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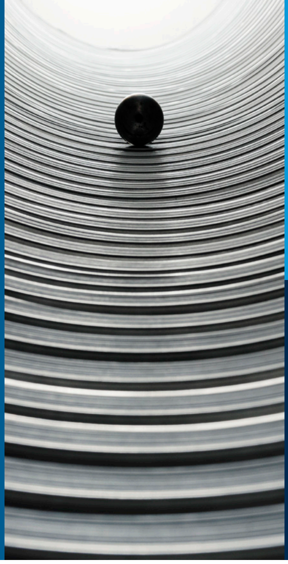
Quantum Computing Revisited

Error Correction Changes the Problem



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Quantum Computing: Then and Now

Six years ago, we argued that quantum computing was approaching the transition from scientific theory toward commercial reality. Since then, the field has made meaningful progress, although significant challenges remain. Most importantly, researchers have demonstrated a critical principle of quantum error correction: under the right conditions, adding more physical qubits can make quantum information more reliable rather than less.[1,2] That development changes the nature of the problem. The central question is increasingly shifting from whether fault-tolerant quantum computing is scientifically possible to how quickly it can be engineered and scaled—and when it might begin solving economically valuable problems.

From Physical to Logical Qubits

A classical computer stores information in bits that take a value of either 0 or 1. Quantum computers use qubits, which exploit the properties of quantum mechanics to represent and manipulate information differently. Adding qubits rapidly expands the mathematical state space a quantum computer can represent, but useful computing power depends on more than qubit count. It also requires accuracy, speed, connectivity, and, critically, error correction.[1]

That is why the industry is shifting its attention from **physical qubits to logical qubits**. Physical qubits are the individual hardware components and are inherently noisy. A logical qubit spreads quantum information across multiple physical qubits so the system can detect and correct errors without destroying the information being protected.[2]

[1] Counterpoint Global, "Quantum Computing," Counterpoint Global Insights, October 2020. The original paper described quantum computing as approaching commercial reality and identified error correction and scaling as central challenges.

[2] Google Quantum AI and Collaborators, "Quantum Error Correction Below the Surface Code Threshold," Nature 638, 920–926 (2025), DOI: 10.1038/s41586-024-08449-y.

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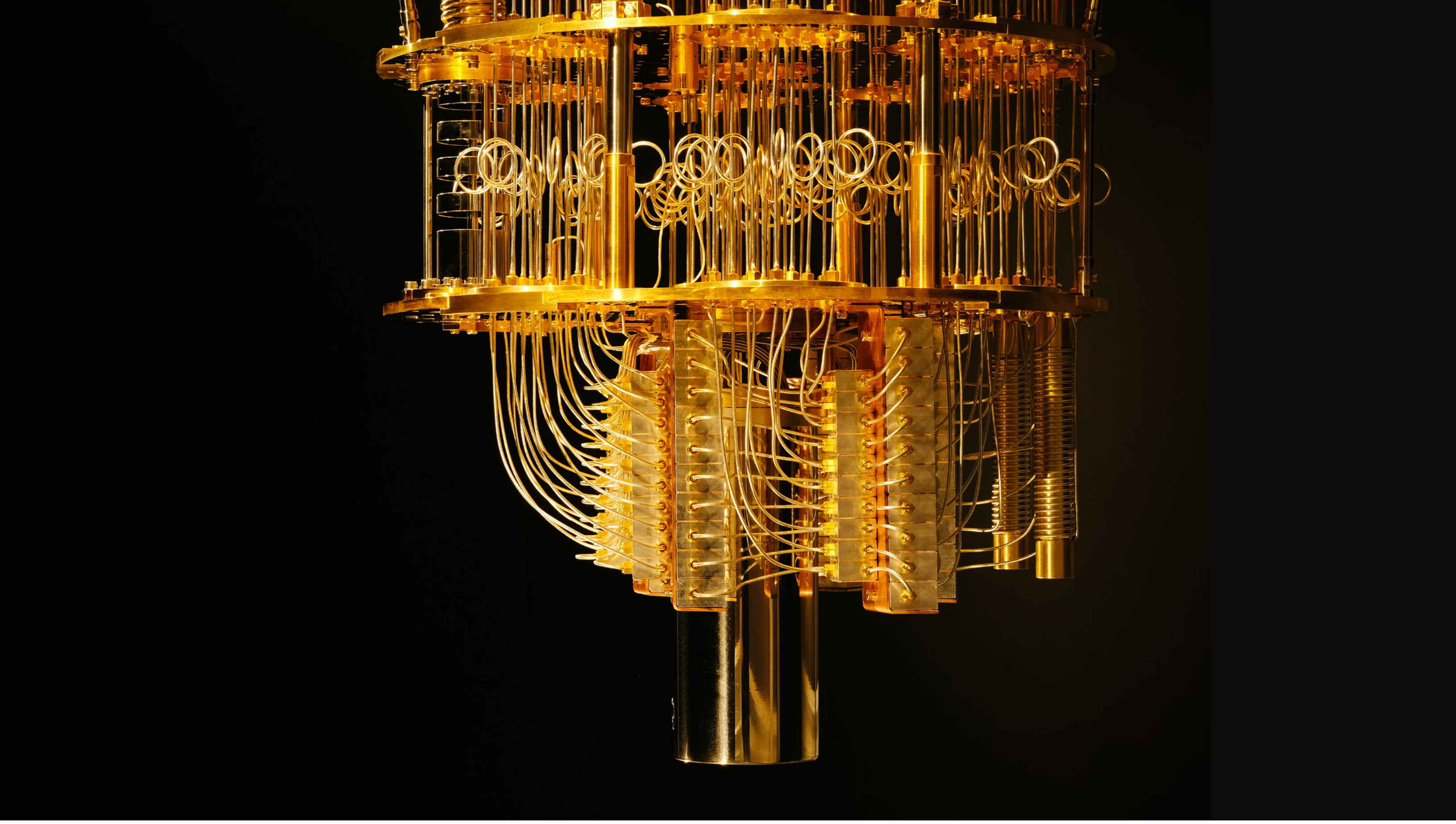

