software is required. However, the software required to perform processes in a quantum computer is extremely limited. Further, writing quantum software code is challenging because this is an entirely new computing paradigm and debugging in real time is not possible because of decoherence times and the sheer cost of performing an operation on a quantum computer.

Additionally, the queue to use a quantum computer is long, so even if a user has two hours of access guaranteed per month, if their algorithm is not working, they are only going to get so many attempts before their time in the queue runs out.

Specialized algorithms must be developed that can take advantage of the unique properties of quantum computers and can run computations in parallel in a manner that is impossible on a classical computer. However, only specific kinds of problems are likely to be effectively addressed, at least initially, with a quantum computer. These problems are called nondeterministic polynomial time problems. NP problems are difficult to solve but relatively easy to check. The reason for this right now is simply a cost question. Many algorithms are calculated to offer quadratic speed advantages, which is certainly meaningful, while the most impactful algorithms can deliver exponential speed advantages. Classical computers are already excellent for many tasks in terms of speed, accuracy, and cost, so in order for the cost of quantum computers to be justified, the speed advantage must be significant by orders of magnitude.

In the early days of mainframe computers, software could be in the form of punch cards—actual paper with holes punched in specific positions that drove the computer to perform prescribed tasks. Today we think of software as being stored on more advanced media like solid-state drives. Applications like Microsoft Excel help users do everyday tasks that we take for granted, but we cannot simply run Excel on a quantum computer.

The output a classical computer generates then is also different than the output from a quantum computer. A classical computer is deterministic and a quantum computer is probabilistic. Therefore, if a classical computer added $1+1$, it would conclude the answer definitively is 2. However, the output from a quantum computer would conclude that the most likely answer is 2. While on its face the fact that quantum computers are effectively calculating all possible answers in parallel is a positive for computational speed, the flip side to this is that the same computer also produces all possible results. Again, this is based on the probabilistic nature of quantum mechanics, which is not very helpful when the user wants a specific answer. The trick then, is to make all of the wrong results cancel each other out, or at least measure the probability of them being correct as very low. This process is known as quantum error correction and represents one of the areas under development for quantum computing.

We are years into experimenting with quantum computers, and the industry has only produced a limited number of useful quantum algorithms. In fact, according to Quantum Algorithm Zoo, as of October 2025 there are 74 primary quantum algorithms, while other similar surveys put the number at approximately 130. Either way, there are only just dozens of quantum algorithms. Some of the more groundbreaking quantum algorithms are described in the table below. For more details on quantum algorithms, see Note 5 in the appendix.

Exhibit 13 Some Problems Can Be Solved Exponentially Faster With Quantum Algorithms

Algorithm	Description	Applications
Deutsch-Jozsa	Determines if a system is balanced or constant, with balanced being an equal distribution of either of two states (1 and 0), and constant being all of the same state (either 1 or 0)	Quantum advantage demonstration
Shor's	Factors large numbers exponentially faster than a classical computer; largest integer factored = 35	Cryptography, cybersecurity, blockchain, and cryptocurrency
Simon's	Enables detection of repeating patterns within a mathematical formula exponentially faster timeframe than a classical computer	Cryptography
Grover's	Speeds up search in unstructured data; equivalent to a brute force attack where a program simply tries every combination of characters until it finds the key	Database queries, cybersecurity, optimization
Quantum Phase Estimation	Allows data extraction regarding the quantum state phase; can be thought of as physical IP libraries from semiconductor firms	Building block in other quantum algorithms
Quantum Fourier Transform	Useful in converting quantum states back into frequencies we can understand, or in other words, porting data from the quantum realm to the classical realm	Building block in other quantum algorithms like Shor's
Variational Quantum Eigensolver (VQE)	Hybrid approach that uses both classical and quantum computers to find a certain state of a system; VQE finds the lowest energy state of a system	Drug discovery, materials science, optimization problems
Quantum Approximate Optimization (QAOA)	Hybrid approach that uses both classical and quantum computers to find a certain state of a system; solves for a system of parameters alongside a classical computer to adjust the parameters	Complex logistics, manufacturing, scheduling, and other optimization problems

Source: Morningstar.

Given that Shor's algorithm is generally heralded as an early breakthrough in quantum algorithms, it is important to note that it was developed in 1994, and 31 years later it is still the most widely discussed quantum algorithm. This suggests that advancements in something as cutting-edge as quantum algorithms are still skewing toward incremental. In fact, the largest integer factored using Shor's algorithm on quantum computers is the number 35. Despite far more advanced technology in general today, quantum development is lagging behind the pace of atomic energy development of yesterday. In some instances, like for VQE- and QAOA-related applications, we think a quantum computer will be used in tandem with a classical processor to change the variables. In short, the technology may not be ready for prime time, but we think we are on the precipice of commercialization for early adopters, which we think happens around 2030.

Quantum Computers Are Still Years Away From Commercialization

Dan Romanoff
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivyaa Vaidya
Associate Equity Analyst
+1 872-371-4154
jivyaa.vaidya@morningstar.com

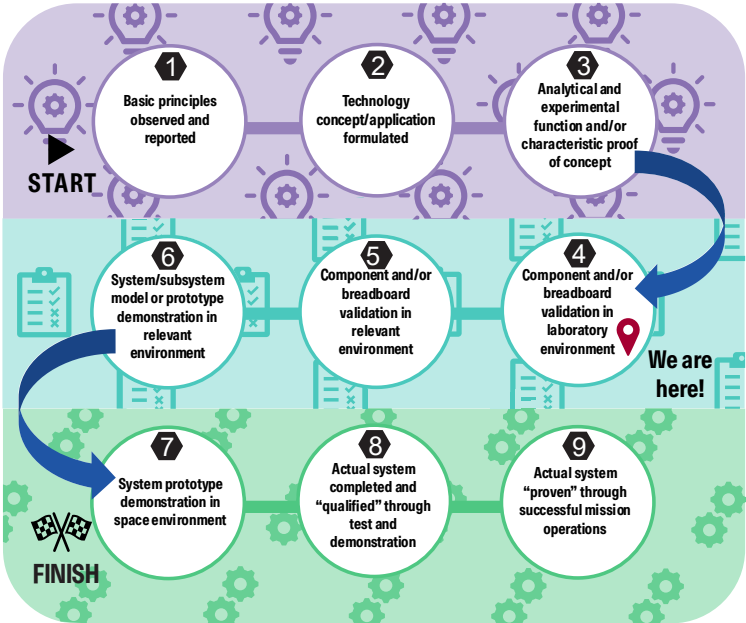
Key Takeaways

- ▶ We already see IBM in the lead, but believe that with their current quantum offerings and quantum computing R&D programs, that Microsoft, Alphabet, and Amazon are primed to benefit from this long-tailed technology evolution too.
- ▶ The cloud service providers have an opportunity to push the entire quantum computing industry forward and establish clear leadership positions. Given the accepted public cloud model, adding quantum computers to the menu of cloud services would likely be a smooth transition for customers.
- ▶ The technical prowess has already been demonstrated and the technology is truly impressive, but given the engineering issues in terms of scaling qubit counts and further developing quantum error correction techniques, the main issue around commercialization is more of timing, with five to 10 years being our base case for the early stages of commercialization with limited scale quantum computers, and the beginning of mass commercialization beginning in about 20 years.

Obstacles Must Be Overcome Before Quantum Computing Is a Commercial Reality

Identifying where we are on the journey toward quantum computing is no easy task. One relevant high-level model for pinpointing where we are in the quantum computing journey we came across while writing this report is NASA's technology readiness level framework. It is a nine-step process for determining if a rocket is ready for space flight. We adapted it by broadening the framework to be more applicable to technology advancement in general. While we assess quantum computing as currently at level four, we think somewhere between level three and level five is reasonable.

Exhibit 14 Some Problems Can Be Solved Exponentially Faster With Quantum Algorithms

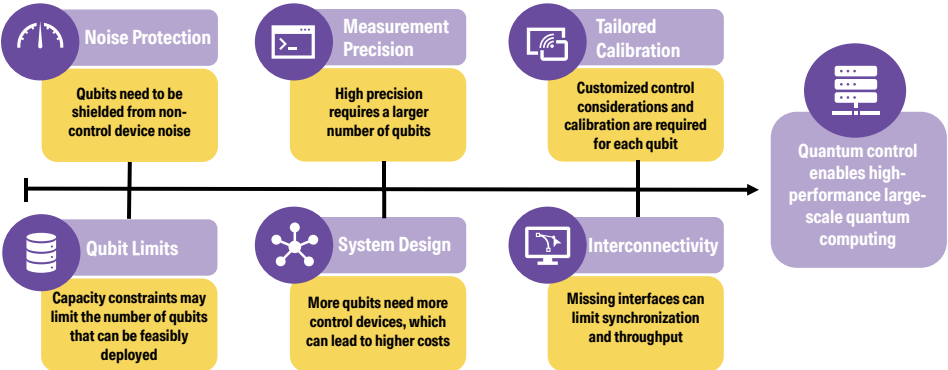


Source: NASA, Morningstar.

Quantum computers face a variety of obstacles that come in many forms and present a range of levels of difficulty. These include soft objections over ethical concerns, to a lack of a proper ecosystem, to hardcore engineering issues. We think the engineering questions are the most pressing, including but not limited to the following:

- ▶ The difficulty in creating usable qubits in the first place;
- ▶ The fragile state of the qubit as having short decoherence times; and
- ▶ The unanswered question as to the inherent ability, or lack thereof, of a quantum system to scale from hundreds of qubits to millions of qubits.

Exhibit 15 Quantum Control Challenges Are as Important as Scaling Qubit Counts



Source: Morningstar.

On the soft side of the spectrum, we have seen ethical questions raised that we can dismiss with relative ease insofar as technological progress is unstoppable in general. Advancements will happen and the ethics are ultimately up to the user and how they apply these systems. We are actually deep in this debate right now with another rapidly advancing technology, generative AI, and how it potentially makes portions of existing software obsolete, or so the fear goes.

The likelihood of quantum computers rendering current cryptology techniques obsolete seems high to us. There is an entire effort around consulting and regulations that companies are going through to help ensure they are prepared for post-quantum cryptography, or PQC. Therefore, we have to believe other cybersecurity methods will grow in usefulness or effectiveness, whether from existing technologies or solutions that emerge from quantum computing itself. We also believe that the ultimate “good,” or utility, of quantum computers will outweigh any “bad,” or negative externalities, over time.

The absence of an ecosystem can also be overlooked, in our opinion. As quantum technology is developed, the ecosystem will emerge and expand. This has been the case with other major technological advancements over the last 75 years. Personal computer demand grew rapidly at the onset despite the lack of a common operating system. Even different PCs from IBM could have different operating systems. Today of course, Windows has taken over and we have PCs in every home and on every corporate desk. Aside from technology evolution precedents, we see meaningful signs of the quantum ecosystem broadening.

We believe that quantum hardware, quantum use cases, and the quantum ecosystem will grow organically in concert with one another. It took years to introduce personal computers powered by Arm-based processors largely because Windows was written for Intel chips. Eventually, however, it happened, and Arm-based PCs are available today. Basically, the desire to calculate complex equations faster and more efficiently drove use cases to emerge and thus created a market. We strongly suspect that a great deal of the experimentation occurring on production quantum computers today involves writing proprietary algorithms. We also note that nearly all the leading quantum computing companies we reviewed had an entire portfolio of services around quantum computing beyond just the hardware itself. These companies are also well aware of the history we just laid out.

The rise of the public cloud model offers an important precedent. At this point in the computing timeline the use cases for computers in general have been taken for granted. Even to somebody who does not have the slightest clue how a classical computer works, the power the technology possesses to increase productivity is undeniable, because users can access the internet, send emails, create spreadsheets, and compose letters. Even in the most recent computing paradigm shift to the public cloud, investors understand the business model and can identify the benefits of this new model. In 2006 at the birth of Amazon Web Services, the use cases for public cloud were limited, and AWS certainly had not built the library of peripheral software elements to make the service more broadly applicable. Not even 20 years later, the top five public cloud service providers generated more than \$250 billion in revenue annually from public cloud services. Further, there is already a pretty decent understanding of what the early use cases are likely to be for quantum computers.

Lack of software is a specific instance within the absence of an overall ecosystem, as it implies the absence of use cases and the need for creating more specific applications. As we discussed in this report, there are approximately 100 quantum algorithms today. These algorithms are indeed software, but they are not software applications in the way we think of them. It might be helpful for some investors to categorize quantum algorithms as “technical software,” which generally apply to engineering applications and would include simulation software from companies like Synopsys. The “software” available at the time of the Univac was effectively none, including a complete lack of an operating system.

To continue the methodical evolution of quantum computing overall, the number of physical and logical qubits in a quantum system must be ramped, error rates must be decreased, and more practical uses must emerge. Other researchers have also recognized the need to improve qubit coherence and decrease error rates with techniques ranging from different types of qubits with different fault tolerances and building in more qubits to allow groups of physical qubits to become entangled and act as logical qubits with built-in error correction. This is the great promise of topological qubits, for example. We view all these steps as important efforts to commercialize quantum hardware.

Inherent in these challenges is also the fact that cutting-edge research is expensive and may take decades to pay off. As discussed within this report, the large companies—such as Microsoft, Google, and Amazon—working on advancing quantum computing have effectively unlimited ability (within reason) to fund these types of projects. At Microsoft, for example, quantum computing is the company’s longest-running research project, at 19 years as of this writing. These large companies enjoy vast stores of financial resources and engineering talent, and are well-suited to continue advancing the entire field if need be.

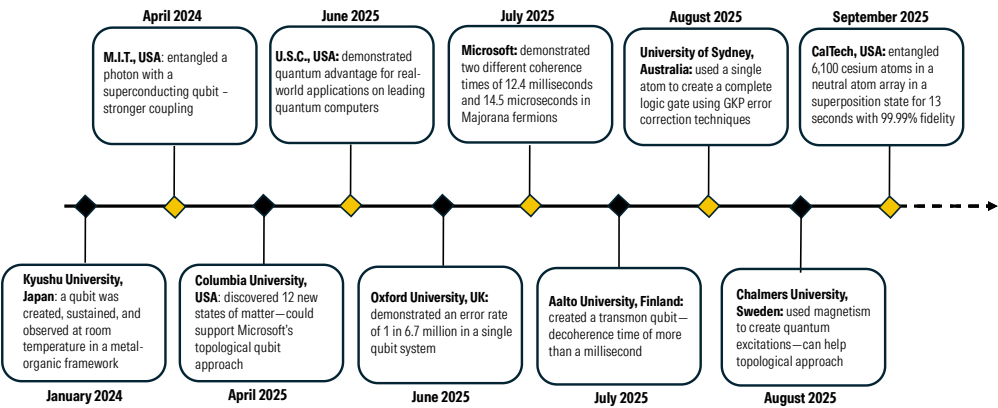
Exhibit 16 Our Large Tech Coverage Can Continue to Advance Quantum Computing

Company	Revenue	Free Cash Flow	FCF Margin (%)	R&D (% of Rev)
Amazon	637,959	48,419	7.6%	13.9%
Google	350,018	81,170	23.2%	14.1%
Microsoft	281,724	76,961	27.3%	11.5%
Nvidia	130,497	70,236	53.8%	9.9%
IBM	62,753	10,447	16.6%	11.9%

Source: Company reports, Morningstar, and PitchBook for each company's most recent fiscal year. Data as of December 2025.

Teams of engineers and researchers from corporate, startup, academic, and governmental organizations have been working feverishly to address these challenges. The technological advancements are mind-boggling and the pace of innovation is breathtaking.

Exhibit 17 Quantum Hardware Challenges Are Being Solved Daily



Source: Morningstar.

We certainly do not think that any one of these advancements by itself is the silver bullet that will make quantum computing immediately viable for mass adoption, but they all indicate consistent progress. What really struck us is the sheer number of research teams around the world working on very different challenges within quantum computing while also using widely varied approaches. Not only do we see a path to commercialization, but we see many such paths.

Historically, the time gap between early advancements and commercial deployment has been large. A case study in point is ASML, who formally started its extreme ultraviolet, or EUV, program in 1997 but didn't deliver its first production unit until 2017. Within this timeframe, it took 20 years and the direct financial support from giants within the semiconductor industry with additional cash infusions to answer physics questions and solve monumental engineering challenges. It worked, although we remember well reading many reports along the way saying EUV was probably not possible and would never happen. We believe quantum computing is going through a similar trajectory right now. We have already gone from no algorithms to dozens of proven algorithms in less than 35 years with limited ability to test these algorithms. As the hardware scales, the algorithms will increasingly be put to the test and additional software applications will be created. Additionally, continued investment and patronage from cloud computing giants will be necessary to maintain the current momentum and increase the technology's acceptance and adoption.

Although quantum computing remains years away from full viability, its potential is undeniable. Key advancements emerge every month, each serving as a stepping stone toward fault-tolerant systems and offering glimpses of quantum computing's true potential. Given the current rate of investments, technological progress, and innovation, we expect quantum computing to eventually stand shoulder to shoulder with classical computing—even surpassing it on several fronts—and eventually becoming the new norm.

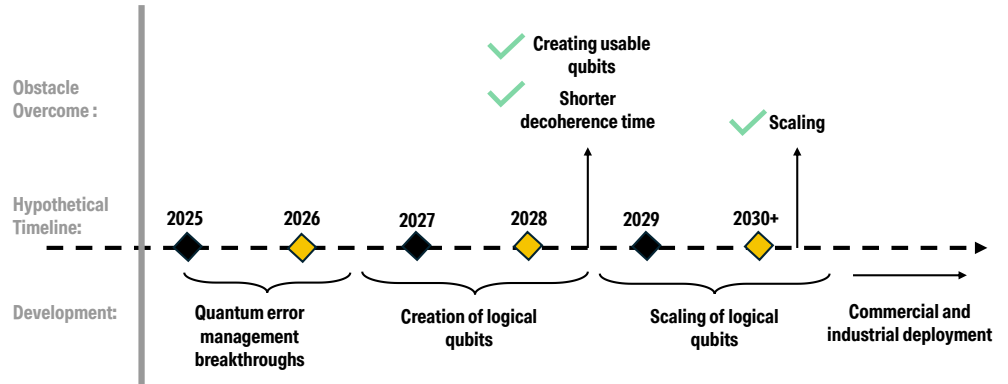
Exhibit 18 Quantum Computers Will Eventually Surpass Classical Computers for Many Tasks

Status Quo			
Criteria	Quantum Computing	VS	Classical Computing
Error Correction	Minimal to none	<	Built in
Performance	Slower	<	Faster
Scalability	Very limited	<	Cloud-scale
Cost/Accessibility	Expensive, mostly cloud-based	<	Cheap and ubiquitous
Ecosystem Development	Tools are mostly stand-alone, early-stage and experimental	<	Mature and fully integrated
Potential Future Baseline (Fault-Tolerant Era)			
Criteria	Quantum Computing	VS	Classical Computing
Error Correction	Quantum error correction (QEC) protected	≥	Still highly reliable
Performance	Faster for more complex problems	>	Likely still better for general operations
Scalability	High	>	Limited by Moore's law/transistor scaling
Cost/Accessibility	Affordable (via cloud)	≤	Continued affordability
Ecosystem Development	More developed architectures and integrated stacks	>	Growth will likely plateau

Source: Morningstar.

Satya Nadella, CEO of Microsoft, in a February 2025 LinkedIn post, said we are years, not decades away from the commercialization of quantum computing. Julian Kelly, director of quantum hardware for Alphabet, in a CNBC interview in March, concurred, with a more specific five-year number. In contrast, John Preskill, a giant in the quantum physics world, said in an August interview at the World Science Festival that we are 10-20 years away from quantum computers making an impact and decades away from commercial quantum computing. Estimate dispersion is high, and understandably so. We also remind investors that quantum computers exist today and are already in fact solving problems in experimental settings. We expect the growing integration of quantum computing with classical to catalyze the development of use cases across various industry verticals, as we describe in the next section, and pave the way for a quantum world.

Exhibit 19 We Are Five Years Away From the Early Stages of Commercialization



Source: Morningstar.

Of the few quantum computing deployments that we have seen, a significant portion of them use quantum annealing. Quantum annealers are a type of quantum computer, different from general-purpose quantum computers, also technically known as universal gate computers. General-purpose quantum computers function more like classical computers with different types of logic gates based on qubits. A quantum annealer specifically solves optimization problems by finding the lowest energy state of a quantum system without logic gates. They are relatively easy to scale and best suited for simple optimization applications. However, they have limited applicability compared with gate-based systems, and can't, for example, execute key algorithms like Shor's. For a more detailed discussion of logic gates in quantum systems, please see Note 3 in the appendix.

Much early work on quantum computers was directed toward quantum annealers, such as the efforts of D-Wave Quantum, who we profile later in this report. We believe general-purpose quantum computers will be more flexible and will therefore be where the most commercial interest lies over time. This is certainly where a great deal of financial resources are currently being directed. The focus of this report is more on general-purpose quantum computers, even if annealers are implicitly involved at times. Until universal gate quantum computers are able to scale in terms of qubit count and error rates, we think annealers can have a place in the quantum computing field. Eventually, known quantum algorithms can be applied to a quantum computer to perform the same workload. Until then, the annealer is likely to serve as a proof of concept for customers and to help establish use cases.

Quantum Computing Likely to Evolve Similar to Cloud Computing

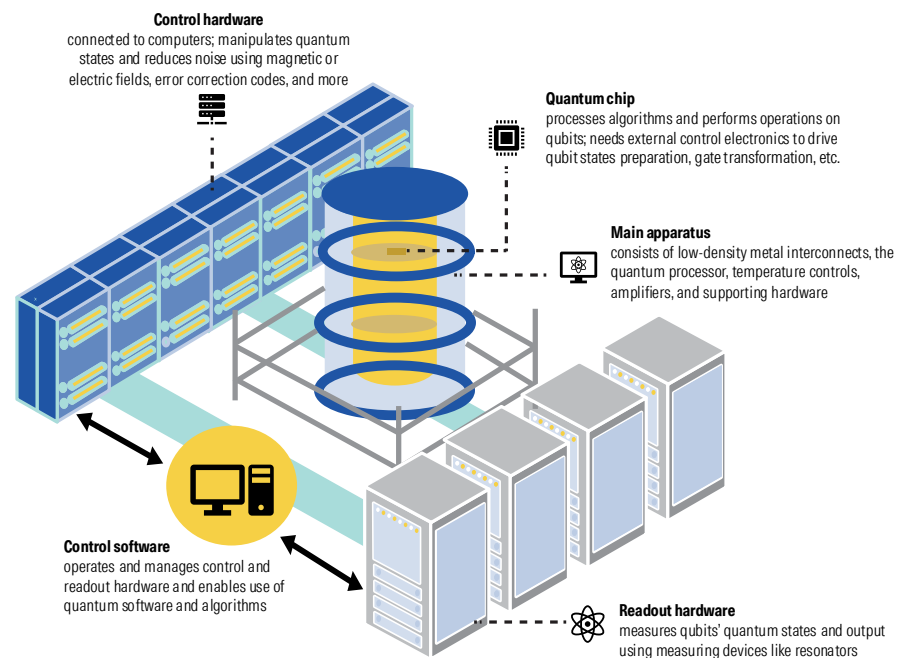
Looking ahead a decade, opinions on the timeline for practical quantum computing varies widely from five to over 30 years. Quantum annealers, which are limited-use quantum computers, might be able to bridge the gap and find broader, real utility use over the next five to 10 years, which is the critical time frame for commercialization, in our view. However, due to their limited scope in handling more complex computations, they will likely be phased out over time in favor of more powerful general-purpose quantum computers.

Business leaders and scientists have conceded that, despite its potential, quantum computing remains far from ready for scalable, commercial deployment. In our view, a critical barrier to overcome is the error rate, and by extension, qubit coherence. Fault-tolerant quantum computers aim to use quantum error correction to perform computations at least on par with classical systems—ideally faster. While the theoretical minimum fidelity threshold of 99.9% (0.1% error rate) seems achievable given current advancements, the real challenge lies in maintaining accuracy across tens of thousands and even millions of qubits without compromising probabilistic accuracy beyond acceptable limits. Recall that Intel famously recalled \$500 million in Pentium chips in 1995 over an error rate of one in a billion.

We are at this level today in terms of achieving 0.1% error rates in subscale systems, which is basically good enough for experimentation purposes. Current milestones, like "quantum supremacy" demonstrations, do not, in our view, fully reflect this barrier to meaningful real-world applicability. Even if the technology was more advanced today, we think AI is crowding out other investments so quantum computing would not likely gain traction in the several years regardless.

Scalable, fault-tolerant universal gate quantum supercomputers still appear unlikely within the next decade. Early iterations may emerge, but their use will likely remain confined to academic or experimental settings. Instead, we expect more immediate progress in hybrid classical-quantum deployments where quantum computers act as “co-processors” alongside classical hardware. This approach should allow for more usable systems beginning in five years. These systems will undoubtedly lay the groundwork for scalable, commercially viable quantum supercomputers in the years that follow. Progress is inevitable.

Exhibit 20 A Quantum Computer Is Highly Complex and Still Employs Classical Computers



Source: Morningstar.

Quantum Vendor Consolidation Is Inevitable

In that spirit, it is also unlikely that the industry can sustain dozens of competitors in the future. Continued indecision by customers, capital requirements, and talent constraints will likely drive consolidation. Dominant players are likely to be larger, well-funded, and diversified tech giants controlling cloud-based platforms like IBM, Microsoft, Alphabet, and Amazon, in our view.

Still, we do not rule out the rise of a few breakout upstarts. For instance, there are four publicly traded quantum computing pure plays with an aggregate market cap in excess of \$50 billion and aggregate revenue of more than \$60 million in 2024. This results in an industry multiple of approximately 840 times 2024 revenue. While Morningstar does not cover IonQ, D-Wave, Quantum Computing, or Rigetti, clearly there is plenty of excitement for the industry, paired with relatively few publicly available investment options, and we leave it to investors to opine on a revenue multiple of 840 times.

Investors seem to be valuing these stocks as though quantum computing commercialization will begin in 2026, which is highly unlikely.

That said, we assume quantum revenue built into consensus expectations for cloud providers hovers near \$0, so this opportunity represents a long-term call option, in our view. Investors should be aware that the publicly traded quantum companies are hotly debated, with some categorizing them as meme stocks. We would liken them more to biotechnology companies with minimal revenue, no way to support themselves without additional capital infusions, and uncertain technologies.

Exhibit 21 Publicly Traded Quantum Companies Enjoy Big Market Caps but Little Revenue

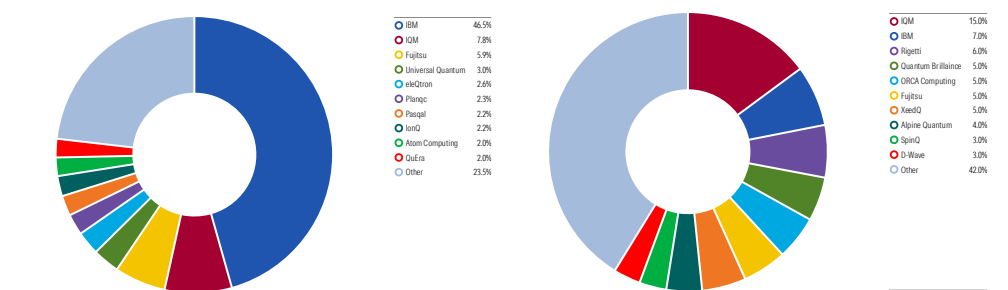
Name	Ticker	Market Cap (\$m)	2024 Revenue (\$m)	2025E Revenue (\$m)	2025E Rev Growth	2024 FCF (\$m)
IonQ	IONQ	18,667	43	108	151%	(116)
D-Wave	Q BTS	9,640	9	25	187%	(66)
Quantum Computing	QUBT	2,878	0	1	75%	(23)
Rigetti	RGTI	9,277	11	8	-30%	(59)

Source: Morningstar. Data as of Dec. 8., 2025.

For perspective, if we assume our \$200 billion market size in approximately 30 years is correct, and we further assume these four publicly traded companies survive to become the winners, they will likely need to control perhaps nearly all of the market, not unlike the cloud service industry that we see today. This would equate to \$200 billion in annual revenue. Further, if we apply a price/sales multiple of 10 times, which is the current cutoff to be included in the top quartile of the fastest growing software stocks, this yields a \$2.0 trillion in aggregate market cap. The required rate of return to make math work would be 16%. However, a more realistic venture capital required rate of return of 25% applied against that \$2.0 trillion valuation in 30 years yields a current value of \$7.6 billion.

A glaring obstacle for the publicly traded pure-play firms would be dethroning IBM, who is the clear leader by any measure in quantum computing today and has a market cap of around \$285 billion (Oct. 24, 2025), with very little, if any, value ascribed to its quantum computing business. However, the industry revenue multiple of 840 times would suggest that IBM should have about \$115 billion in market just from its quantum business alone, which we do not think is anywhere near the case. These pure-play firms will also have to hold off the other private firms, the cloud service providers, and the various other competitors in order to achieve these lofty valuation levels, which seems unlikely, given their positioning today.

Exhibit 22 Share of Total Deals Amount (Left) and Total Systems Sold (Right), 2020 to June 2025

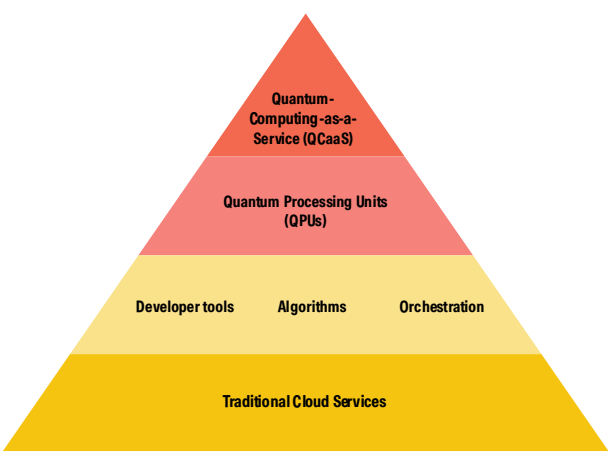


Source: The Quantum Insider, Morningstar.
Note: Other includes nondisclosed deals by vendors listed above and other vendors.

The Platform Approach Will Be Required and the Cloud Service Providers Are Positioned to Win

Nearly every quantum computing company we examined is offering a combination of hardware systems available for sale along with something resembling a cloud-based quantum-computing-as-a-service, or QCaaS, model, not unlike the current cloud service providers. We think the holistic quantum platform is going to be a requirement for the industry to move forward.

Exhibit 23 We Think the Quantum Platform Strategy Is the Right Approach



Source: Microsoft, Morningstar.

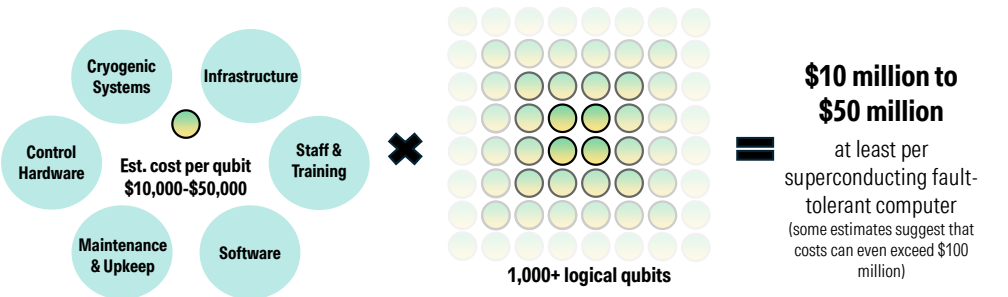
Early leaders in the space will likely be marked by successful commercialization. QCaaS will continue to grow, alongside broader acceptance of quantum solutions in cybersecurity, supply chain optimization, and other verticals where early use cases are already taking shape. Like other emerging technologies with huge potential, we expect a land grab in the early phase of commercialization.

Given the investment already sunk, the progress made, and the platforms built, and enormous leadership positions within cloud services, we think the reigning cloud service provider leaders will be strong players in quantum computing. After all, they perfected the infrastructure-as-a-service, or IaaS, and platform-as-a-service, or PaaS, model for outsourced compute.

While they all employ homegrown silicon to some limited extent, it is safe to say they are mainly using custom servers built with off-the-shelf parts. So even if Microsoft’s Majorana One quantum chip does not pan out, we do not think it has to in order for Microsoft to be a quantum computing leader. Microsoft and its cloud peers can simply buy third-party quantum computers and deploy them in their existing data centers that will benefit from being immediately next to arrays of traditional servers, which will likely be required for many use cases, especially early on in the quantum computing lifecycle.

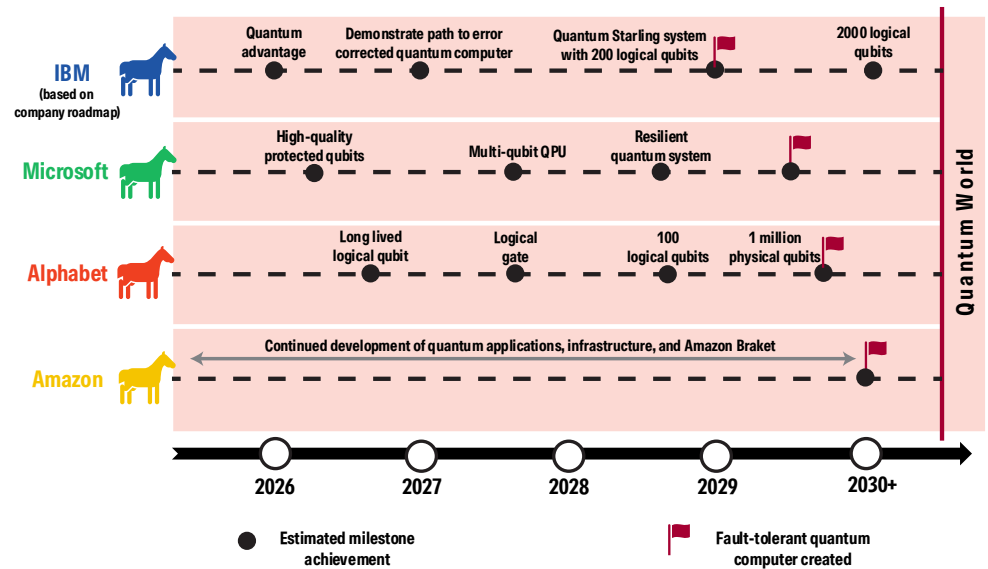
A cloud-based model makes even more sense for quantum computers, given the high cost. It might cost \$30 million for the most advanced quantum computer today, compared with perhaps \$400,000 for a leading GPU server for AI workloads, and a few thousand dollars for a vanilla Intel-based server. The leading cloud service providers already have established quantum ecosystems and other resources that comprise holistic platforms and customers are already comfortable with the cloud model, so the cloud model seems like a relatively easy transition, in our view.

Exhibit 24 Fault-Tolerant Quantum Computers Could Cost North of \$50 Million



Source: PatentPC, FitDesign, Morningstar.

While IBM is clearly the leader in quantum computing today, we see no reason why the largest cloud providers will also not be among the long-term winners in this category. Microsoft is emerging as a leader specifically for chemistry applications, which we think will be a very important initial use case. Alphabet is generating a fair amount of interest for its quantum software kits, while Amazon also has an emerging set of quantum solutions. Of the larger companies we profile in this report, Nvidia is lagging, but has the financial and engineering resources. It finally began to focus more intently on the space over the summer of 2025. Given the R&D dollars the cloud service providers are pouring into developing quantum technology, we think it is simply a matter of time before they have their own quantum computers installed in their own data centers anyway.

Exhibit 25 Our Large-Cap Coverage Is in a Race to Drive Quantum Advancement

Source: Company roadmaps, Morningstar.

The Bull and Bear Case Pivot on Time to Commercialization

We are convinced that quantum computing is a real technology that can offer significant performance advantages, tackle problems current computers cannot solve, and will eventually enjoy wider adoption. The key question then becomes one of timing for commercialization, for which there are widely divergent views. We therefore triangulated bullish and bearish scenarios across key factors driving quantum computing adoption.

We think the bear case for quantum computing revolves around slower technical progress and failure to achieve acceptable error rates, which would be major barriers to commercial viability and long-lived funding. So far, quantum stacks remain confined to experimental and academic settings, and we estimate broad commercial acceptance is at least 15 years away. While the theoretical potential of quantum computing has spurred retail investment, any highly visible failure or continued lack of returns for pure-play quantum companies could burst the bubble, triggering sharp valuation resets and a potential industry downturn.

The bull case centers on the fact that real quantum applications and hardware do exist today, albeit with limited commercial deployment and barely any revenue industrywide. Still, the pace of current advancements is encouraging and the continued backing by major players like Microsoft, Alphabet, Amazon, and IBM should help keep investor sentiment afloat. The bull scenario builds on promising developments in logical qubit construction, pointing toward a viable path to fault-tolerant computing—and making large-scale adoption a quicker and more plausible outcome. Under these circumstances, more meaningful commercialization begins in approximately five years, which is in line with statements from Alphabet and Microsoft.

Our view straddles between the bull and bear case. We think the most critical question is the timeline for commercialization, which we tend to be optimistic about. Further, we are envisioning the early stage of commercialization, which would be for early adopters. We think mass commercialization could be approximately 20 years away.

Exhibit 26 A Tug of War for the Ages on Quantum Computing

Scenario	Bear Case	Bull Case
Technological Advancement		
Time to Real Quantum Utility	15-20 years (around 2040)	5-10 years (around 2030)
Error Correction	The ratio of physical-to-logical qubits remains prohibitively high , preventing commercial viability	Success in logical qubit scaling demonstrates path to fault-tolerant scalability and commercial viability
Qubit Modality Convergence	Excessive, long-term fragmentation in hardware modality (superconducting, trapped ion, etc.) with the disparate investment in incompatible stacks, creating a “format war” and preventing continued technical progress	Healthy exploration of qubit modalities with eventual convergence to a few dominant architectures for continued development
Software and Algorithms	Lagging development and acceptance of algorithmic improvements and key foundational platforms	Increased adoption and development of intuitive, application-specific quantum solutions
Commercialization and Market Drivers		
Revenue	Usage remains limited to academic and experimental settings , preventing growth of durable revenue streams	Growth of QCaaS, providing low-cost access to quantum hardware. - Development of quantum computers and supporting hardware for hybrid deployments
Operational Overhead	A high physical-to-logical qubit ratio will make usage too expensive and complex	A lower physical-to-logical qubit ratio will improve error correction and reduce operational overhead
Investment and Funding	- Low revenue or lack of profitability in investments may tip investor patience over the edge - Pure-play quantum companies in particular could face a massive valuation write-down	Healthy, large investments by governments and large companies alongside slow yet steady technical progress could spur broader investor confidence
Consolidation	- The industry may remain fragmented, leading to diluted customer spending and sovereign funding Failure or bankruptcy of a highly visible pure-play quantum company could spiral negative investor sentiment	Consolidation would accelerate commercialization and focus funding and investments , leading to cohesive technical development and a healthier market structure
Total Addressable Market (TAM)	\$50 billion	\$400 billion
Macroeconomic Factors		
Regulation	Stricter regulation in mission-critical verticals like financial services and healthcare may prevent broader adoption and development	Government support and funding alongside favorable policy may support global collaboration and scientific discovery
Talent Requirements	A talent pool bottleneck will definitively hinder technical progress, commercialization, and overall adoption	Growing industry-led upskilling can help create a pipeline of quantum engineers and specialists

Source: Morningstar.

The Opportunity for Quantum Computers Is Enormous

Dan Romanoff
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivyaa Vaidya
Associate Equity Analyst
+1 872-371-4154
jivyaa.vaidya@morningstar.com

Key Takeaways

- ▶ We think the market can be \$200 billion annually at maturity, which we think is 30 years from now, and will be driven by fundamental performance advantages, new use cases for problems that cannot be addressed by computers today, and mass-market adoption.
- ▶ Primary initial use cases are likely to be in pharmaceuticals, chemicals, materials science, and cybersecurity. We see the potential expansion of R&D budgets for firms operating in these fields to take advantage of this powerful technology.
- ▶ Given the opportunity, investment dollars have poured in and created a crowded field already. This reinforces the notion that the established cloud service providers should be able to first differentiate, and later thrive, given their engineering capabilities, R&D programs, and financial resources.

Use Cases Are Likely to Focus on Optimization and Simulation in Early Commercialization

We think even as the commercialization of quantum computing begins in limited use cases, classical computers are still likely to be better suited for most workloads. Further, we also think classical computers will be required alongside quantum computers to make the system function. As quantum technology improves, we can see the possibility of further workload proliferation. We also think that far enough into the distant future, quantum computers can start cannibalizing classical computers for some workloads.

Because they will be more efficient at solving nondeterministic polynomial time problems, we think the earliest use cases for quantum computers will be for optimization, simulation, and encryption problems. Given the parallel processing advantage quantum computers have, this should be intuitive, as many solutions can be explored simultaneously until the computer arrives at the best one. Within those types of problems, compelling use cases in pharmaceuticals, chemistry, route scheduling, manufacturing planning, financial services, cybersecurity, and agriculture are likely, in our view. Drilling down another level, molecular analysis, quantum analysis, and simulation all point to chemistry, and chemistry leads us to conclude that materials science and pharmaceutical development are likely to be key use cases for quantum computers. In this section, we provide an overview of some of the major applications.

Chemistry and Materials Science

Molecule analysis can be performed to some extent by classical computers. Finding the ground, or most stable, state of a hydrogen atom is relatively simple.

However, as more atoms, more elements, and different particle charges or isotopes are introduced, molecules can become extraordinarily complex very quickly. Variational quantum eigensolver, or VQE, is an obvious approach to driving quantum molecule analysis, as it employs classical computers, which we understand well, and the massive efficiency gains from superposition inherent in quantum computers, to find the ground states of complex molecules. Quantum annealers can perform these workloads as well. Massive server arrays available with the rise of cloud computing and cloud service providers have helped in this regard, but ever-more complex analysis will effectively require a new paradigm, which quantum computing is well-suited for. Microsoft seems to be aggressively targeting chemistry (and pharmaceutical) use cases. It follows that chemical and specialty chemical industries are obvious candidates to be an important customer cohort for quantum computing as well.

Morningstar’s materials analyst, Seth Goldstein, notes that specialty chemical companies, in particular, have already embraced AI and other advanced technologies to speed up R&D efforts, gain efficiencies, and accelerate innovation by unlocking new molecules. He concurs with our incremental R&D approach as a means to explore the market opportunity. Further, he believes the specialty chemical companies could afford to expand R&D budgets by 100 basis points and would likely even embrace quantum technologies if it helped introduce new molecules and increase revenue. Even more basic chemicals manufacturers, with smaller R&D budgets and narrower margins, would still be interested in exploring new technologies like quantum computers for these reasons. Companies such as Dow Chemical would be significantly larger in terms of revenue, but limited to perhaps 20 to 50 basis points of incremental R&D investment.

Exhibit 27 Specialty Chemical Firms Are Likely to Be Quantum Computer Users

Company	Ticker	Revenue	FCF	FCF Margin	R&D (% Rev)
Corteva	CTVA	16,908	1,791	10.6%	8.3%
Entegris	ENTG	3,241	425	13.1%	9.8%
International Flavors & Fragrances	IFF	11,484	717	6.2%	5.8%

Source: Company reports for each company's most recent fiscal year, PitchBook, Morningstar. Data as of December 2025.

Chemistry extends beyond chemicals and specialty chemicals to any materials science, from electronics, to military, and to coatings—all of which are areas quantum computing can help drive long-term innovation. Name-brand companies, including Taiwan Semiconductor, Dow Chemical, and Merck, from fields that rely on chemistry, are well-represented in terms of funding quantum computing research and partnering with quantum computing providers for pilot programs and experimentation.

We see Microsoft in front of the quantum computing wave specifically as it relates to chemistry. Azure is already a global leader in high-performance computing, public cloud services, and AI, and offers a variety of tailored solutions related to chemistry use cases.

Notably, Microsoft describes a process of using Azure high-performance computing to gather data from molecule simulations that are then used to train and fine-tune models that then predict chemical properties. These predictions are further refined by Microsoft's quantum platform.

Pharmaceuticals

Pharmaceutical usage is largely an extension of chemistry applications. However, given the massive R&D budgets involved in the pharmaceutical and biotech industries and the importance of molecule innovation, we see drug discovery as perhaps the one of the single most important use cases. Our commentary around chemistry in general applies directly to pharmaceuticals and can be extended to the analysis of complex proteins.

Exhibit 28 We Expect Pharma Companies to Be Early Adopters of Quantum Computers

Company	Ticker	Revenue	FCF	FCF Margin	R&D (% Rev)
Novo Nordisk	CSE:NOVO B	42,124	11,844	28.1%	16.6%
Eli Lilly	LLY	45,043	5,799	12.9%	24.4%
Merck	MRK	64,168	21,763	33.9%	28.0%
AbbVie	ABBV	56,334	20,614	36.6%	22.7%
Novartis	SWX:NOVN	51,722	14,511	28.1%	19.4%
Gilead Sciences	GILD	28,754	11,185	38.9%	20.5%
Regeneron	REGN	14,202	4,157	29.3%	36.1%
GlaxoSmithKline	LON:GSK	40,090	1,086	2.7%	20.4%
Johnson & Johnson	JNJ	88,821	16,222	18.3%	19.4%
Roche	SWX:ROG	70,862	14,513	20.5%	24.5%
Amgen	AMGN	33,424	8,029	24.0%	17.8%
AstraZeneca	LON:AZN	54,073	8,168	15.1%	25.1%
Bristol-Myers Squibb	BMJ	48,300	13,132	27.2%	23.1%
Pfizer	PFE	63,627	12,900	20.3%	17.2%
Sanofi	PAR:SAN	47,922	6,522	13.6%	16.7%
Biogen	BIIB	9,676	2,671	27.6%	21.1%

Source: Company reports for each company's most recent fiscal year, PitchBook, Morningstar. Data as of December 2025.

For drug discovery, pharmaceutical companies have shifted their focus from physically bombarding x-rays through crystalized molecules to determine their 3-D structures to using a computer modeling approach dubbed crystal structure prediction, or CSP. This technique allows researchers to predict the behavior of electrons based on the principles of quantum mechanics in order to determine the structure of the molecule. CSP requires many highly complex calculations in cloud data centers and can still take up to four months to model a single molecule. Using quantum computers in conjunction with other techniques researchers at Pfizer are now doing this in a few days.

This is particularly impressive given the hardware limitations of current quantum computers. “A process that used to take us so much time that we almost didn’t even attempt it has become the norm, and now we can try it on almost every small molecule project,” said Bruno Hancock, global head of materials science (now retired) at Pfizer’s Groton, Connecticut research site¹.

Another pharmaceutical giant, Merck, is also leaning into quantum computing for drug discovery and materials science through a variety of partnerships. The company has partnered with HQS Quantum Simulations to develop and commercialize applications for chemistry and drug development. Merck is leading the BAIQO project in concert with Ludwig-Maximilians-Universitat Munchen and funded by the German government to advance drug development and streamline clinical trials. The company has also had some encouraging early results in a joint quantum computing project in conjunction with Amgen, QuEra Computing, and Deloitte that used neutral atom quantum reservoir techniques to predict molecule behavior based on small data sets. Separately, AstraZeneca has been experimenting with IonQ, where it has achieved a 20-times faster time-to-solution than previous methods using just cloud infrastructure from AWS in isolation.

Encryption and Cybersecurity

Quantum cryptography uses data encryption and transmission methods based on quantum mechanics for cybersecurity. Expected to improve detection and resolution of both quantum and traditional threats to systems, quantum cryptography has been a key focus for several companies. Tech giants like IBM, Alphabet, and Microsoft have focused largely on post-quantum cryptography, that is, development of quantum-resistant algorithms that can be run on classical systems. Other companies like Toshiba are increasingly focusing on building quantum hardware for distribution and generation of cryptographic keys, or quantum key distribution. However, despite being a more developed application than others, quantum cryptography has had limited acceptance. In addition to the current, core limitations of quantum computing, PQC algorithms tend to have larger keys, need higher bandwidth, and can be latency-sensitive, which can lead to increased operational overhead and limit their scalability.

Agriculture

Quantum computing most likely also holds promise for transforming agriculture, which should also be thought of as largely falling under the chemistry umbrella. This new technology could help through its ability to analyze vast, complex data sets. By leveraging data from satellite imagery, video footage, climate sensors, and more, quantum technology can enhance the predictive accuracy of crop yields, resource (fertilizer, pesticide, and water) allocation, and environmental impacts. Quantum-enabled sensors can collect and process detailed information on soil moisture, microbiome composition, nutrient levels, pest populations, and other critical variables. This can support precision agriculture and targeted irrigation strategies. We think in this particular use case a variety of quantum technologies beyond quantum computing may be required to work in concert together.

¹ Pfizer. https://www.pfizer.com/news/articles/how_quantum_physics_and_ai_is_disrupting_drug_discovery_development.

Emerging research suggests that quantum-driven precision agriculture could reduce water and fertilizer usage by up to 25%, promoting more sustainable and efficient farming practices. In addition, quantum algorithms, such as the quantum approximate optimization algorithm, or QAOA, show potential for applications in livestock management, including predicting breeding cycles and monitoring animals for illness or aggressive behavior. In a proof-of-concept project, Bayer partnered with Fujitsu to use the Digital Annealer for optimizing seed production planning and materials campaign scheduling. We also think seed development and fertilizer and pesticide solutions will be advanced through the application of quantum computing. More recently, D-Wave collaborated with software company Staque to apply quantum annealing in developing a commercial solution for optimizing agricultural vehicle movement and route planning.

Optimization and Scheduling

The use of quantum computing in process optimization has seen good progress. Applications include, but are not limited to, supply chain optimization, warehouse management, product innovation, scheduling, and maintenance. Quantum annealers, due to their effectiveness in solving optimization problems, have been particularly successful in this use case. For instance, D-Wave's Quantum Annealer has been successfully used by automotive companies like Volkswagen and Ford Otosan for route planning and manufacturing scheduling, respectively. Gate-based quantum computers using hybrid algorithms like the QAOA have also seen success, although their scalability has been limited. Pattison Food Group has used optimization to cut route planning time by 80%, while Savant X has increased cargo throughput at the Port of Los Angeles by 60% using 40% less crane resources, both on D-Wave annealers. However, we think that given the competing reliability and efficiency of classical algorithms and software, quantum computers are still largely being used in very limited use cases.

Financial Services

The financial services sector is expected to be one of the primary beneficiaries of fault-tolerant quantum computing. In the future, quantum computing is poised to significantly enhance efficiency and accuracy in financial prediction models and simulations. It could also enable more proactive customer service, improve combinatorial optimization for portfolio diversification, and deliver greater precision in modeling complex risk scenarios. Additional applications may include credit scoring, asset valuation, and fraud detection. Despite its potential, the practical adoption of quantum computing in finance has so far been constrained by high regulatory barriers and the current limitations of the technology. However, a recent breakthrough² demonstrated its promise: HSBC partnered with IBM to estimate the probability of a trade being executed at a quoted price. Using real trading data and statistical models running on IBM's Heron quantum processor, the project aimed to predict the likelihood of winning customer inquiries in the European bond market. The trial delivered a 34% improvement in prediction accuracy, compared with traditional classical methods.

² Davis, R. 2025. "HSBC breaks new ground in quantum-enabled algorithmic trading with IBM quantum computers." Sept. 24, 2025. <https://www.ibm.com/quantum/blog/hsbc-algorithmic-bond-trading>.

Artificial Intelligence

We do not think AI will be an immediate use case for quantum computing. On the one hand, the probabilistic and predictive nature of generative AI suggests that quantum computing should be a natural fit. On the other hand, the latency involving loading all of the data into quantum memory—which is imperfect at best or nonexistent at worst—would exceed the decoherence time associated with any known quantum hardware architecture. As the technology matures, it seems like quantum could potentially push generative AI to a new level. It also seems reasonable that quantum simulations can be performed and results of workloads performed on quantum workloads could be fed into large language models to help refine their training or perhaps add new capabilities. While we think quantum computing can contribute significantly to AI in the long term, we do not think the impact will be meaningful within early adoption use cases in the next decade.

Other Quantum-Related Use Cases

Beyond what we think are likely to be the primary use cases early on for quantum computing outlined above, other areas of quantum technology repeatedly tripped our radar while researching the topic. We consider these to be related to quantum computing but not really the same. Notably, there seems to be some industry excitement around quantum sensing and quantum networking. While we think they are a bit beyond the scope of this report, we include a high-level overview for investors to ponder.

Quantum Networking

Quantum networking harnesses the principles of superposition and entanglement to transmit information using individual particles of light—photons. Among the various types of qubits, photonic qubits are the most promising for quantum networking because they can travel long distances at the speed of light through fiber-optic cables. They also exhibit lower decoherence and can be easily manipulated into quantum states using well-established optical components such as beam splitters and phase shifters. Researchers are actively developing quantum communication protocols to enable reliable photon-based information transfer across future quantum networks. This field is considered a critical foundation for scalable and distributed quantum computing.

Recently, IonQ achieved a significant milestone by demonstrating the conversion of visible light photons into telecom wavelengths—a key step toward building a functional quantum internet. Meanwhile, Cisco Systems' Quantum Labs is working on a full quantum networking software stack, having released prototype tools in September, including a quantum compiler now available for download. Despite their advantages in long-distance transmission, photonic qubits are still subject to decoherence, particularly during interactions with matter or within complex systems—a persistent hurdle to scalability.

All of that said, quantum computers are being trialed by network operators to improve asset utilization and optimize traffic flow. NTT Docomo, for example, achieved a 15% improvement in network performance using D-Wave's quantum annealer, which we think is another proof point of quantum computing for broad use cases.

Quantum Sensing

Quantum sensing is the use of quantum mechanics for high-precision data collection. Quantum sensing itself is a fairly broad use case of quantum computing, but its applications include medicine, seismology, navigation, material sciences, and more. We consider quantum sensing to be one of the more well-developed use cases for quantum technology. The most well-known applications include atomic clocks and MRI machines, with upcoming developments in navigation and magnetometers. Since data is collected at the atomic level, quantum sensors can be used to collect different types of data, like frequency, temperature, pressure, rotation, and more, with more precision than traditional lab equipment. However, as a result, quantum sensors can also be more sensitive to electromagnetic interference. Other key challenges to scale this technique include high operational costs and custom integration requirements. Firms investing in and researching in the field include Qnami, SBQuantum, and Frequency Electronics.

Despite the relative maturity of this use case, we believe most of the potential applications for quantum sensing are still in the “prototype” phase, although they may be ready for use in the next few years.

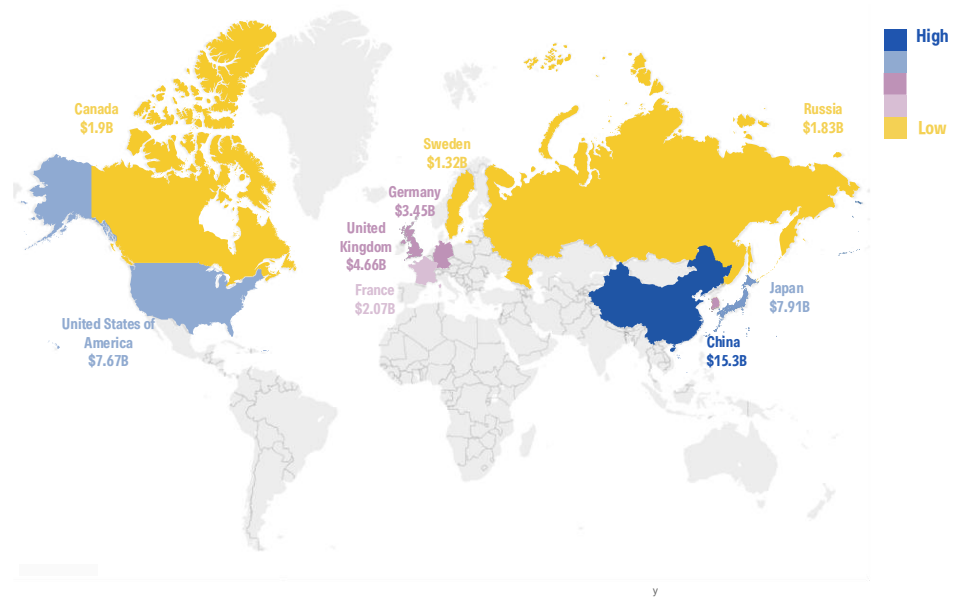
The Overall Market Can Be Enormous, but for Now It Is Quantumly Small

Given that revenue is already being generated from quantum computing, saying the industry has not reached commercialization is not quite true. It has. However, the revenue generated is mostly because of test cases and application development, rather than commercial usage. More precisely, the technology is not ready for mass adoption at this point, as it lacks an ecosystem, including use cases and the business case for return on investment, or ROI, on those use cases, software applications, middleware, and consultants. Perhaps most importantly, initial quantum hardware has proven that the technology works and has theoretical functionality, but no team has produced a chip containing enough qubits to make it applicable to general-purpose real-world solutions. Further, no chip is scalable in terms of manufacturing, as these are mainly research projects. Despite these challenges, in this section we will attempt to gauge the market opportunity.

Investment Level Matches Buzz

Qureca describes \$55.7 billion in cumulative global governmental investment (or announced investments) in 2025 alone into quantum computing. Countries that are investing \$1 billion or more in 2025 in quantum computing include the US, Canada, the Netherlands, France, the UK, Spain, Germany, Sweden, China, Russia, Japan, and South Korea. In October 2025, US President Donald Trump's administration was reportedly in talks to invest in direct equity positions of several US-based quantum computing companies. The administration denied that, but advancing critical industries has generally been a priority, so we think that discussions could be ongoing. A sampling of news sources suggests this is reasonably accurate. Investment is certainly high.

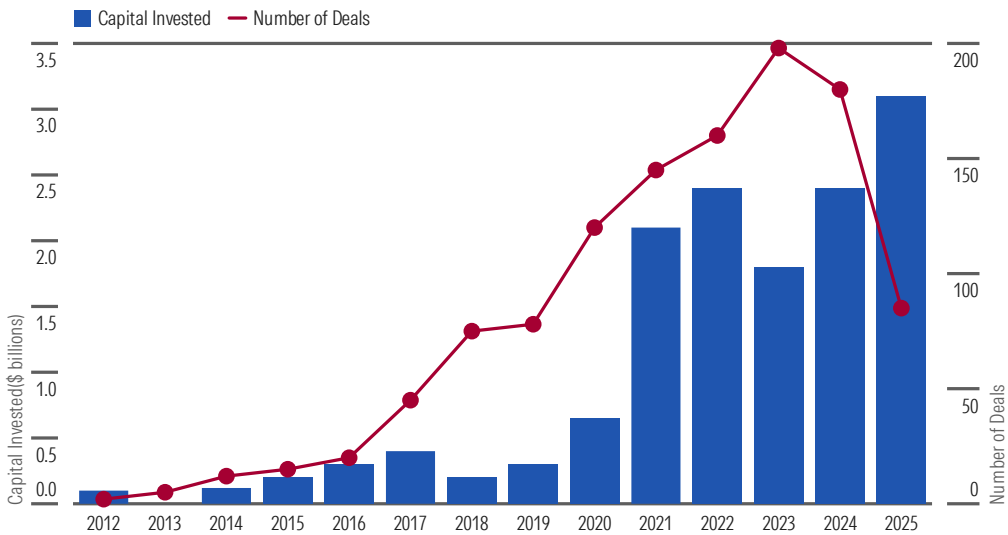
Exhibit 29 Global Public Investment Has Been Massive



Source: Qureca, Morningstar.

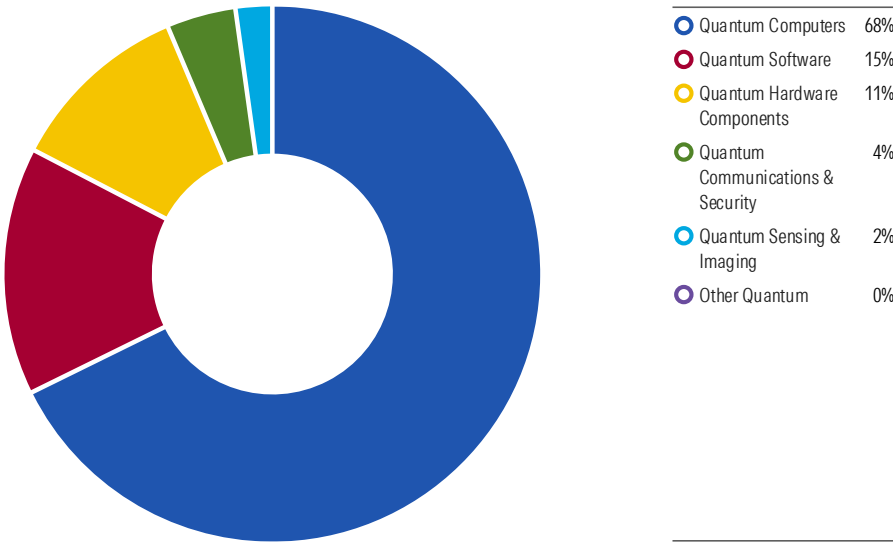
We can examine the deal and new startup formation around quantum computing and see that while healthy, these factors are not indicative of a market that can potentially generate hundreds of billions of dollars in the not-so-distant future. Still, venture capital investment in quantum computing has been pumping at least a couple billion dollars annually into the space for the last five years, with a slight dip in 2023. Generative AI has likely been crowding out investment in other advanced technologies over the last three years. Indeed, we count only three quantum computing unicorns, companies valued at \$1 billion or more. Given milestone technological improvements, the keen interest by large companies and governments, and the lure of a massive market opportunity, we expect investment to pick up over the next several years.

Exhibit 30 Funding for Quantum Computing Has Been Increasing Over the Last Few Years



Source: PitchBook. Data as of October 2025.

Exhibit 31 Quantum Computing Attracted More than \$1.2 Billion In Funding in Q1 2025 Alone



Source: Quantum Insider, Morningstar.

The Actual Technology Remains More of a Research Obsession

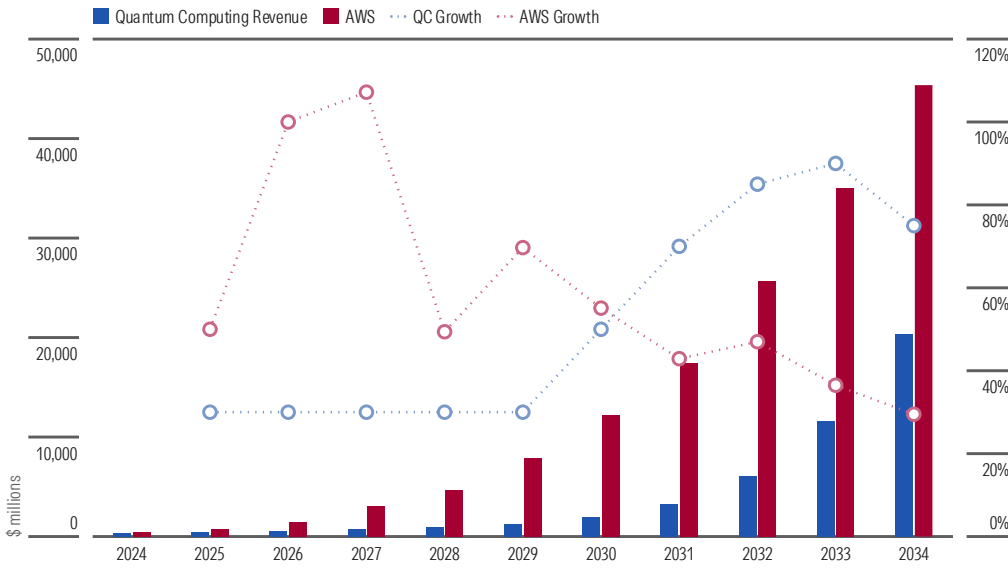
Exploring investment into quantum is insightful and attempting to dimension the market potential further supports the excitement around quantum computing. However, we feel compelled to take the final step in this analysis and describe how we think this market evolves over the next five to 10 years. After all, the timing of commercialization is a critical point with the emergence of quantum computing.

Quantum computing is in its infancy. Many players are largely in the experimental phase of quantum computing but are generating at least modest revenue. IBM is the only major company we have seen provide a hint of the size regarding its quantum computing business, where management said in February 2025 that the company had booked nearly \$1 billion of cumulative sales since 2017 and was averaging about \$36 million in revenue per quarter. Amazon, Microsoft, and Alphabet have not disclosed quantum-related revenue but we suspect IBM is the ceiling and low-single-digit million dollars per quarter seem more likely. Publicly traded companies like Rigetti and D-Wave regularly generate a few million dollars in revenue per quarter, although this has grown meaningfully as 2025 has unfolded.

According to Quantum Insider, the quantum computing industry generated approximately \$1 billion in combined hardware and software revenue and is expected to grow to more than \$5 billion by 2030. McKinsey's April 2024 Quantum Technology Monitor estimated the quantum market to generate between \$8 billion and \$15 billion in 2025. Based on what we can observe from publicly disclosed sources, we will assume the market was approximately \$400 million in 2024, which includes post-quantum crypto consulting. We also assume solid growth over the next several years as experimentation continues and likely proliferates. However, we see revenue as beginning to inflect upward in 2029, with surging growth lasting through 2034, when the quantum computing market hits \$20 billion in annual revenue. As a comparison, Rigetti's estimate is of \$15 billion to \$30 billion in annual revenue during the 2030 to 2040 timeframe. We caution investors that we think the early stages of commercialization begin in five to 10 years and our analysis focuses on it starting in five years, which could be optimistic, but is in line with what Microsoft and Alphabet are publicly saying.

We plotted our quantum computing forecast along with AWS, so 2024 for quantum computing in this exhibit compares with 2010 for AWS. We do not view this as a perfect corollary, we only meant to give AWS the benefit of having generated revenue for several years to make the growth comparison more relevant. When AWS was launched the use case was relatively obvious, as users could use the cloud-based compute and storage functions for the same workloads they used those functions internally, and the software applications were all the same. The use cases were obvious immediately. This is not the case for quantum computing, where the underlying hardware is the same and there is no meaningful software ecosystem, which makes the use cases and the associated return on investment less obvious. We, therefore, think the inflection upward will not be as severe as it was for AWS and will not be as prolonged. Still, we can see \$20 billion in quantum computing revenue annually by 2034 (or 2039 if we centered our five- to 10-year focus to the long end of that range), which we still think fits with our initial commercialization for limited use cases framework.

Exhibit 32 Quantum Computing Could Follow a Similar Trajectory to AWS Early On

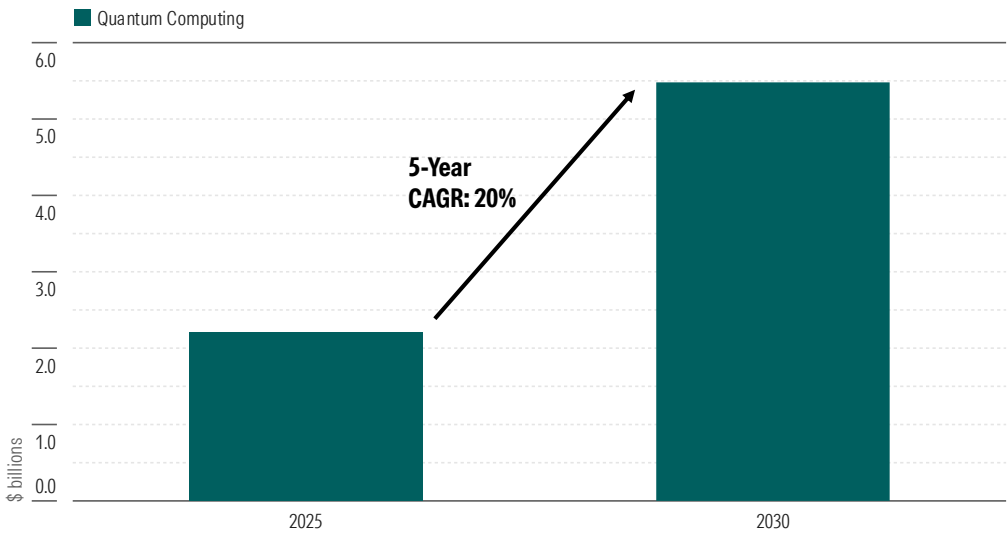


We think this is consistent with Alphabet's and Microsoft's expectations for noisy intermediate-scale quantum, or NISQ, becoming reality by approximately 2030. While early iterations of fault-tolerant computers may start to emerge and be deployed in experimental settings during the tail end of this time frame, we think it will take another five to 10 years for them to reach meaningful adoption. At this time, the computing paradigm will begin to resemble what investors currently understand current computers to be. Further, we think the model will favor a centralized model, similar to the current cloud service provider model. This will pair quantum systems with powerful classical capabilities in public cloud service providers' data centers. That said, we still expect on-premises systems to exist—perhaps accounting for 10% to 25% of quantum computing workloads.

A Second Opinion on the Market Size and Growth Today

We reviewed the current market size from a variety of angles and found no consistency across limited data points. Qureca points to \$56 billion in cumulative government investments or announced investments through September 2025. McKinsey posits that the revenue generated by the quantum computing market will be between \$8 billion and \$15 billion in 2025, growing to \$28 billion-\$72 billion by 2035. Quantum Insider says the market is \$1 billion right now. Other sources start getting comically aggressive as market size estimates use the word “trillion” within the next 10 or 20 years. Yes, an enormous market is possible, but we would prefer to see more use cases and more actual revenue before we start throwing the T-word around. Third-party estimates on PitchBook are closer to our own estimate of a \$1 billion market today.

Exhibit 33 According to PitchBook, the Market Is Small but Should Grow Rapidly



Source: PitchBook, Morningstar. Data as of October 2025.

Realistically, until we see some of the key engineering problems solved, or at least substantial progress made toward solving those issues, we do not expect the market to inflect upward. Further, based on direct observations of publicly traded companies and an assessment of other players, we conclude the total revenue generated in quantum computing was closer to \$400 million in 2024. So, overall we see impressive growth for the next several years, but we still see the industry as experimental. As the ecosystem is more developed, the engineering issues in terms of scaling the number of qubits on a chip, improving error correction, and increasing coherence, and manufacturing in volume are resolved, and as use cases mature, we expect revenue to grow into the hype. Based on our assessment of the state of the quantum computing industry in 2025, we can see a more meaningful ramp beginning within five years. We think that is consistent with Microsoft’s and Google’s recent assertions that the development process is years away rather than decades away from more meaningful commercialization.

Revenue Potential Is Certainly Buzzworthy

Beyond the investment being plowed into quantum computing from governments, universities, established corporations and venture capital funds, we also considered the size of the markets where we think the underlying use cases for quantum computing will be an important technology. We dove into broad industry for what we think will be the initial or primary use cases for quantum computing. Those areas included pharmaceuticals, chemistry, route scheduling, manufacturing planning, financial service, cybersecurity, and agriculture, among others.

Exhibit 34 Quantum Computing Can Meaningfully Affect Enormous Areas of the Global Economy



Source: Morningstar.

At a high level, those highlighted industries currently generate \$36 trillion in annual revenue. Based on this high-level approach, we can start assessing the impact of quantum computing by assuming how much R&D might be allocated to the technology. As a starting point, 1% of this aggregate revenue is \$360 billion, which seems like an aspirational goal for the technology as it matures.

If the technology offers breakthrough molecular analysis for the pharmaceutical industry, we think 1% of revenue could be more of a floor than a lofty goal. Large pharmaceutical companies have average R&D budgets of approximately 22% of revenue, so shifting projects around, allocating more dollars, or raising prices slightly would easily cover this cost of innovation. In other industries with slimmer margins, companies might have less flexibility to increase R&D spending, so perhaps an increase of 25 basis points might still generate improved operations in some capacity for a logistics company or allow a specialty chemicals company to innovate. If we focus on a blended R&D uptick across industries, 0.5% of revenue can be reasonably managed. At this level of incremental R&D, we can see the market for quantum computing hitting approximately \$200 billion annually. We reiterate that the technology would need to continue to improve over time and that this is a long-term view.

Exhibit 35 The Market Could Hit \$200 Billion at Maturity

Revenue (\$ billions)	Incremental R&D (% of Revenue)										
		0.10%	0.20%	0.30%	0.40%	0.50%	0.60%	0.70%	0.80%	0.90%	1.00%
	47,916	48	96	144	192	240	287	335	383	431	479
	43,560	44	87	131	174	218	261	305	348	392	436
	39,600	40	79	119	158	198	238	277	317	356	396
	36,000	36	72	108	144	180	216	252	288	324	360
	32,400	32	65	97	130	162	194	227	259	292	324
	29,160	29	58	87	117	146	175	204	233	262	292
	26,244	26	52	79	105	131	157	184	210	236	262

Source: Morningstar.

For perspective, public cloud services from Amazon, Microsoft, Google, Alibaba, and Oracle combined for just north of \$255 billion in revenue during calendar 2024. Amazon introduced AWS in 2006, so it took 18 years to cross the \$200 billion threshold for public cloud services, which had an obvious market when introduced, even if \$255 billion was not really on the radar at the time. Therefore, while this level of revenue may be possible one day for quantum computing, we do not foresee that milestone in the next 10 years. Further, even within 20 years this strikes us as unlikely, given that we have not reached true commercial viability yet for quantum computing. When AWS was launched, all of the technology was already proven, so it was basically a paradigm shift in computer usage. We do not view public cloud services as fully mature at this point, so perhaps this precedent is relevant in terms of both size and timescale.

A Second Opinion on Potential Market Size

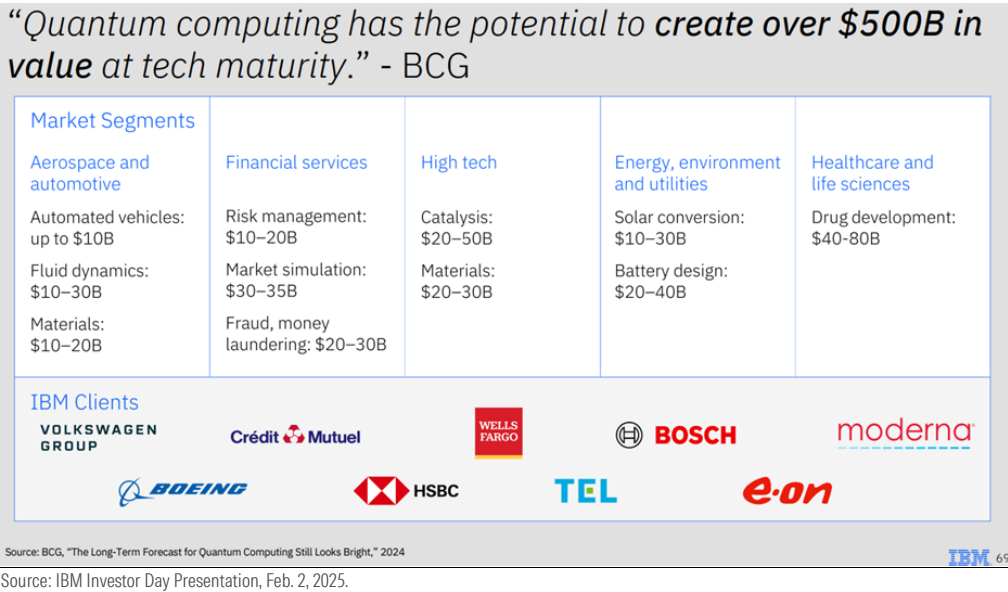
Finally, we see estimates from reputable third parties. McKinsey, for example, projects \$900 billion to \$2 trillion in value added by 2035³, while Boston Consulting Group thinks that quantum computing could create more than \$500 billion at maturity⁴. We view value-added analyses like these as softer than a total addressable market analysis, but we think they nonetheless illustrate the substantial market that lies ahead for quantum computing.

³ McKinsey Digital QuantumTechnology Monitor, April 2024.

<https://www.mckinsey.com/-/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf>.

⁴ As referenced in Exhibit 36.

Exhibit 36 We Concur With IBM's Enthusiasm Around the Potential Market



New Technology and High Uncertainty Can Drive a Wide Range of Outcomes

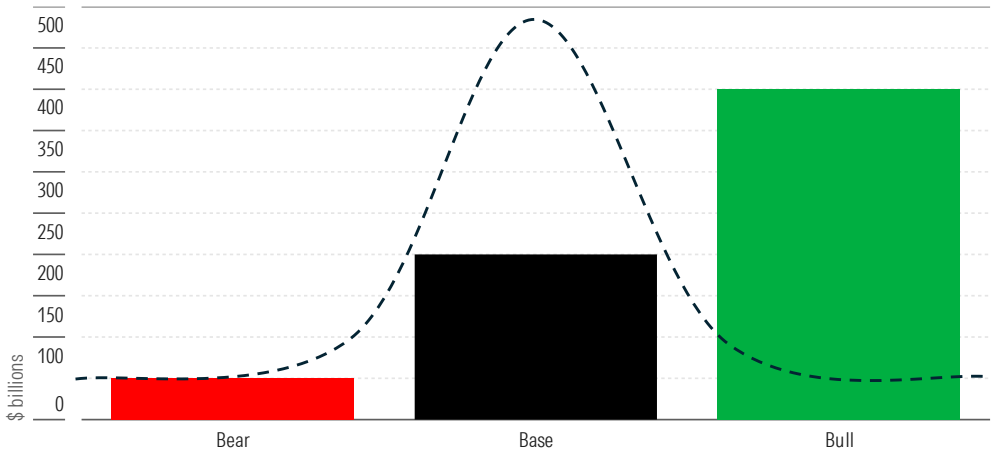
Given the uncertainty inherent in an emerging technology like quantum computing, we have also attempted to erect some guardrails around our estimate of the market potential. Under the most bearish scenario, we could assert the technology will never be ready or it will be too expensive, so the opportunity is effectively \$0. While we do not believe this is realistic, given that modest revenue is already being generated, a more plausible downside scenario would be that it simply takes longer for quantum computers to be commercialized. Instead of our five- to 10-year time frame, early commercialization could happen in 15 to 20 years. This may not change the ultimate opportunity much, but it certainly will push the industry revenue curve out considerably and render immediate investor interest in this category near zero.

On the more bullish side, we would have to assume not only faster adoption than we have mapped out, but we would also have to assume that quantum computers eventually begin replacing traditional servers and perhaps even GPU-based servers. If the cloud services market is approximately \$400 billion today and growing 20% annually, even at a decelerating rate, certainly within 10 years it will surpass \$1 trillion. Far enough into the future, it seems possible to make the case that some portion of traditional workloads will be executed on quantum computers rather than existing server types. This view would likely incorporate the possibility that Moore's law finally splinters, but traditional workloads can still be performed on hardware that only sees minor annual improvements. The most bullish scenario is that all workloads become quantum computing workloads, which would require all of the challenges we describe throughout this report being overcome. Perhaps in 50 years that may be possible, but within a more reasonable time frame of 10-20 years, a small portion of all workloads shifting to quantum seems possible.

In this case, we can double our market size estimate from \$200 billion of purely quantum use cases, plus additional \$200 billion of workloads shifting to quantum, resulting in a market of \$400 billion for quantum computing during its maturity.

Tying it all together, we believe the annual market for quantum computing could be \$200 billion at maturity, which we do not think should be thought of as peak revenue, even if this takes 30 years to achieve. Even within that time frame, we still envision attractive growth for the industry, similar to the state of the public cloud industry today. On the downside, a longer development period could push out revenue such that it is still under \$1 billion in 15 years, which would likely put the market size at \$50 billion 30 years from now. More optimistically, assuming quantum can begin to cannibalize traditional workloads, we can see the market topping \$400 billion annually.

Exhibit 37 We See a \$200 Billion Market, Even If It Takes 30 Years to Realize and Has Fat-Tailed Possibilities



Source: Morningstar.

Leading Companies in the Quantum Computing Field

Despite the seemingly impossible physics and extreme engineering involved, we observe a wide variety of companies directly engaged in designing and manufacturing quantum computers. The potential market opportunity is clearly attracting many competitors.

We are not surprised to see the hyperscalers, including Amazon (AWS), Microsoft (Azure), and Alphabet (GCP), actively involved in the field, as it is not a stretch to envision today’s supercomputers—massive arrays of GPU clusters—evolving into quantum computers at some point in the future. The specialization required to create and operate a quantum computer seems likely to serve as a governor on who can own a bleeding-edge device of this sort. Additionally, potential customers are now used to having their compute resources outsourced to the cloud. IBM is also making quantum advancements, as the company has long had an interest in servers and mainframes, is one of few mainframe computer producers today, and currently has the largest existing quantum business we are able to identify.

We also think classical computers will be required to use quantum systems for readout and orchestration over the next ten years, which we think underscores the importance of the cloud service providers to the emerging field of quantum computing.

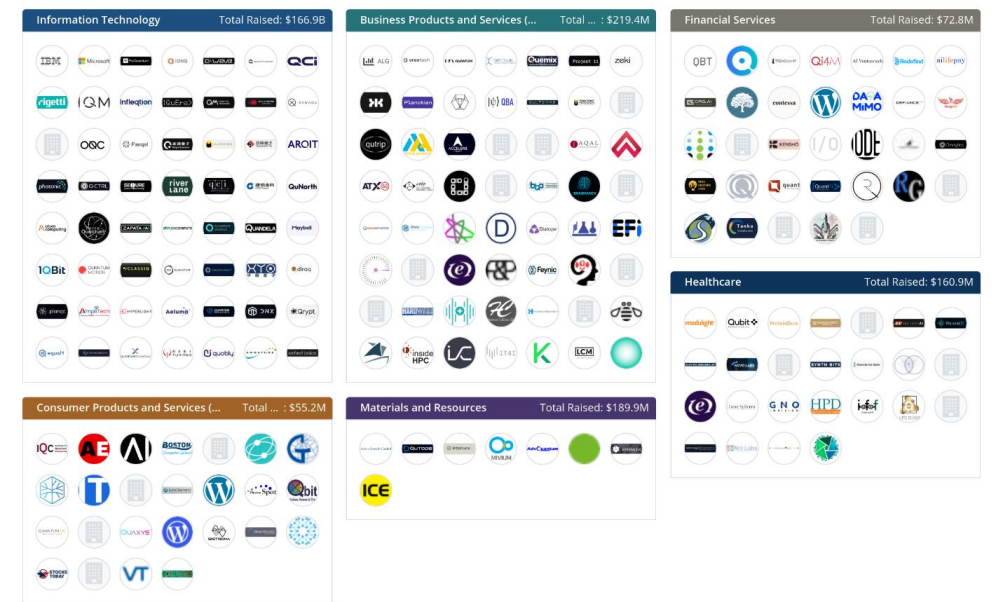
Exhibit 38 We Expect Our Cloud Service Providers and IBM to Be Key Quantum Players

Company	Area of Focus	Latest Hardware Innovation	Immediate Market Position	Long-Term Goal	Key Verticals
Microsoft	Topological qubits	Majorana 1 QPU – Feb 2025 (8 topological qubits, but a single chip has the potential to be scaled to millions of qubits)	- No material commercialization - Azure Quantum can be used to access IonQ, Rigetti, Pasqal, and Quantinuum quantum computers.	A quantum supercomputer of 1 million rQOPS/sec with an error rate below 10 ⁻¹² , scaling to 100 million rQOPS/sec	Material sciences, quantum networking, chemistry, and pharmaceuticals
Google	Superconducting qubits	Willow QPU – Dec 2024 (105 qubits)	No material commercialization	A large quantum error-corrected quantum computer of 1 million qubits and 10+ error corrected quantum computing applications	
Amazon	Cat qubits	Ocelot QPU – Feb 2025 (9 qubits – 5 cat qubits + 4 transmon qubits)	- No material commercialization - Amazon Braket can be used to access IonQ, IQM, Rigetti, and QuEra quantum computers.		
IBM	Superconducting qubits	Heron r2 QPU – April 2025 (156 qubits)	\$1 billion cumulative quantum signings since Q1 2017 (average: \$36 million per quarter)	A quantum computer with circuits of a billion gates and up to 2,000 logical qubits (Blue Jay)	Financial services, cryptography, manufacturing/optimization, chemicals, and pharmaceuticals

Source: Company releases, Morningstar.
Note: rQOPS = reliable quantum operations per second.

We observe a variety of small, specialized companies conducting R&D and offering limited quantum computing solutions, including IonQ, D-Wave, Quantinuum, and Xanadu. In fact, we count well in excess of 100 discrete companies developing quantum computer hardware, software, or services.

Exhibit 39 The Landscape Is Already Crowded



Source: PitchBook.

These companies are approaching quantum computers from many different angles, with multiple companies driving down each of the paths. We stress that it is way too early to describe any one approach to quantum computing architecture as “better,” or any one of companies involved as “the winner,” although we have opinions on the latter. Rather, like many broader technology applications, we think the use case will be the best determinant of which quantum computing technology is employed. For example, IBM seems to have an early lead overall, Microsoft has built a full-service suite for chemistry, and Xanadu is well-known for Monte Carlo simulations. While we discuss a variety of the larger or seemingly leading industry players below, we stress that it is early in the development of quantum computers. We expect that landscape to evolve along many vectors over the next decade and we do not assume all of these companies will be around 10 years from now.

In the pages that follow we provide an in-depth analysis of the quantum computing involvement for key industry participants we cover within Morningstar’s US technology team, including Amazon, Alphabet, IBM, Microsoft, and Nvidia. We follow this up with high-level overviews for some privately held companies, industrial conglomerates, or small publicly traded quantum computing pure-plays that we uncovered during the course of our research.

Amazon

Given that Amazon created the public cloud model when it launched its earliest services in 2002, it should come as no surprise that the company has been investing heavily in quantum computing since 2019. The firm has extensive experience in offering a broad array of discrete services under the broad AWS umbrella, such as with generative AI, whereby Amazon offers its own proprietary chips for handling AI workloads, has created its own large language models, and offers Bedrock as a managed AI service that serves as a platform to access third-party foundational models like Anthropic. As such, it comfortably follows that the company has taken a similar approach to quantum computing, where Amazon has produced both a quantum chip, dubbed Ocelot, and already offers a managed quantum service, called Braket.

We assume that as quantum computing matures, Amazon’s AWS unit will continue to add quantum services to its menu. We also assume given the company’s dominance in public cloud and strong positioning in generative AI, that Amazon’s quantum focus will be on commercialization of quantum computing services as though it was any other hardware within its data centers. Within the approximately \$125 billion in AWS revenue that we estimate AWS will generate in 2025, we assume that quantum related revenue is greater than zero but still trivial within the segment.

In 2021, AWS partnered with Caltech to create the AWS Center for Quantum Computing, or CQC, which included a new dedicated building and a variety of leading-edge professors and research teams. The premise was to create quantum computers and related technologies that could have a meaningful impact on the broad field of computing. At a high level it combines cutting-edge academic research with emerging applied technology.

When the venture was formed CQC had two primary technology goals, which were scaling up the number of qubits in a quantum system and building an architecture that incorporates error correction directly into the hardware. Oskar Painter, head of quantum hardware for AWS, recently noted that the company's next quantum hardware update is likely a few years away.

In February 2025, Amazon announced a prototype that achieves both of CQC's objectives, with a scalable architecture with error correction inherent in the quantum system. The achievement is an important advancement in quantum computing in general as it demonstrates the feasibility of using oscillators to create cat qubits. Based on testing of the Ocelot chip, AWS believes it can reduce the costs of implementing quantum error correction by up to 90%, compared with current approaches. It is also important to note that the device can be manufactured at scale employing existing chip fabrication process technology, meaning that it could cost as little as 20% of the cost of current quantum approaches. This is important, as we believe cost has slowed industrywide development down and has kept interest somewhat subdued.

Ocelot is a proof of concept for a quantum chip with built-in error correction, which it seems to deliver upon, rather than a complete quantum system. In technical terms from the Amazon Science Blog, bit-flip errors are exponentially suppressed at the physical-qubit level, phase-flip errors are corrected using a repetition code, and noise-biased controlled-NOT, or C-NOT, gates enable phase-flip detection, while preserving the cat qubit's bit-flip protection. This is achieved through the use of five data qubits that each contain an oscillator used to store quantum data. Each qubit is connected to two additional transmon qubits for phase-flip error detection, coupled with a buffer circuit to stabilize the cat qubit states. Bit-flip times approach one second, which is in excess of 1,000 times longer decoherence periods than typical superconducting qubits.

Beyond the technological achievements on the hardware side, AWS has also been busy developing the software and ecosystem side of its quantum computing offerings as well. AWS offers Braket, which has several elements, including a software development kit, or SDK, a simplified local quantum circuit simulator, access to three more robust simulators, the ability to embed other quantum simulators (bring your own simulator), and access to various production quantum computing hardware solutions.

The Braket SDK allows users to create their own quantum algorithms and then test them using Amazon's three quantum simulators. These simulators include SV1 for full-state vector simulations up to 34 qubits, DM1 for simulating noise on circuits up to 16 qubits, and TN1 for simulating quantum circuits with higher local entanglement up to 50 qubits. Testing algorithms in a simulated quantum environment can help identify and resolve potential issues more quickly and cost effectively before running the algorithms on quantum hardware. This is critical given the severe time restrictions placed on access to production quantum hardware. Users can also access quantum computers from IonQ, IQM, Rigetti, and QuEra directly through Braket. Pricing is generally straightforward with either a fixed reservation of up to \$7,000 per hour, or on a per run basis, which can cost as little as a few cents.

Availability is tightly controlled given high demand and limited quantum hardware, which is an industrywide phenomenon and is not likely to ease at any point in the next few years. While not as bad, it surely feels conceptually similar to the GPU crunch the AI industry has been suffering through.

Braket also allows users to collaborate with other quantum researchers and practitioners and on experimental technologies through Braket Direct, which we think is important to foster an environment for advancing quantum technology. Critically, Braket is integrated with traditional AWS services, so the identity access management and control panel will bring in other necessary AWS services as well as provide a familiar feel for existing AWS customers. Given that classical hardware is likely to be employed in conjunction with quantum hardware for quantum computing workloads, we think this pairing should help steer AWS toward a leadership position in quantum computing over time.

Alphabet

Given Alphabet's front-line presence in cutting-edge technology, cloud services, and artificial intelligence, the search giant has been investing in quantum computing for more than a decade. Alphabet's path in quantum computing can be traced to 2013, with the launch of the Quantum Artificial Intelligence Lab, or QuAIL, a joint research initiative between Google, NASA, and the Universities Space Research Association. The company continues to advance its own quantum hardware; has extended its quantum efforts to include Cirq, its quantum development platform; offers access to third-party production quantum computers like D-Wave; and offers a quantum marketplace. We believe Alphabet currently generates immaterial revenue from quantum computing. Nonetheless, given the company's resources and technological prowess, we expect Alphabet to be an important organization in driving quantum computing forward.

In 2015, Alphabet pivoted to developing a more universal quantum computer, specifically, quantum processors based on superconducting qubits. The firm's first notable quantum processor, Foxtail, was released in 2017, with 22-superconducting qubits. Soon after in 2018, Bristlecone, housing 72 qubits, was released. Bristlecone was intended to test the trade-off between qubit volume and error rates in Alphabet's pursuit of quantum supremacy. Subsequently, the firm's next chip Sycamore, despite having only 53 functional qubits, enabled faster qubit connectivity and double gate fidelity through adjustable couplers, instead of relying on a higher qubit count.

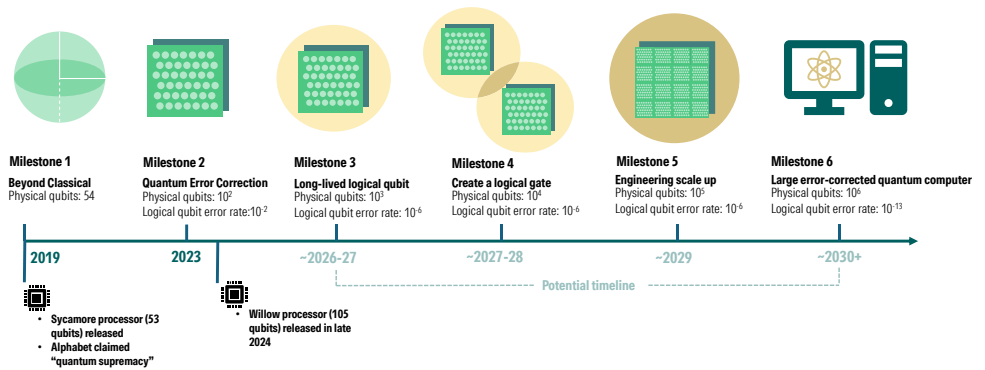
In September 2019, a leaked Alphabet white paper indicated that the firm had achieved quantum supremacy. Sycamore had reportedly performed a random circuit sampling calculation in 200 seconds, beating one of the fastest supercomputers of the time, IBM's Summit would have taken 10,000 years to complete the same calculation. Alphabet and IBM hurled technical challenges back and forth regarding the incident, but the firm maintained its claim of having achieved quantum supremacy and continued to plough forward in its quantum journey.

Alphabet continued to focus on achieving longer coherence times through advanced calibration techniques, marking improvements in higher-qubit volume versions of Sycamore.

By 2023, the company had demonstrated a working model of a logical qubit, laying the foundations for developing scalable quantum technology. Soon after in 2024, Alphabet announced Willow, a 105-qubit chip, and demonstrated superior error correction through higher qubit volume. The chip crushed two key long-standing benchmarks—quantum error correction and random circuit sampling. Willow was able to compute a random circuit sampling problem in less than five minutes—a challenge that would have taken Oak Ridge Lab’s Frontier supercomputer, one of the fastest in the world, 10 septillion (10^{25}) years to complete. Willow’s debut triggered a spike in enthusiasm around quantum computing across the globe, sending shares of quantum computing pure-play and big-tech stocks like IBM and Amazon up.

In its roadmap, Google Quantum AI has made its way to milestone 3, having achieved milestones 1 and 2 by demonstrating “beyond-classical computation” through its Sycamore processor in 2019, and creating a quantum-error-corrected logical qubit in 2023. Milestone 3 targets the construction of a long-lived logical qubit, with an error rate of 10^{-6} (one one-millionth) through scalable error correction on a useful quantum computation problem. The introduction of Willow was one step closer to this milestone, as the firm intends to leverage higher qubit volume, targeting 1,000 physical qubits in its long-lived logical qubit. Eventually, in milestone 6, Alphabet aims to connect and control 1 million qubits to develop an error-corrected quantum computer. Google’s vice president of engineering and head of Quantum AI, Hartmut Neven, has stated that he is optimistic about real-world quantum computing usage emerging by as soon as 2030.

Exhibit 40 Alphabet’s Timeline Should Help Drive Commercialization, Beginning in 2030



In true Alphabet form, the company’s quantum roadmap focuses on technological development over commercialization. Still, its quantum technology is not inaccessible. Like other quantum technology companies, the firm has developed its own open-source quantum framework, Cirq, which enables users to build and execute NISQ algorithms on quantum processors. This platform can be integrated with Qsim, Alphabet’s quantum circuit simulator, which can enable the execution of simulations of up to 40 qubits.

Featured libraries in Google's Quantum AI platform also include OpenFermion, an open-source platform for compiling and analyzing algorithms in quantum chemistry, and TensorFlow Quantum, a library for hybrid quantum-classical machine learning. Importantly, along with milestone 6, Alphabet plans to unveil more than 10 quantum applications.

Alphabet has been deft in leveraging collaborations to advance its technological progress. In 2024, Google Quantum AI and Nvidia announced the integration of Nvidia's CUDA-Q software and GPU tools into Google Quantum AI to run advanced simulations of 40-qubit devices. This has enabled Alphabet to test the scalability of its processors and study the noise in quantum hardware and operations. Additionally, the company offers access to quantum processors by IonQ and Alice & Bob, among others, on its Cloud Marketplace, which is likely to drive increasing attention to its quantum resources as the technology matures. Google Quantum AI also collaborated with DeepMind, another Alphabet subsidiary, to introduce AlphaQubit, an AI-powered neural network-based error decoder to identify quantum computing errors. Formal commercialization of its quantum offerings is likely still at least several years away, but we expect Alphabet to continue to invest in these building blocks for an error-corrected quantum computer.

Apart from investing in its own technology, Alphabet also participated in a \$230 million funding round for QuEra Computing to support the development of a large-scale fault-tolerant computer. The company also holds a stake in SandboxAQ, an AI-quantum startup borne out of Alphabet's incubator "X, the Moonshot Factory." SandboxAQ combines quantum computing, AI, and high-performance computing to develop real-world applications, without depending on fully developed quantum hardware. SandboxAQ was spun out of Alphabet in 2022 as an independent company.

IBM

IBM has invested meaningfully in quantum computing and has played a significant role in both foundational and ongoing research for the industry overall. Its dedicated division, IBM Quantum, was launched in 2017 with a mission to develop scalable, serverless quantum technologies aimed at delivering faster, higher-quality calculations. While the firm has contributed to significant advancements in quantum research and is the clear early leader in the space, its large investments have not resulted in significant contributions to firmwide revenue growth.

IBM's work in quantum research and manufacturing is fairly capital-intensive. While the firm has not historically disclosed an exact dollar amount invested in its quantum research, in 2025, IBM announced its intention to spend up to \$30 billion over five years to further develop quantum and mainframe systems, with no details on the mix. At IBM's 2025 investor day, CEO Arvind Krishna disclosed nearly \$1 billion in cumulative quantum signings since the first quarter of 2017—implying an average of \$36 million per quarter. Management has avoided providing specific revenue figures, suggesting that meaningful monetization is still on the horizon. We note that IBM is the only one among its larger competitors to quantify the commercialization of its quantum business, which makes sense to us, given that the company operates the largest quantum fleet in the world.

Initially focused on building and executing quantum circuits, IBM has since shifted its strategy toward creating commercially and industrially deployable quantum systems. IBM's superconducting qubit technology is at the heart of its quantum strategy, as it supports long coherence times, component compatibility, and scalability across quantum processors. However, this approach also involves significant challenges and costs, particularly due to the need for cryogenic dilution refrigerators and complex fabrication processes for effective error correction.

A major milestone came in 2019 with the launch of the IBM Q System One—the world's first commercially available integrated quantum computer, featuring 20 superconducting qubits. Since then, IBM has continued to advance its hardware, focusing on increasing qubit counts and improving gate operation fidelity. The first iteration of its latest line of processors, Heron, included 133 qubits and can execute circuits with up to 5,000 two-qubit gate operations. In a 2023 utility experiment, Heron completed a task in 2.2 hours that previously took 112 hours on a classical system. The latest iteration of the Heron lineup is Heron r2, a 156-qubit processor that was released in April 2025. The firm's newest modular quantum computer, IBM Quantum System Two, is equipped with three IBM Heron processors and supporting control devices. As of February 2025, IBM had 13 utility scale quantum computers operating continuously in its flagship data center located in New York as well as in a few other locations around the world.

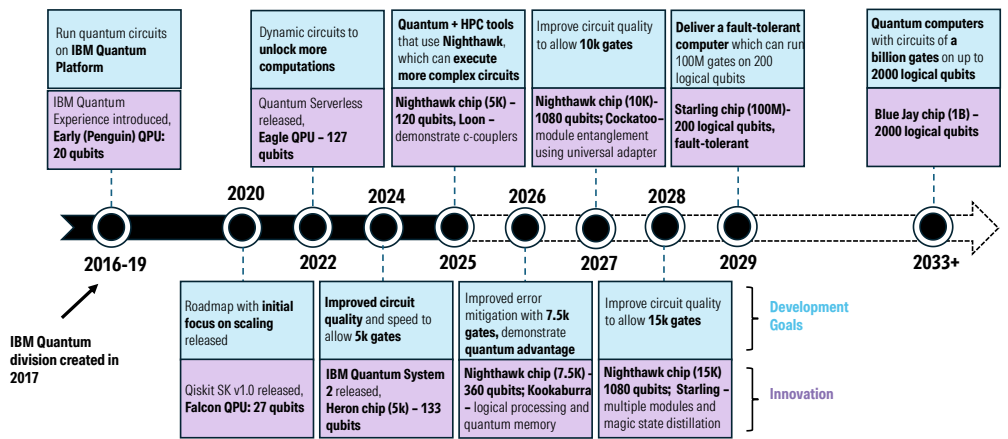
IBM is actively exploring specific quantum-based use cases, such as IBM Quantum Safe, an end-to-end solution designed to defend classical systems against emerging quantum threats. The platform identifies and analyzes cryptographic dependencies across software environments, helping organizations prepare for a post-quantum security landscape. Post-quantum crypto is an area where companies are investing today to prepare for cybersecurity once quantum theoretically renders current cryptography methods useless. IBM Quantum Safe has already gained some commercial traction as a part of the company's software ecosystem, with plans to expand into telecom, financial services, and government sectors. Additionally, IBM aims to leverage Red Hat Enterprise Linux to provide users with tools to test and implement post-quantum cryptographic algorithms using its extensive libraries and infrastructure.

IBM also offers commercial access through the IBM Quantum Platform, a cloud-based service providing access to quantum devices and simulators. The freemium model allows users to start with as little as 10 minutes of QPU runtime for a specific period, with premium plans available via prepaid minutes, pay-as-you-go, and enterprise subscriptions. Again, this underscores the ultralow levels of availability for production quantum hardware and limits meaningful commercialization.

To support adoption, IBM has emerged as a strong advocate for quantum utility by actively fostering the growth of a quantum developer community as the technology itself gradually matures. A key enabler is Qiskit, IBM's open-source SDK for building and manipulating quantum circuits. The company also provides a range of educational resources for both general quantum knowledge and practical use of its tools.

IBM's 2025 roadmap outlines ambitious goals. By 2033, the company aims to develop processors with 2,000 logical qubits and the ability to handle over 1 billion gate operations during runtime. Near-term efforts are focused on improving modular architectures with enhanced connectivity between quantum chips, gate quality, and self-calibrating error correction. One of IBM's key objectives is to demonstrate quantum advantage—performing computations more efficiently than classical systems in terms of speed, cost, and accuracy. The company targets its first such breakthrough by 2026. Over the next decade, IBM plans to build a scalable, fault-tolerant quantum system that integrates classical and quantum nodes, ultimately supporting thousands of logical qubits.

Exhibit 41 We Expect Our Cloud Service Providers and IBM to Be Key Quantum Players



Source: IBM.

Microsoft

Given Microsoft's large umbrella of services around specific leading-edge compute services, such as generative AI, it easily follows that the company should have an analogous array of services for quantum computing. Microsoft is developing a menu of quantum services, including software, services, partnerships, and hardware. In this case, the company has been formally conducting primary research on quantum physics and quantum computers for nearly 20 years and engaged in related one-off projects for a decade prior to that. We think this represents a coherent long-term strategy within the broader context of public cloud offerings, as it seems like a natural evolution that eventually the public cloud providers will offer one more quantum solution within a broad portfolio of outsourced computing needs. We also appreciate that from the onset the company has established a specialized chemistry use case umbrella within Microsoft Quantum, as we think this will be a core use case for the technology.

While the offerings between Microsoft Azure, Amazon AWS, and Alphabet GCP are similar, and the Azure website generally easy to navigate and find relevant services, Microsoft's marketing department has not teamed up with the product development team to hone the presentation and messaging around Microsoft's quantum computing offerings in a similar manner. Further, pricing for these services from the company is not transparent, although the software development kits, dubbed quantum development kits, or QDKs, are free.

Given relatively low usage today, we do not think pricing is a driving force, but we found the company's price per shot and per use generally similar to what is offered by other cloud service providers.

Because quantum computers do not function the same as classical computers and related software, having a well-developed software ecosystem will be critical for the technology to be widely adopted. Under the Microsoft Quantum service, we see the software elements taking shape, including Q# and the simulation software. Q# is Microsoft's high level open-source programming language for running quantum algorithms and quantum programs and can be used either locally or on Azure. Some important features of Q# include qubit management, qubit agnosticism, support for auto-generated code, first-class operation treatment, classical control flow, and support for both classical and quantum computations. Microsoft's GitHub already has tutorials and substantial libraries of relevant code. Importantly, the QDK integrates easily with Microsoft's Visual Studio IDE, which millions of developers are already familiar with.

Within Microsoft Quantum, users can select various established quantum algorithms to test their programs. Again, there are libraries of algorithms available on GitHub. The simulators are also cleanly integrated into the software development kit. Microsoft also offers various training modules, called Quantum Katas, to help developers and engineers better understand various elements of a quantum approach to software development.

On the simulation side, Microsoft offers an in-memory simulator and has also partnered with Quantinuum to offer their H-Series emulator for free in limited use cases. Microsoft also offers third-party hardware usage from other leading quantum vendors, including IonQ, Pasqal, Quantinuum, and Rigetti. Microsoft also links traditional high-performance computing as being a service needed in tandem with quantum computing. Azure compute resources are indeed powerful and can run all manner of simulations, such as complex molecules or quantum circuits. We think quantum is ultimately just another service offering within a complete Azure menu, and that same thinking extends to Amazon and Alphabet.

Most of the work that Microsoft seemingly highlights for the outside world to see is in the development of quantum technologies on the hardware side. These efforts culminated in the February 2025 announcement of the Majorana 1 chip, which employs a breakthrough technology. Microsoft claims to have used a new state of matter, the Majorana, to create qubits. Additional data around the Majorana 1 published in July 2025 demonstrates several quantum advancements, mainly around improved decoherence times and the ability to measure the quantum state of a system along two distinct vectors. Still, it is not clear that the company created a new state of matter. For our purposes we note both the actual technological advancement as well as debate within the physics community and suggest Majorana is either another important step in the journey to quantum commercialization, or a monumental leap toward it. Either is good for the industry, in our view.

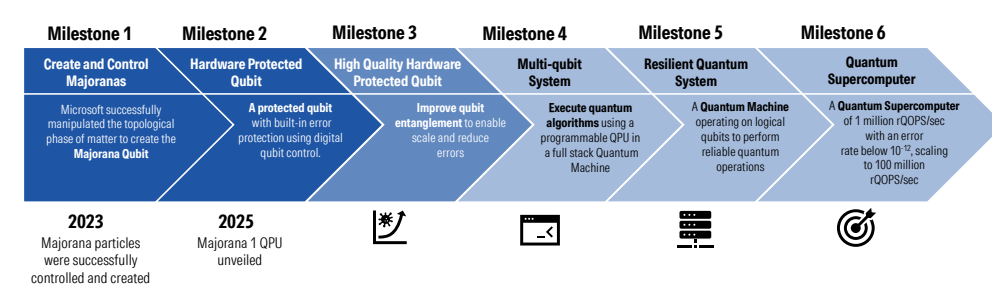
Combining topological qubits into a single chip allows the chip to behave both as a semiconductor and as a superconductor.

Using topological qubits also inherently includes error correction within the hardware. Instead of protecting a single physical qubit with many other qubits around to build in quantum error correction, the topological qubit is intrinsically far less prone to external noise. This architecture allows the chip to scale not to 100 qubits on a single chip, but to millions, and a million qubits is loosely thought to be the mass commercialization stage for quantum computers in general. Microsoft estimates that this means commercialization happens in years rather than decades.

Microsoft is not putting all of its eggs in the same basket. The company has partnerships with both Quantinuum and Atom Computing, both of which are leading developers of quantum computing hardware. While Majorana 1 chip development is entirely Microsoft’s, these two collaborations are focused on creating more reliable quantum hardware. The focus is largely on improving logical qubit performance, improving the error rate, and reducing the number of physical qubits needed to perform error correction functions for logical qubits. Microsoft also seeks to push the Azure Quantum platform in an effort to become the industry standard, or at least a leader in what could be an oligopoly market for quantum computing cloud services.

Microsoft has laid out a road map for building a quantum computer that consists of six milestones. By creating and controlling Majoranas and fabricating a hardware protected qubit, the company has already accomplished the first two essential items. CEO Satya Nadella has said he believes Microsoft can deliver a chip with a million qubits between 2027 and 2029, which would put meaningful commercialization of quantum computing shortly thereafter. The technology nerd in us is shocked and certainly rooting for this bravado but we are less sanguine given the physics, technological, and fabrication challenges that we think still need to be overcome.

Exhibit 42 We Expect Our Cloud Service Providers and IBM to Be Key Quantum Players



Source: Microsoft.

Nvidia

Nvidia’s first expression of quantum computing came at its analyst day in January 2025 when CEO Jensen Huang expressed skepticism toward the immediate viability of the technology and quipped that he thought 20 years was a reasonable timeline for commercialization. That remark sent shares of publicly traded quantum computing companies, such as D-Wave, IonQ, and Rigetti down sharply. Since then, Nvidia has been more bullish on the technology, starting with hosting a panel discussion during its GTC developer conference.

At the event, Huang conceded that he was unaware of the firestorm he brought about with his comments, not even realizing that several of the aforementioned pure-play quantum firms were publicly traded. The panelists, such as D-Wave, quickly educated Nvidia and its audience on some of the specialized quantum applications being conducted already.

The March GTC discussion brought about several announcements from Nvidia on the quantum front, most notably its commitment to the technology by opening a dedicated research lab in Boston, Massachusetts, hoping to collaborate with researchers at Harvard and MIT. Further, over the summer the company participated in funding rounds of \$1 billion for PsiQuantum and \$594 million for Quantinuum. We think this is a reactionary but necessary response.

Perhaps Nvidia's greatest contribution to date is its CUDA-Q platform, where developers can build applications to run on accelerated quantum supercomputers. Nvidia is also offering CUDA-Q Academic with partner universities. The company has also announced partnerships with other companies, like the Ansys partnership to apply quantum algorithms to fluid dynamics, and SEEQC to develop the first interface chip to connect quantum computers with Nvidia's GPUs.

That said, Nvidia has also been clear that quantum computing will likely be additive to classic computing and not a replacement. We agree with this thesis over any meaningful investment horizon. Ultimately, we often see high customer switching costs in a host of applications, which allows several chipmakers to carve out economic moats. There is likely no need for quantum computing to replace, say, a microcontroller in a toothbrush, or even a vision processor in an automotive safety system.

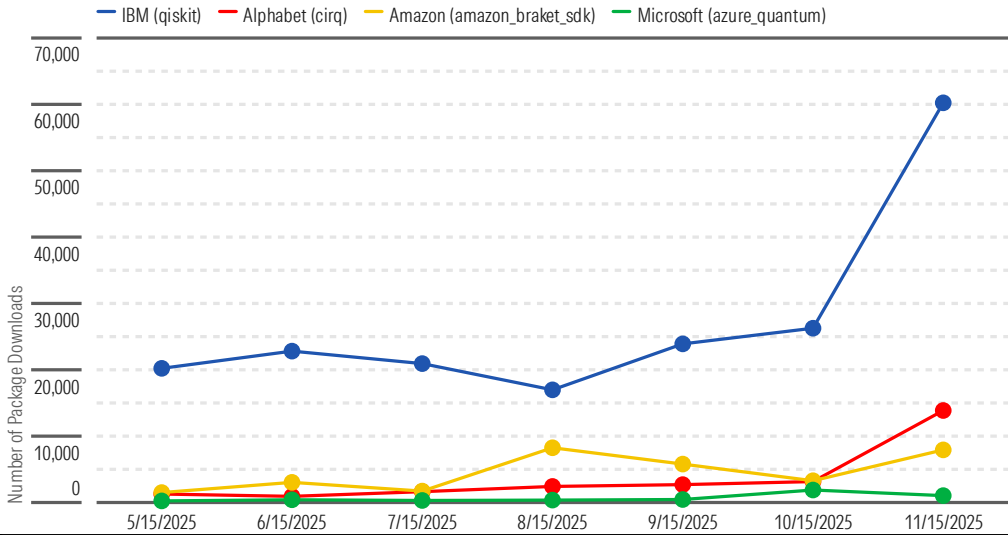
Given that Huang was unaware of publicly traded companies in quantum computing and the rush to make a variety of quantum announcements surrounding the fallout from off-the-cuff remarks he made, we are left to conclude that Nvidia has not taken quantum seriously and it is therefore behind in this race. We certainly see within the company's announcements this year that it is now investing more aggressively in this emerging area. We do not recognize quantum computing as a threat to Nvidia's GPU dominance over any reasonable investment horizon. Longer-term, however, some workloads seem like they will be better suited to quantum processors. Because we are years away from large-scale commercialization, we do not believe Nvidia has missed the boat, as it certainly has the engineering chops and financial wherewithal to help develop quantum technologies.

Our Large-Cap Coverage Is Appropriately Employing a Platform Approach to Attract Interest

IBM, along with the large cloud service providers that we cover, and also nearly all of the other companies we explore on an individual basis later in this report, have assembled a variety of quantum services. We are particularly interested in the cloud service providers, who each have their own software development kit, or SDK, available. We explored data from GitHub to gain some perspective on usage trends regarding the SDKs. Over the last six months we have seen a steady increase in downloads and project usage among the SDKs from IBM and the large cloud service providers.

IBM is clearly in the lead. However, given that it is so early in the quantum journey, we think the more important trend is the steady and increasing usage that indicates an interest in the technology and ongoing experimentation on quantum computers.

Exhibit 43 Interest In Quantum SDKs Is Growing



Source: PyPI Stats, Morningstar. Data as of Dec. 8, 2025.

If we were to consider the SDK downloads as an early indication of interest in various quantum platforms, we would conclude that IBM is running away from the field. This is obviously true insofar as IBM is early to the table in terms of having a true product. The bigger picture, as we see it, is again the fledgling ecosystems that the major cloud providers have established well in advance of the quantum computers even reaching the early-adopter phase.

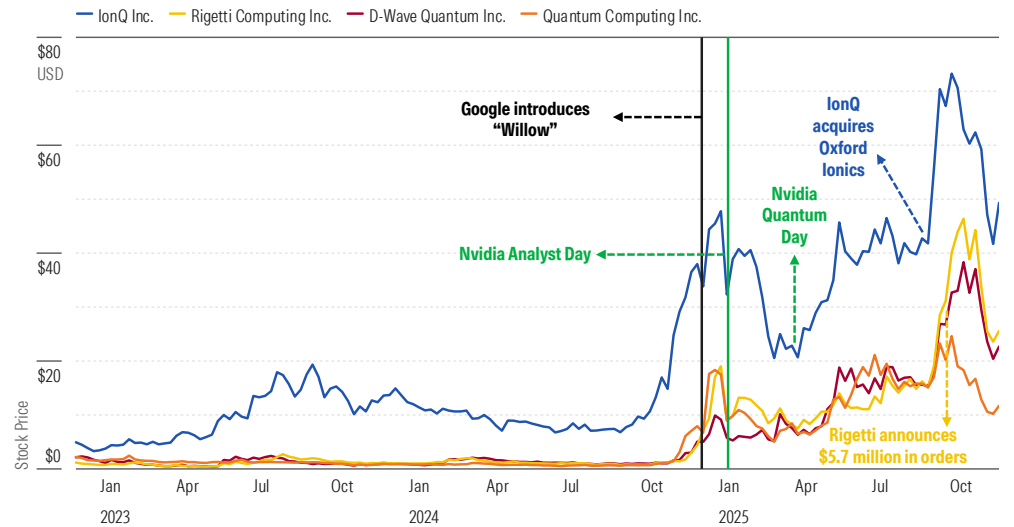
Exhibit 44 IBM Is Off to an Early Lead, but Is the Only Quantum Game in Town

Company (SDK)	Mentions/ Imports in Public Repositories	Dependent Repositories/ Packages	Issues Opened/Closed	Contributors	Stars	Forks
GitHub Metric Definition	No. of people that have written code that included the SDK generally	No. of public projects that currently directly depend on the SDK	No. of real-world users that encountered bugs or asked for features	No. of people currently actively improving or extending the SDK	General signal of awareness and interest	No. of people experimenting or customizing the SDK
Why it Matters	Proxy for active usage/general integration	Indicates actual SDK ecosystem size and adoption	High open issue traffic = active user base; High closed issues = healthy maintenance	Proxy for developer community size/engagement	Comparable to "likes on social media," can signal active use/interest	Higher forks indicate a richer research and experimental ecosystem
IBM (Qiskit)	~370,000	~7,600	Open = 929, Closed = 4,414	634	~6,800	~2,700
Alphabet (Cirq)	~231,000	~1,100	Open = 110, Closed = 2,321	252	~4,800	~1,200
Amazon (Braket SDK)	~14,100	322	Open = 16, Closed = 119	73	350	140
Microsoft (Azure-Quantum/QDK)	~2,800	Unavailable	Open = 149, Closed = 601	50	811	157

Source: GitHub, Morningstar. Data as of Dec. 8, 2025.

Other Pure-Play Quantum Players

There are too many companies involved in quantum computing to describe each in detail. Beyond the companies involved in quantum computing that Morningstar does cover (Alphabet, Amazon, IBM, Microsoft, and Nvidia), we endeavored to provide a high-level discussion of names we do not cover that we came across most frequently. These include publicly traded companies IonQ, D-Wave, and Rigetti, along with privately held companies like Quantinuum, Xanadu, Alice & Bob, SpinQ, and the Chinese Academy of Sciences, along with other conglomerates like Toshiba and Fujitsu that have meaningful quantum programs. In our view, the growing enthusiasm from global leaders—alongside increased investments in quantum computing by major tech companies—has contributed to a notable rise in the stock prices of pure-play firms such as IonQ, D-Wave, and Rigetti over the past year.

Exhibit 45 Quantum Stocks Have Run in Recent Months

Source: PitchBook, Morningstar Direct. Data as of Dec. 8, 2025.

While we endeavored to describe the efforts of the large technology firms within our coverage at Morningstar, including IBM, Microsoft, Alphabet, Amazon, and Nvidia, we also discussed a variety of other companies, notably the four publicly traded quantum pure-plays, that are actively engaged in quantum advancement and seem to be in a good position within the emerging quantum computing industry. That said, we could have easily detailed 10 more companies and gone through what we believe are recognized research teams at leading universities around the world. It is truly a global effort and advancements are being made daily. We are genuinely surprised at the breakneck pace of technological developments and the myriad different ways researchers are coming at the challenges within quantum computing. We also think quantum technology is destined to present a meaningful market opportunity, which is supported by the sheer number of organizations working on the technology.

Exhibit 46 Ultimately, Leading Quantum Computing Companies Will Have to Consolidate

Company	Quantum Computing	Area of Focus	Immediate Market Position	Key Verticals
IonQ	✓	Trapped-ion qubits	Sold 6 quantum systems to date	Financial services, chemicals, and quantum networking
D-Wave	✓	Quantum annealing + gate-based technologies	- Has 135 customers, as of 2024 - Reported sold 3 physical quantum systems to date	Financial services, life sciences, and optimization
Rigetti	✓	Superconducting qubits	Relies heavily on government contracts, purchase order of 2 systems received in late 2025	Pharmaceuticals, chemicals, financial services, cryptography, and optimization
IQM Quantum Computers	✓	Superconducting qubits	Sold 15 quantum systems	Pharmaceuticals, material sciences, optimization, AI & ML
Quantinuum	✓	Trapped-ion qubits	Nvidia recently integrated Quantinuum's System Model H2 in its supercomputer GB200 NVL72 for research	Pharmaceuticals, material sciences, specialty chemicals and agrochemicals
Xanadu	✓	Photonic qubits		
Alice and Bob	✓	Cat qubits	Reportedly in advanced talks with supercomputing centers interested in early prototypes of its chips	Physics research, agriculture pharmaceuticals, materials science, cryptography, and optimization
SpinQ	✓	Nuclear-magnetic resonance (NMR) spin qubits and superconducting qubits		Pharmaceuticals, financial services, and optimization
Fujitsu	✓	Superconducting and diamond spin qubits + quantum annealers		Optimization, digital marketing, and pharmaceuticals
Toshiba	✓	Superconducting qubits		Optimization, cryptography, and quantum networking
Samsung		Quantum dot technology	The firm has sold quantum dot-technology-equipped commercial electronic devices in the past.	Display technology and cryptography
Chinese Academy of Sciences (CAS)	✓	Photonic and superconducting qubits		Quantum networking and communication

Source: GitHub, Morningstar. Data as of Oct. 14, 2025.

IonQ

Founded in 2015, IonQ is the largest pure-play quantum computing company by market cap, valued at \$25 billion (Oct. 9, 2025). It leverages trapped-ion technology, using ionized ytterbium atoms as qubits and lasers to perform quantum gates. The firm's key offerings include cloud access to its quantum computers and simulators, as well as quantum safe networking hardware and consulting services. IonQ benchmarks its technological progress using its proprietary metric algorithmic qubits, #AQ, which reflects the number of qubits required to run a full set of quantum gates reliably. A higher AQ implies better fidelity and entanglement.

The firm's quantum systems are accessible on public clouds like Amazon Braket, Azure Quantum, Google Cloud Marketplace, as well as IonQ's own platform, IonQ Quantum Cloud Forte Enterprise (#AQ36) is the company's most powerful commercially available computer and is optimized for data center integration and quantum machine learning. In September 2025, IonQ announced Tempo (#AQ64), its latest quantum system designed to drive commercial advantage in certain applications. Tempo is yet to be available for cloud access but is expected to perform calculations much faster than its predecessor.

To fund its ambitious technological roadmap, IonQ relies heavily on sales of quantum hardware and its quantum-computing-as-a-service, or QCaaS, offering. The firm is also collaborating with AstraZeneca and Airbus to develop quantum solutions in drug discovery and supply chain optimization, respectively. Notably, the company recently secured a \$22 million agreement with the Electric Power Board of Chattanooga, Tennessee to build a joint quantum computing and networking hub, which included the sale of a Forte Enterprise quantum computer. We believe the company has sold at least six quantum systems to date, including one Forte Enterprise and one Tempo unit. Despite limited monetization thus far, IonQ has made meaningful contributions in advancing quantum technology, with CEO Niccolò de Masi likening IonQ to the "Nvidia of quantum computing."

D-Wave

D-Wave, founded in 1999, develops both quantum annealing and universal gate quantum technologies to support quantum and hybrid quantum applications. It recently demonstrated quantum supremacy with its 1,200-qubit Advantage2 prototype by simulating a complex magnetic material in minutes—an achievement that would take nearly one million years on classical supercomputers like Oak Ridge National Lab's exascale system, and at a fraction of the energy cost. D-Wave's systems can be accessed through its cloud service Leap, which includes hybrid solvers for optimization problems in areas such as resource allocation and portfolio management. The firm's latest iteration of Advantage2 features 4,400 qubits integrated across a Zephyr topology for higher energy scale, increased coherence, and less noise, and has product roadmaps of systems with up to 100,000 qubits.

D-Wave was the first to commercialize quantum computing and has seen early adoption, thanks in part to the lower cost of annealing-based systems. Recent use cases include Ford Otosan, which used D-Wave's technology to optimize manufacturing for its transit vehicle line. Developers can integrate D-Wave's systems by leveraging its open-source Ocean toolkit. As of 2024, the company has 135 customers and has sold three physical quantum computers. However, D-Wave faces skepticism around annealing's potential relative to gate-based models. Notably, the company was not selected for the US Defense Advanced Research Projects Agency's Quantum Benchmarking Initiative, which included firms like IonQ and Rigetti. While D-Wave is investing in gate-based systems—particularly for chemistry and molecular discovery—progress has been limited thus far.

Rigetti

Rigetti is a prominent player in full-stack quantum computing that leverages superconducting technology to develop hybrid quantum infrastructure. Its latest quantum system is an 84-qubit implementation of its Ankaa architecture, achieving a 2-qubit gate fidelity of 99.0%—equivalent to about a 1% error rate, which is higher than many competitors. The company has partnered with Quanta to scale its systems toward exceeding 10,000 qubits within the next five years—a critical milestone on its path to building a fault-tolerant quantum system. Rigetti lags peers in the commercialization of its technology. Customers can access Rigetti's QPUs via its Quantum Cloud Services platform, which is also integrated with AWS and Azure. While the company has established a relatively strong presence in government-funded quantum initiatives—including participation in the Defense Advanced Research Projects Agency's Imagining Practical Applications for a Quantum Tomorrow program—its traction in the enterprise market remains limited. However, in September 2025, the firm announced two purchase orders for its 9-qubit Novera system totaling to \$5.7 million, marking notable steps into commercialization outside of government projects and will likely be reflected in future financial statements.

IQM Quantum Computers

IQM is a Finnish startup founded in 2018 that develops superconducting quantum computers for both cloud and on-premises use. The company's proprietary IQM Star and IQM Crystal topological architectures enabled it to achieve 99.9% two-qubit gate fidelity in 2024. IQM's roadmap targets quantum error correction by 2028 and fault-tolerant quantum systems by around 2030. The company already provides cloud access to its 54- and 150-qubit systems, with on-premises "deliveries" of these systems planned for the end of 2025 and 2026, respectively. To date, IQM has reportedly sold more than 15 quantum systems, making it one of the most commercially successful pure-play quantum computing firms. In its most recent funding round, IQM raised nearly \$320 million, bringing its total funding to approximately \$600 million.

Quantinuum

Quantinuum is a stand-alone company formed through the merger of Honeywell Quantum Solutions and Cambridge Quantum. It specializes in trapped-ion quantum technology and employs a racetrack architecture that enables ion shuttling for enhanced error correction and control. The company is set to launch Helios, its next-generation quantum system, later in 2025 (as of October 2025). Helios will feature 98 qubits and a logical error rate of 1 in 10,000 and is expected to be available via cloud in 2025. Quantinuum has made notable strides in applying quantum technologies. Its Quantum Origin solution—the world's first Quantum Random Number Generator validated by the National Institute of Standards and Technology—demonstrates strong potential for post-quantum cryptography and cybersecurity. The company also offers InQuanto, a quantum-powered computational chemistry platform designed for complex molecular and materials simulations. The firm has partnered with major players like Amgen, Nokia, and even Nvidia, who plans to integrate Quantinuum's flagship computer System Model H2 in its supercomputer GB200 NVL72 to advance its research initiatives. Recently, Quantinuum entered into a \$1 billion joint venture with Qatar's Al Rabban Capital to support advanced quantum research and workforce development in Qatar.

The initiative will focus on applications in energy, materials discovery, medicine, finance, and genomics. The company has set ambitious goals, aiming to launch the industry's first 100-logical qubit system by 2027—the same timeframe in which it is expected to go public.

Xanadu

Xanadu Quantum Technologies is one of the few companies worldwide that focuses on photonic quantum computing. The Canadian firm's Borealis quantum computer beat a supercomputer in performing Gaussian boson sampling. Its newest scale model quantum computer, Aurora, consists of 12 physical qubits, 35 photonic chips, and 13 kilometers of fiber optics. Aurora builds on the firm's previous systems, leveraging modular design across interconnected server racks, which can theoretically enable scaling to millions of qubits. Its Gottesman-Kitaev-Preskill approach reduces the energy and space for cryogenic cooling and is expected to take up only 10% of the space in a data center, providing significant energy and cost savings. In terms of software, Xanadu is a key contributor to PennyLane, a widely used open-source software library used to build quantum algorithms. The firm developed Catalyst, an experimental package of hybrid workflows that are automatically compiled for execution on CPUs, GPUs, and QPUs. The firm's collaborations include one with Applied Materials for the development of high-volume fabrication processes for manufacturing. Like Rigetti, Xanadu has also been selected as part of the DARPA project and has a partnership with the US Air Force Research Laboratory for development of silicon photonic integrated circuits for deployment in military and quantum applications. The company aims to focus on reducing light loss till 2028, after which it hopes to build a quantum computing data center with thousands of quantum server racks to facilitate fault-tolerant computing.

Alice & Bob

France-based Alice & Bob is a pioneer in cat-qubit driven quantum computing technology that focuses on creating qubits with high bit-flip lifetimes without increasing phase-flip errors. The company has already accomplished this, as in 2024, it released its Boson 4 chip on cloud with 1 cat qubit and a bit-flip lifetime of 7 minutes. The firm is currently focused on building its first logical qubit and believes that it is a key step in accurately detecting phase flips and connecting qubits in lines to perform more complex operations. The firm is currently developing its Hydrogen chip with 12 to 16 qubits arranged linearly, with strong bit-flip protection and degree-2 connectivity across its qubits. Alice and Bob aims to launch Graphene, its universal gate, fault-tolerant computer with 2,000 cat qubits and 100 logical qubits, by 2030. While the firm is yet to generate material commercial revenue, it is reportedly in advanced talks with supercomputing centers interested in early prototypes of its chip. The firm raises capital to fund its research and operations: in a Series B funding round earlier this year, Alice & Bob raised EUR 100 million, in addition to access to a EUR 500 million fund, shared with four other companies, from the French defense ministry to participate in a competition to build a 128 logical qubit fault-tolerant quantum computer demonstrator. The firm has also been allocated funding for Stage A for DARPA's QBI, alongside IBM, IonQ, Quantinuum, Rigetti, and Xanadu.

SpinQ

Established in 2017 in Shenzhen, China, SpinQ focuses on realizing quantum computing using spins, specifically using nuclear magnetic resonance, or NMR, and superconducting qubits. The firm offers a full-stack product including physical superconducting quantum computers, QPU, quantum control and measurement system, foundry and characterization services, as well as supporting software. The firm's latest superconducting quantum computer functions across 20 qubits, with a 2-qubit gate fidelity of 99%, which is lower than some of its competitors. SpinQ Gemini Lab is the firm's NMR-equipped computing hardware to support pulse, gate, and algorithm level experiments for research. The firm also offers portable quantum computers Gemini Mini/Mini Pro with 2 qubits as well as a 3-qubit desktop version to support quantum programs. Additionally, like other pure-play quantum companies, SpinQ offers cloud access to its 2-, 3-, 5-, and 8-qubit systems via SpinQ Cloud. SpinQ has played a forward role in developing diversified quantum computing lab solutions for high school and university education, in addition to more conventional commercial applications like fintech, biotechnology, and AI.

Other Conglomerates Investing in Quantum Computing

Beyond the cloud service providers and other names covered on the US technology team and the notable private companies, we also see several conglomerates in Japan and South Korea that have some quantum development efforts underway. These include Fujitsu, Toshiba, and Samsung. We also include the Chinese Academy of Sciences, or CAS, in this section.

Fujitsu

Fujitsu's history in high-performance computing and architectures presented a natural transition to quantum computing. Initial efforts came about in the early 2010s, with research focused on quantum algorithms and optimization. In 2017, Fujitsu released its Digital Annealer, a quantum annealer designed to solve combinatorial optimization problems at a fraction of the cost typically associated with quantum computers, for deployment in factory optimization, digital marketing, and drug discovery use cases. The firm also continued to invest in developing universal gate quantum technology, with a focus on superconducting and diamond spin qubits. In the early 2020s, Fujitsu partnered with Riken to lead a concerted effort for the development of a superconducting quantum computer. They unveiled a 64-qubit quantum computer in 2023 and a 256-qubit version in March 2025, which are commercially available for cloud and on-premises deployment. Fujitsu plans to release a 1,000-qubit system by 2026. In terms of software, the firm offers an open-source quantum toolchain for cloud-based quantum computing. The company has made much headway in the development of quantum simulators, having released 36- and 40-qubit, Qiskit compatible quantum simulators for NISQ devices.

Toshiba

Toshiba's quantum computing efforts are largely around quantum cryptography and quantum key distribution, especially in securing communication networks. In 2008, the firm contributed to the development of the first QKD network in Vienna using fiberoptic networks in a step toward scalable quantum security. The firm collaborated with UK telecom giant BT to launch London's first quantum-secured metro network in 2022. In a key milestone in 2025, Toshiba successfully demonstrated transfer of 30 Tbps, or terabits per second, of high-capacity data using secret keys and multiplexing through a

single optical fiber, a marked improvement from the previous 11 Tbps. Similar to Fujitsu's Digital Annealer, Toshiba has its own optimization solution, the Simulated Bifurcation Machine, or SQBM+, that uses combinatorial solving algorithms (the Simulated Bifurcation Algorithm) to find optimal solutions, with applications in traffic alleviation and logistics optimization. The firm has also extended its quantum efforts to research in universal gate computing, focusing on superconducting qubits. In 2024, the firm developed a double-transmon coupler with a 99.9% fidelity for a 2-qubit gate, enabling greater coherence time and high-speed gate operation execution.

Samsung

Samsung's Advanced Institute of Technology, or SAIT, is leading the company's efforts to build a scalable fault-tolerant computer. The firm started researching quantum dot technology in 2001 and pioneered the development of no-cadmium quantum dots, which are now commonly used for electronic screen displays around the world. This technology was commercialized in its super ultra-HD and QLED TVs between 2015 and 2022. Samsung also intends to extend the fruits of quantum cryptography research to its Galaxy smartphones. In early 2025, a subsidiary of Samsung Electronics, Samsung SDS, joined the US National Institute of Standards and Technology-led project to research and develop hardware, software, and services needed for the migration of security systems to PQC. The Quantum Galaxy smartphone lineup has been fitted with quantum random number generator chips from a different company, ID Quantique. Samsung is now investing in quantum software. Starting with the Galaxy S25 smartphone, the firm intends to integrate future product releases with its security platform Knox. Knox is actively being updated with PQC to ensure quantum-safe connectivity across Samsung's upcoming product releases.

Beyond the Startups, China Is Also Pouring Investment Dollars into Quantum Research

The Chinese Academy of Sciences, or CAS, is a research academy for natural sciences and high technology consultancy, based in Beijing, China. The academy has played a pivotal role in the country's quantum computing efforts, and is led by figures like Professor Pan Jianwei, who is known as "China's Father of Quantum." Under its quantum research efforts, CAS focuses its research on developing quantum-driven fiber networks and internet applications. In 2016, the institution developed Micius, its satellite where a QKD was successfully transmitted through entangled photons between a satellite and ground stations—a crucial breakthrough for moving toward quantum-driven internet communication. In 2025, in collaboration with other Chinese scientists, the CAS built a quantum-secured communication network across 12,900 kilometers between China and South Africa, using Jinan-1, a microsatellite released shortly after Micius.

In terms of universal gate quantum computing, a team led by Pan Jianwei leveraged photonic qubits to create the JiuZhang quantum computer series, with 76, 113, and 255 qubits across the different versions. JiuZhang 3 performed a Gaussian boson sampling-based computation in a millionth of a second—about 20 billion years faster than a supercomputer, demonstrating quantum supremacy. The institution has also explored superconducting quantum computing, with Zuchongzhi 2.0 in 2021, a 66-qubit superconducting processor.

This was a notable milestone, particularly as it directly challenged Google's Sycamore processor. In 2024, the CAS developed the Tianyan-504, equipped with a 504-superconducting-qubit chip named Xiaohong. We infer that this system was developed to test the limits of qubit scalability and not necessarily meet higher performance benchmarks. In its stead, in 2025, the Zuchongzhi 3.0 was released, a 105-qubit version of its predecessor that can perform 10^{15} times faster than the world's fastest supercomputer. The processor has impressive stats to back its power, with a single-gate fidelity of 99.9%, two-gate fidelity of 99.62%, and a readout fidelity of 99.13%—running close with Google's Willow, which was released in late 2024.

Realistic Investment Opportunities Are Limited

Dan Romanoff
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivyaa Vaidya
Associate Equity Analyst
+1 872-371-4154
jivyaa.vaidya@morningstar.com

Key Takeaways

- ▶ We stress that quantum computers are not ready for prime time today and, therefore, patience is required.
- ▶ We view quantum computing as a call option on some of our large-cap stocks, like IBM, Microsoft, Alphabet, and Amazon.
- ▶ At present, only Microsoft and Alphabet offer any meaningful upside to our fair value estimates, so those two names are our top picks for long-term quantum computing investors.

How to Invest in Quantum Computing

Picking winners in quantum computing is no easy task, as the technology is still scattered and under development. We see a wide variety of technological paths being forged with an extreme degree of uncertainty as to how the underlying technology drives the evolution of the quantum computing industry. As a result, while the market potential is vast, both the onset of commercialization and the speed of mass adoption are difficult to predict.

Technology modalities are being pursued by companies that are generating little or no revenue and are certainly not producing enough free cash flow to keep their businesses afloat without external capital infusions. Assuming one or more of these survive the next five years or so, even if their technology ends up being subpar, it seems likely the shares would do well as the industry takes off under the axiom of “a rising tide raises all boats.” We include not only the venture capital-funded startups in this category, but also the publicly traded pure-play quantum computer firms as well.

We feel most confident in identifying IBM as the clear leader in the field today. We think the first-mover position is important, but not the only factor that matters for investors with a long-term investment horizon. IBM has taken note of the successful public cloud model popularized by Amazon, Microsoft, and Google, and has built out an entire quantum platform. We think our least controversial opinion regarding quantum computing is that IBM will remain a leader through at least the early phase of commercialization, or at least the next 10 years. If we applied the same multiple the pure-play quantum computer players enjoy, IBM would have at least \$100 billion of market cap solely from its quantum computing business. This quite obviously is not the case, so quantum represents a long-term call option for IBM.

We see the other cloud providers as building natural extensions of their cloud portfolios to offer a menu of quantum services as well. Of course, they do not offer quantum computing services on their own hardware yet, but that seems to be more a matter of timing. Given their leadership positions in outsourced computing, we think the three main cloud providers in the US—Amazon AWS, Microsoft Azure, and AlphabetGCP—will be able to smoothly step into leadership roles as quantum computing takes off.

We do not believe quantum revenue is built into investor expectations at this point, so investing in IBM, Microsoft, Google, or Amazon offers a call option on quantum computing. The downside, of course, is that quantum exposure within each company's revenue mix will likely be a very small portion of revenue for a couple of decades.

Investors also have the option of owning one of the four publicly traded quantum computing pure-plays. We do not cover these companies, so we do not have revenue or earnings estimates, fair value estimates, or opinions on whether these stocks represent attractive investment options. However, we have noted that current valuation levels appear to reflect overly optimistic assumptions and effectively price in a full industry inflection beginning in 2026. This contrasts their nominal revenue, lack of positive free cash flow, and the likely need for capital infusions just to keep the doors open in biotech-like business models. Picking one of these companies today as a long-term winner seems fruitless. If an investor wanted direct exposure, the biotech basket approach might be better where all four publicly traded companies are owned in small weights such that they comprise a single position within a portfolio.

When factoring in current valuation, our top picks in quantum include Microsoft and Google. We see IBM as the clear leader today, with Microsoft and Alphabet as next-best-positioned, followed by Amazon. Finally, we think Nvidia can become more of a quantum force over time if it focuses more time and attention in the area. From a valuation perspective, we see the most upside to Microsoft and Nvidia, with some more modest upside to our fair values for Amazon and Alphabet. We view IBM as overvalued as of Dec. 4, 2025. ■■

Exhibit 47 Microsoft Summary Model**Microsoft (NAS:MSFT)**

Star Rating ★★★★	Fair Value 600 USD	Last Price 520 USD	Uncertainty Medium	Capital Allocation Exemplary	Economic Moat  Wide
Dan Romanoff 312-244-7816 dan.romanoff@morningstar.com		Five-Star Price Fair Value Estimate One-Star Price Market Price P / FVE	420.61 600.87 811.18 517.03 0.86	Estimated COE Pre-Tax Cost of Debt Estimated WACC ROIC * Adjusted ROIC *	9.0% 5.3% 8.4% 42.1% 32.3%

* 5-Yr Projected Average

	Forecast							
Income Statement	2023	2024	2025	2026E	2027E	2028E	2029E	2030E
Revenue	211,915	245,122	281,724	324,929	368,661	415,287	465,048	517,907
Gross Profit	146,052	171,008	193,893	221,474	253,469	286,548	322,046	359,945
Operating Income	88,523	109,433	128,528	150,561	171,257	193,731	219,038	246,265
Net Income	72,361	88,135	101,832	115,427	133,676	158,060	178,705	200,917
Adjusted Income	72,361	88,135	101,832	115,427	133,676	158,060	178,705	200,917
Adjusted EPS	9.68	11.80	13.64	15.49	18.03	21.43	24.34	27.50
Adjusted EBITDA	102,023	129,433	156,528	201,900	236,142	270,144	301,351	367,973
Growth (% YoY)								
Revenue	6.9%	15.7%	14.9%	15.3%	13.5%	12.6%	12.0%	11.4%
Gross Profit	7.7%	17.1%	13.4%	14.2%	14.4%	13.1%	12.4%	11.8%
Operating Income	6.2%	23.6%	17.4%	17.1%	13.7%	13.1%	13.1%	12.4%
Net Income	-0.5%	21.8%	15.5%	13.4%	15.8%	18.2%	13.1%	12.4%
Adjusted EPS	0.4%	21.9%	15.6%	13.6%	16.4%	18.9%	13.6%	13.0%
Adjusted EBITDA	4.1%	26.9%	20.9%	29.0%	17.0%	14.4%	11.6%	22.1%
Profitability (%)								
Gross Margin	68.9%	69.8%	68.8%	68.2%	68.8%	69.0%	69.3%	69.5%
Operating Margin	41.8%	44.6%	45.6%	46.3%	46.5%	46.7%	47.1%	47.6%
Net Margin	34.1%	36.0%	36.1%	35.5%	36.3%	38.1%	38.4%	38.8%
Adjusted EBITDA Margin	48.1%	52.8%	55.6%	62.1%	64.1%	65.1%	64.8%	71.1%
Return on Equity	38.8%	37.1%	33.3%	30.1%	28.6%	28.1%	26.5%	24.9%
Adjusted ROIC	36.5%	33.6%	30.0%	30.3%	31.1%	32.2%	33.2%	35.0%
Leverage								
Debt / Capital	0.2x	0.1x	0.1x	0.1x	0.1x	0.0x	0.0x	0.0x
Debt / EBITDA	0.5x	0.3x	0.3x	0.2x	0.1x	0.1x	0.1x	0.1x
EBITDA / Interest Expense	-129.5x	78.6x	31.9x	26.7x	45.4x	-1301.0x	-1296.0x	-1421.0x
Cash Flow								
Dividends per Share	2.66	2.93	3.24	3.55	3.79	4.03	4.27	4.51
Free Cash Flow to the Firm	54,308	4,405	78,993	77,246	101,686	124,463	142,019	194,801
Dividend Franking	0%	0%	0%	0%	0%	0%	0%	0%
Dividend Payout Ratio	27.5%	24.8%	23.8%	22.9%	21.0%	18.8%	17.5%	16.4%

Source: Morningstar. Data as of Oct. 29, 2025.

Exhibit 48 Alphabet Summary Model**Alphabet (NAS:GOOGL)**

Star Rating ★★★★	Fair Value 340 USD	Last Price 267 USD	Uncertainty Medium	Capital Allocation Exemplary	Economic Moat  Wide
Malik Ahmed Khan 312-244-7803 malikahmed.khan@morningstar.com		Five-Star Price Fair Value Estimate One-Star Price	237.84 339.76 458.68	Estimated COE Pre-Tax Cost of Debt Estimated WACC	9.0% 5.5% 9.0%
Financial Services Other Financial Services		Market Price P / FVE	267.47 0.79	ROIC * Adjusted ROIC *	30.6% 28.8%

* 5-Yr Projected Average

	Forecast							
Income Statement	2022	2023	2024	2025E	2026E	2027E	2028E	2029E
Revenue	282,836	307,394	350,018	399,129	455,076	513,405	576,864	646,247
Gross Profit	156,633	174,062	203,712	236,434	262,947	295,181	332,962	376,221
Operating Income	74,842	84,293	112,390	129,836	143,335	160,972	183,990	212,209
Net Income	59,972	73,795	100,118	131,239	138,211	153,202	172,767	196,754
Adjusted Income	59,972	73,795	100,118	131,239	138,211	153,202	172,767	196,754
Adjusted EPS	4.56	5.80	8.04	10.75	11.59	13.13	15.12	17.58
Adjusted EBITDA	88,317	96,239	127,701	151,788	175,645	202,045	227,254	258,092
Growth (% YoY)								
Revenue	9.8%	8.7%	13.9%	14.0%	14.0%	12.8%	12.4%	12.0%
Gross Profit	6.8%	11.1%	17.0%	16.1%	11.2%	12.3%	12.8%	13.0%
Operating Income	-4.9%	12.6%	33.3%	15.5%	10.4%	12.3%	14.3%	15.3%
Net Income	-21.1%	23.0%	35.7%	31.1%	5.3%	10.8%	12.8%	13.9%
Adjusted EPS	-18.8%	27.3%	38.7%	33.7%	7.8%	13.3%	15.2%	16.2%
Adjusted EBITDA	-0.8%	9.0%	32.7%	18.9%	15.7%	15.0%	12.5%	13.6%
Profitability (%)								
Gross Margin	55.4%	56.6%	58.2%	59.2%	57.8%	57.5%	57.7%	58.2%
Operating Margin	26.5%	27.4%	32.1%	32.5%	31.5%	31.4%	31.9%	32.8%
Net Margin	21.2%	24.0%	28.6%	32.9%	30.4%	29.8%	29.9%	30.4%
Adjusted EBITDA Margin	31.2%	31.3%	36.5%	38.0%	38.6%	39.4%	39.4%	39.9%
Return on Equity	23.6%	27.4%	32.9%	37.5%	34.4%	33.1%	32.1%	31.0%
Adjusted ROIC	36.5%	34.0%	35.5%	33.2%	29.7%	27.7%	26.8%	26.5%
Leverage								
Debt / Capital	0.1x	0.0x	0.0x	0.0x	0.0x	0.0x	0.0x	0.0x
Debt / EBITDA	0.2x	0.1x	0.1x	0.1x	0.1x	0.1x	0.0x	0.0x
EBITDA / Interest Expense	25.1x	-67.6x	-17.2x	-5.2x	-9.1x	-10.5x	-11.8x	-13.4x
Cash Flow								
Dividends per Share	-	-	0.80	0.84	0.88	0.93	0.97	1.02
Free Cash Flow to the Firm	40,455	54,702	53,627	39,581	52,775	68,154	87,657	113,556
Dividend Payout Ratio	0%	0%	0%	0%	0%	0%	0%	0%
Dividend Franking Ratio	0.0%	0.0%	9.9%	7.8%	7.6%	7.1%	6.4%	5.8%

Source: Morningstar. Data as of Oct. 30, 2025.

Appendix

Dan Romanoff
Senior Equity Analyst
+1 312-244-7816
dan.romanoff@morningstar.com

Jivyaa Vaidya
Associate Equity Analyst
+1 872-371-4154
jivyaa.vaidya@morningstar.com

Note 1: A More Detailed Primer on Quantum Mechanics

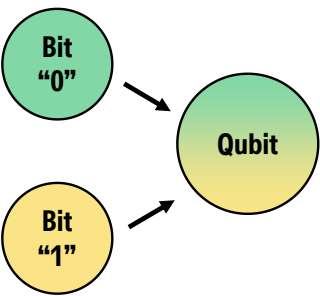
We admit it is perhaps ludicrous to have a brief primer on quantum mechanics because 1) quantum mechanics is extremely complex, and 2) we are engaged in equity research for software companies. While we have attempted to explain terms and concepts throughout the main body of this report, we have also consolidated these definitions in an appendix at the end of this report. Mercifully, we will only introduce several important principles of quantum mechanics rather than embarrass ourselves with an in-depth discussion of the subject matter.

While classical physics can describe the behavior and properties of objects at the macro scale, it breaks down at the atomic scale. Quantum mechanics, then, is a theory of fundamental physics that describes the behavior of atomic and subatomic particles. Despite being born as a theory in the 1920s, given the inherent challenges of observing and experimenting with subatomic particles, key breakthroughs and advancements within quantum mechanics are happening 100 years later. We think the five key principles of quantum mechanics that are particularly important for a better but still rudimentary understanding of quantum computing are as follows, 1) probabilistic rather than deterministic, 2) superposition, 3) entanglement, 4) wave-particle duality, and 5) quantum tunneling. We added quantum tunneling in the appendix because it helps underscore the weirdness that occurs at the quantum level.

Uncertainty Principle. Classical mechanics is deterministic in nature and dictates that if you know a particle's speed and position, you can perfectly predict everything about that particle. Quantum mechanics is probabilistic in nature. In other words, if you know a particle's position then you cannot be certain about its momentum, and vice versa.

Superposition. Unlike in classical systems where objects can be defined in one state or another, such as a light switch being on or off, superposition refers to the ability of a quantum system, such as an electron, to exist in multiple states simultaneously. In the case of the light switch, it could be both on and off at the same time.

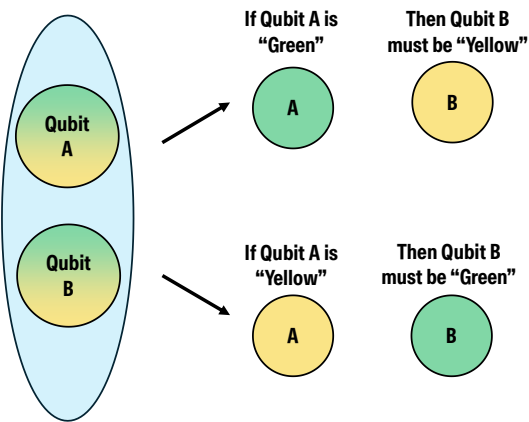
Exhibit 49 The Qubit . . . Is It a One or a Zero? Yes



Source: Morningstar.

Quantum Entanglement. Quantum entanglement is also a key principle of quantum mechanics, and therefore critical to our analysis of quantum computing. Entanglement was described in a series of three papers by Schrodinger in 1935, but it took decades of milestone experiments to demonstrate the effect was indeed real. Quantum entanglement is the phenomenon that the quantum state of any particle in a system cannot be defined independently of the quantum state of other particles within the system. In practical terms that means that once you observe a quantum particle, you know the state of the entangled particle as well, regardless of where that particle is.

Exhibit 50 Einstein Referred to Entanglement as “Spooky Action at a Distance”

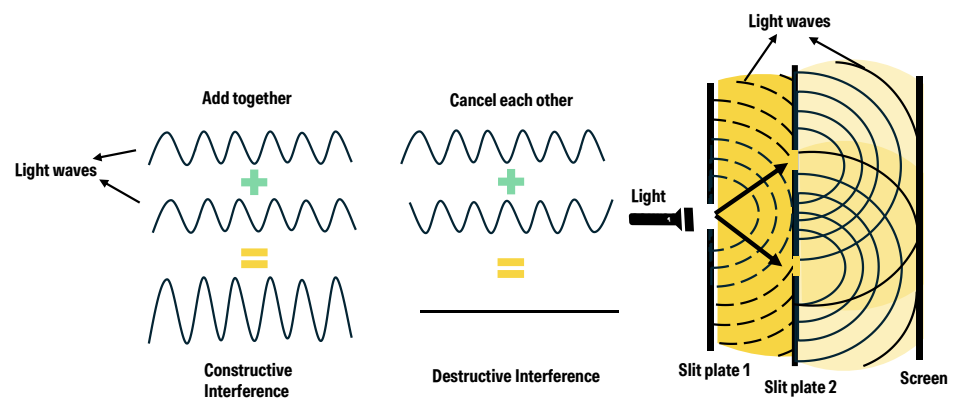


Source: Morningstar.

Wave-Particle Duality. There is no way to sugarcoat this—everything you thought you knew about reality is probably wrong. Energy and matter are both particles and waves. More precisely, they are probabilistic waves until you observe them. As soon as a particle is observed, the probability wave collapses and it becomes a particle. This has been born out repeatedly in experimentation for more than 200 years through the double-slit experiment. Early versions of this experiment showed that shooting a beam of light through a narrow slit would unsurprisingly produce a single line behind the slit.

However, when a beam of light is shot at two slits next to each other, the light produced a series of lines on the target with each line representing a point of interference between intersecting waves. This phenomenon remains baffling to physicists such that the experiment is continually repeated with ever advancing technology. For instance, detectors have been put next to the two slits so it is known which slit the particles pass through. When this is done, the interference pattern disappears and shows just two slits appearing on the target. The conclusion is that the act of observing the photon prevents it from acting as a wave, but if the photon is unobserved, it acts as a wave. The double slit results were confirmed yet again in July 2025 by a team of researchers at MIT that fired individual photons through the space between two atoms arranged in a lattice in order to achieve maximum control.

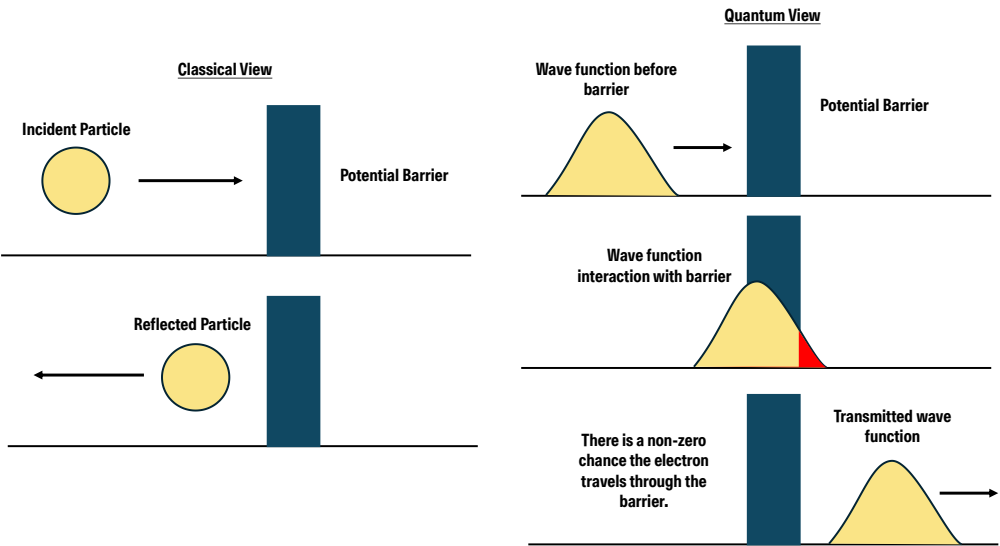
Exhibit 51 Well, That Was Weird



Source: Morningstar.

Quantum Tunneling. We add a bonus feature of quantum mechanics because it is an important phenomenon that physically occurs in the real world and has profound impacts on physical properties of particles at the nanoscale. Quantum tunneling refers to the ability of a particle to pass through a barrier that has greater potential energy than the kinetic energy of the particle. This is because in the subatomic world, there is a probability distribution as to where an electron can be in relation to the nucleus of an atom. As a wave function describing an electron moves close to a barrier, there is a nonzero probability, however minute, that it is on the other side of the barrier based on Schrodinger's equation. As it turns out, the tunneling phenomenon is observed regularly. In nature we observe single protons in the form of hydrogen nuclei fusing together. Given that the hydrogen nucleus is positively charged, it should repel other hydrogen nuclei. However, given the probability waves each of these atoms have, some hydrogen atoms will inevitably fuse together even if most of them do not. Additionally, radioactive decay is another natural occurrence of quantum tunneling, whereby subatomic particles are ejected from their orbitals based on probabilities (eventually after enough collisions) even though they lack the necessary energy to actually do so. To bring this topic closer to home, in October 2025, Michel Devoret, chief scientist of quantum hardware at Google Quantum AI, won a shared Nobel prize in physics for his team's groundbreaking work on the field.

Exhibit 52 Quantum Tunneling . . . Reality Is Stranger Than Fiction



Source: Morningstar.

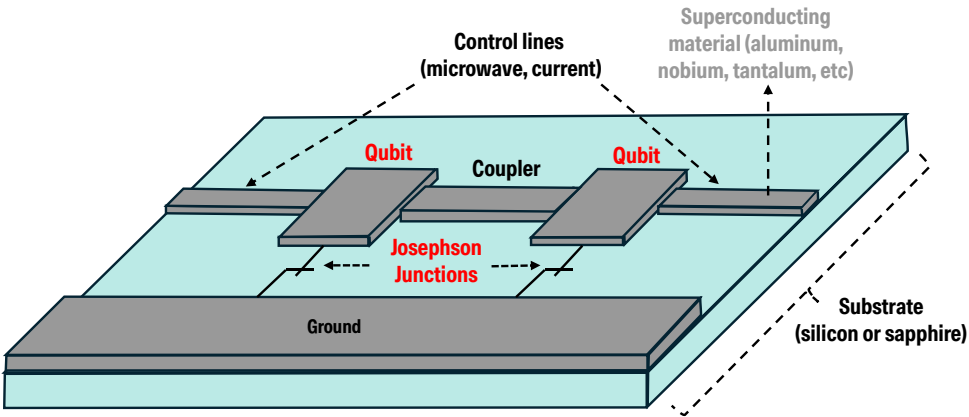
Note 2: Qubits

Given the attributes of different types of qubits along the various vectors in the table above, it quickly becomes obvious that no single qubit is likely to solve all quantum computing challenges. Further, while superconducting qubits may seem unattractive, so much investment has been poured into them, they are well-understood and entangling these types of qubits is relatively straightforward. Below, we briefly describe the most widely studied, employed, and promising qubit approaches.

Superconducting

Superconducting qubits are based on electrical circuits that carry current with no resistance at extremely low temperatures. They comprise nanoscale circuits, typically Josephson junctions, and use microwave pulses to manipulate the current. Josephson junctions are a critical concept in quantum mechanics as they allow pairs of electrons to tunnel through the insulating barrier of the junction, creating a superconducting current even without a voltage being applied. This then allows for the creation of several different types of qubits, including transmon qubits where the energy level within the particle demonstrates its quantum state; flux qubits, which can be manipulated within a magnetic flux within a superconducting loop; and phase qubits, which are created and manipulated by electrical currents.

Exhibit 53 Superconducting Qubits Are Very Interesting



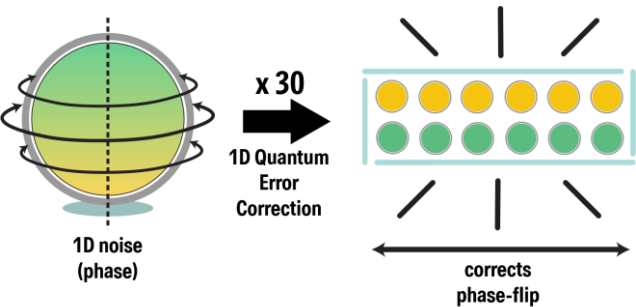
Source: Toshiba, Morningstar.

The quantum state of the qubit is derived from the energy level of the circuit. These types of qubits require the system to operate at supercooled temperatures that are barely above absolute zero to help control quantum decoherence, which drives the cost and complexity up drastically. Most development efforts for quantum computers focus on superconducting qubits, as this approach is based on existing technology currently used in semiconductors and it tends to perform calculations quickly.

Cat Qubit

A cat qubit is named after Schrodinger's famous thought experiment involving a feline in a precarious situation. It is a specific kind of superconducting qubit created using microwave oscillators and a Josephson junction. The oscillator can be manipulated to control the amplitude, which can be made to be in two relatively large and divergent extremes, like the high and low points of a sign wave. In this case the probability of measuring a 1 or a 0 is more certain, which then makes a cat qubit less prone to errors. For this reason, researchers and industry observers believe cat qubits should be important to quantum computing. However, as things stand, cat qubits require complex setups and very precise control of fragile light states, thereby limiting their adoption in the quantum computing world. That said, Amazon's Ocelot chip employs a cat qubit architecture.

Exhibit 54 Cat Cubits Are a Novel Approach to Improving Error Correction

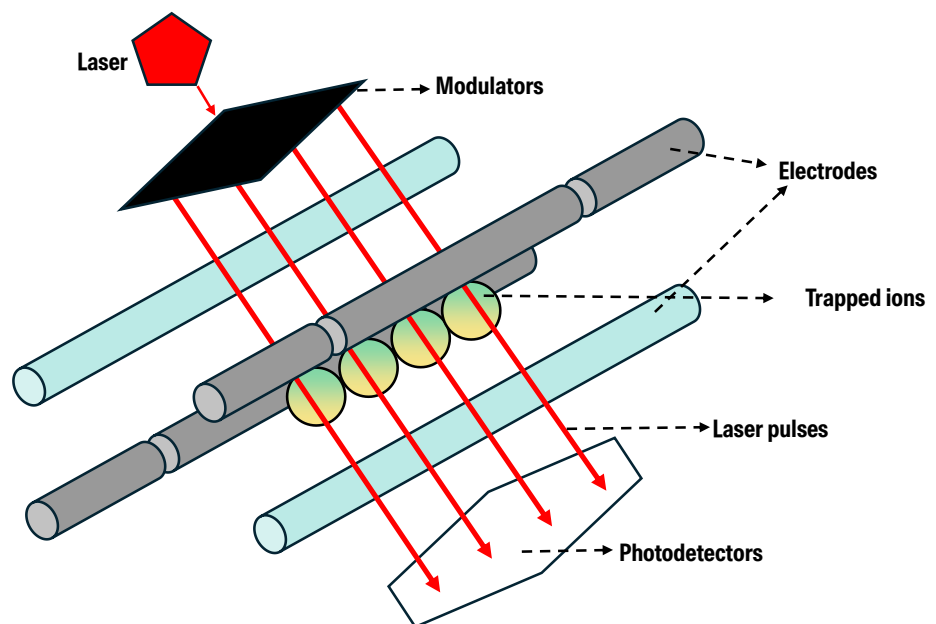


Source: Alice & Bob, Morningstar.

Trapped-ion

Trapped-ion qubits are based on isolated ions, or charged atoms, that are trapped in electromagnetic fields. Lasers are used to guide atoms close to one another and manipulate their energy levels, thus entangling them. Quantum information is stored in the hyperfine internal energy levels of the ions. Because they were the first type of qubit discovered, trapped-ion quantum computers are fairly advanced at this point. The downside of trapped-ion qubits is that computation is slow.

Exhibit 55 Trapped-ion Technology Is Well-Established



Source: Adapted from Wikimedia.

Photonic

Photonic qubits use the properties of light waves and particles, or photons. The photons can be manipulated using well-understood optical technology. Photonic approaches within quantum applications have also been proven and are advancing. While photons can operate at room temperature and offer low decoherence across greater distances, they are difficult to entangle. With weak entanglement, computation is challenging.

Neutral Atom

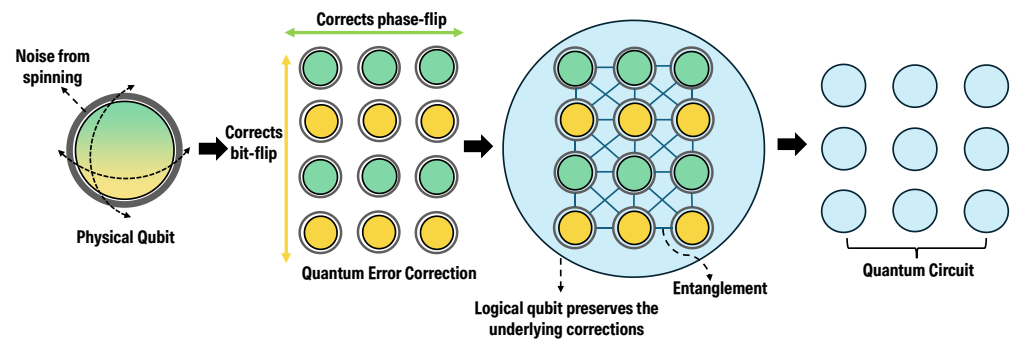
Neutral atom qubits use atoms that have electrons that appear as far away from the nucleus as possible, which typically can be found in alkali metals such as rubidium, cesium, and ytterbium. Electrons that are further away from the nucleus are more prone to excited states from external factors. The atoms are trapped using lasers and then further manipulated with lasers to change the excited state of the atoms to entangle them and store their information in the spin or energy state of the atoms.

The shortcomings of neutral atoms include a slow rate of computation, difficulty in manipulation, control, and measurement of individual atoms. That said, neutral atoms can operate at room temperature.

Quantum Dot

Quantum dot qubits involve trapping an electron within a nanoscale semiconductor structure and manipulating it with electromagnetic properties in the form of gates and fields such that either the spin or charge can be used to represent the qubit states. Spin represents the angular momentum of a particle and can be either up or down, or of course both simultaneously in the quantum realm. Quantum gates manipulate the spin or charge states of these qubits—built using quantum dots—with sequences of these gates forming quantum circuits. Based on our research, quantum dot qubits, spin qubits, and charge qubits appear to be substantially similar in their approach to quantum computing.

Exhibit 56 Quantum Dots Also Offer an Avenue to Lower Error Rates



Source: Morningstar.

Diamond Nitrogen-Vacancy Center

A diamond nitrogen-vacancy center qubit relies on the nitrogen-vacancy defect within a diamond crystal lattice, where a nitrogen atom is substituted for a carbon atom and a neighboring carbon atom is missing, creating a vacancy. The NV center's electron spin determines the qubit state. Importantly, NV qubits can operate at room temperature.

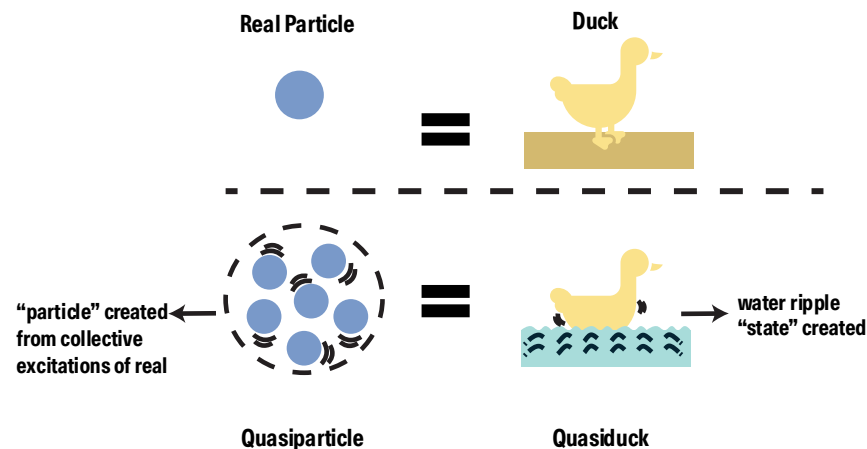
Nuclear Magnetic Resonance

Nuclear magnetic resonance uses the spin states of nuclei as qubits. The nuclei are suspended in a powerful magnetic field, creating a bifurcated energy system that can be used to manipulate and observe quantum information. The qubits are manipulated through radiofrequency pulses. This technology is well-understood, given it commercially exists through MRI medical equipment, among a variety of other applications, therefore this approach is being studied for use in quantum computers as well. One immediate shortcoming is NMR is extremely difficult to scale.

Topological

As if our exploration of quantum computing was not weird enough, topological qubits further drive our descent into madness. These qubits are based on the theoretical fundamental particle known as a Majorana particle, which is a fermion (a particle with mass) that has the unique property of being its own antiparticle (the particle is the same but numerical signs are inverted, so charge, for example would be the opposite). First proposed in 1937, thus far, only circumstantial evidence of these particles has been uncovered as quasiparticles in certain materials, such as superconducting nanowires. However, there is enough evidence to strongly suggest they exist. Nonetheless, groups of these particles can theoretically be entangled, resulting in the entangled particles “remembering” information contained in their counterparts. This makes topological qubits more a system, or fabric of qubits. Because qubits in general are extremely sensitive to interference, topological qubits would theoretically be much more resilient against such external noise since they operate as a group. Entangling qubits is an area of critical interest in efforts to achieve quantum error correction. Microsoft’s Majorana One quantum chip uses a topological architecture.

Exhibit 57 Topological Qubits Could Hold the Key for the Entire Industry



Source: Morningstar.

Note 3: Logic Gates

Beyond the differences between software and hardware, we must recognize that the logic gates used in classical computers are different than those employed by quantum computers. A quantum processor performs a calculation based on qubits. In order to actually use qubits, the state of the qubit is measured in its quantum state. However, once the measurement is made, the wave collapses into classical bits. The results are then stored in a classical register. Therefore, even in a quantum computer, we still need classical logic gate operations to orchestrate and interpret information output from a quantum system.

Readers familiar with semiconductors will know that a traditional processor relies on logic gates, which are the fundamental building blocks of circuits.

There are seven primary types of classical gates, including AND, OR, XOR, NOT, NAND, NOR, and XNOR. The bits, or 1 and 0s, are manipulated according to these gates. The base state is typically zero volts running through a circuit, which logically would be said to be a 0 in the bit duality nomenclature. An AND gate, for example, outputs a 1 when all inputs are at 1. That seven operations can comprise the entirety of a complex microprocessor with billions of transistors is nothing short of miraculous.

Exhibit 58 Classic Logic Gates Have No Corollary in Quantum Computing

Logic Gate	Description
AND	Output is 1 when all inputs are at 1, otherwise the output is 0
OR	Output is 1 when one or more inputs are at 1, otherwise the output is 0
NAND	Output is 0 when all inputs are at 1, otherwise the output is 1
NOR	Output is 0 when one or more inputs are at 1, otherwise the output is 1
XOR	Output is 1 when one and only one input is 1, otherwise the output is 0
XNOR	Output is 0 when one and only one input is 1, otherwise the output is 1
NOT	Output is 0 when the only input is 1, and output is 1 when the input is 0

Source: Morningstar.

Given that qubits are more complex than bits, there are many more types of quantum gates, most of which do not have classic corollaries. In fact, there is an infinite number of possible quantum logic gates that the quantum state of a qubit can be described by combinations of probabilities of 1 and 0. While this may seem daunting, there are a variety of gates that can effectively be employed to perform most any task in quantum computing. Further, some gates would apply to one qubit system, some apply to two qubit systems, and some apply to systems containing any number of qubits. To further complicate quantum gates, they are reversible, whereas classic logic gates are not. Additionally, because particles have multiple variables that can be used as qubits, the spin of a particle or the position of a particle for example, rather than just the on-off nature of a classical bit, there are various types of quantum gates to account for these complications. Quantum platforms like those offered by Microsoft and IBM allow users to design and test quantum gates on simulators and on actual quantum hardware. We view this as an important part of the ecosystem development.

Note 4: Semiconductors

Materials science plays a crucial role in semiconductors. This starts in the silicon wafer, as silicon atoms each have four electrons in their outer band that bond with other silicon atoms via covalent bonds, forming a uniform lattice crystal structure. Silicon does not conduct electricity, as there are no free electrons to bond with anything else. However, the semiconductor fabrication process introduces impurities to the silicon in a step called doping in order to change the properties of silicon such that it can conduct electricity.

Within a silicon atom, there are two bands of energy, a conduction band and a valence band, and a critical gap that separates the two. In the conductive band, there are fewer electrons and more gaps that electrons can move into, while the valence band is the opposite and contains bonded electrons that cannot move freely. The holes have positive charges while the electrons have negative charges. In a semiconductive material, the electrons can break free from the conductive band when in an excited, or charged state, and pass through the bandgap. Information is moved and stored using these charges around the paths etched within a silicon wafer. Effectively, the charge of any individual circuit is either on or off, 1 or 0. With this simple concept, engineers can put many such circuits within a single processor to perform complex tasks. The 14th generation of Intel processors, dubbed Raptor Lake, is a 64-bit processor, meaning it can handle 64 bits of data at a time. In other words, it can process 64 1s and 0s together.

Note 5: Notable Quantum Algorithms

- ▶ **Deutsch-Jozsa algorithm:** The Deutsch-Jozsa algorithm was the first quantum algorithm that demonstrated an exponential improvement in performance over a classical approach. DJ determines if a system is balanced or constant, with balanced being an equal distribution of either of two states (1 and 0), and constant being all of the same state (either 1 or 0). This approach uses superposition to run a query one time, but it offers a single evaluation on a quantum superposition of all inputs. A classical system has to attack problems like this with brute force by repeating the query until the solution is reached. We do not immediately see practical applications to the method itself, but we note its importance in demonstrating quantum advantage.
- ▶ **Shor's algorithm:** Shor's algorithm is a quantum approach to factoring large numbers that is exponentially faster than doing so with a classical computer. The largest integer the algorithm has been successfully applied to is 35, which clearly does not live up to anything resembling a promise of quantum computing. That said, the algorithm has been proven and it has been used to successfully factor numbers. The limiting factor is the number of qubits available on a quantum computer. To deliver the practical superiority of Shor's algorithm, a quantum system would need to factor a 600-digit number to beat RSA 2048 encryption, which might require millions of physical qubits... or perhaps just 10,000, nobody seems to be sure. The practical use case for Shor's algorithm once quantum technology is more fully developed is likely to be for cryptography, cybersecurity, blockchain, and cryptocurrencies.
- ▶ **Simon's algorithm:** Simon's algorithm allows users to detect repeating patterns within a mathematical formula in an exponentially faster timeframe than possible using a classical computer. It was reviewed by Peter Shor, of Shor's algorithm fame, at a mathematics conference but was rejected for presentation by the full panel. However, Shor immediately recognized the importance of Daniel Simon's work and began a collaboration with him. The end result of this collaboration was Shor's algorithm, which received accolades that should have perhaps partially been directed at Simon. We note Daniel Simon currently works in cryptography at AWS.
- ▶ **Grover's algorithm:** Grover's algorithm speeds up search in unstructured data. It is relatively straightforward to query a dataset, say a phone book, by asking to return the phone number of a person named Erwin Schrodinger. However, it would be a different operation to solve the query about if a certain phone number was in the phone book. This method has been borne out in trials on quantum computers.

Similar to Shor's algorithm, the most obvious uses for Grover's algorithm are general database queries and cybersecurity, whereby the approach would be equivalent to a brute force attack where a program simply tries every combination of characters until it finds the key, albeit faster than classical approaches allow for. It also seems possible that this technique could be used in conjunction with other approaches to find optimal states for complex systems.

- **Quantum phase estimation:** Quantum phase estimation allows users to extract data regarding the phase of the quantum state. We think of QPE as a building block used within other quantum algorithms. This should conceptually be familiar to many tech investors, as it can be thought of as physical IP libraries from semiconductor firms or as a micro-service within a software platform. Many, but not all, quantum algorithms will require an initial phase position for qubits, so the ability to gather knowledge of the quantum state of a system is critical. While QPE may not grab headlines in the way that some of the other major quantum algorithms do, we think it is indispensable to quantum computing more broadly.
- **Quantum Fourier transform:** Quantum Fourier transform is useful in converting quantum states back into frequencies we can understand, or in other words, porting data from the quantum realm to the classical realm. Therefore, we view QFT as a building block quantum algorithm that appears in more complex formulations, such as Shor's algorithm.
- **Variational quantum eigensolver:** VQE is one of two critical hybrid approaches in our short list of critical quantum algorithms that use both classical and quantum computers to find a certain state of a system. In the case of VQE, it finds the lowest energy state of a system, which is valuable for molecule modelling and therefore drug discovery and materials science, and could likely be applied to other optimization problems, such as complex supply chains.

Quantum approximate optimization algorithm: The quantum approximate optimization algorithm is the other hybrid approach to optimization problems that we present that uses a quantum computer to solve for a system of parameters and a classical computer to adjust the parameters. The use cases here revolve around complex logistics, manufacturing process, scheduling, and other optimization problems.

Research Methodology for Valuing Companies

Overview

At the heart of our valuation system is a detailed projection of a company's future cash flows, resulting from our analysts' research. Analysts create custom industry and company assumptions to feed income statement, balance sheet, and capital investment assumptions into our globally standardized, proprietary discounted cash flow, or DCF, modeling templates. We use scenario analysis, in-depth competitive advantage analysis, and a variety of other analytical tools to augment this process. We think analyzing valuation through discounted cash flows presents a better lens for viewing cyclical companies, high-growth firms, businesses with finite lives (mines, for example), or companies expected to generate negative earnings over the next few years. That said, we don't dismiss multiples altogether but rather use them as supporting cross-checks for our DCF-based fair value estimates. We also acknowledge that DCF models offer their own challenges (including a potential proliferation of estimated inputs and the possibility that the method may miss short-term market-price movements), but we believe these negatives are mitigated by deep analysis and our long-term approach.

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Four key components drive the Morningstar rating:

- ▶ our assessment of the firm's economic moat.
- ▶ our estimate of the stock's fair value.
- ▶ our uncertainty around that fair value estimate.
- ▶ the current market price.

This process ultimately culminates in our single-point star rating.

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+1 312 696-6000

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Chicago, IL 60602 USA

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