A simple analogy is storing an important record in several locations and continually checking the copies. One component may fail, but the group can preserve the underlying information. Physical-qubit counts describe the size of a machine. Logical qubits begin to describe how much reliable work it may eventually perform.

Error Correction Changes the Problem

Quantum error correction is not new. What remained unproven on a quantum processor was the scaling behavior required for a practical computer: whether adding more physical qubits to an error-correcting code could produce a lower logical error rate.

Google's Willow processor provided an important demonstration. Google built progressively larger error-correcting logical qubits and found that reliability improved as the amount of error correction increased. In its largest test, the logical memory preserved information longer than its best constituent physical qubit, and Google demonstrated real-time decoding across as many as one million error-correction cycles.[2]

This is known as operating **below threshold**. Above the threshold, additional hardware introduces more errors than the redundancy can correct. Below it, making the error-correcting code larger can make the logical qubit increasingly reliable. That is the scaling property fault-tolerant quantum computing requires.

The pattern is not limited to one architecture. Infleqtion has demonstrated fault-tolerant operations on logical qubits using neutral atoms, while a Microsoft and Quantinuum experiment on trapped-ion hardware reported large improvements in logical error rates using combinations of correction and detection.[3,4] These experiments use different hardware, codes, and metrics, so their results are not directly comparable. The broader point is more important: logical performance has begun to exceed physical performance across multiple systems.

Logical qubit count helps determine how much information a machine can process; logical error rate helps determine how long it can keep calculating before an uncorrected error spoils the result. A useful quantum computer needs both

[3] Woo Chang Chung et al., "Fault-Tolerant Operation and Materials Science with Neutral Atom Logical Qubits," npj Quantum Information 11, 193 (2025), DOI: 10.1038/s41534-025-01095-w.

[4] Adam Paetznick et al., "Improved Quantum Processor Logical Error Rates via Correction and Detection," Nature 654, 349–355 (2026), DOI: 10.1038/s41586-026-10628-y.

enough logical qubits to represent an important problem and sufficiently low error rates to finish solving it. Company roadmaps increasingly frame progress in those terms rather than physical-qubit counts alone.[5]

Q-Day Moves into the Planning Horizon

One of the best-understood applications of quantum computing is breaking public-key cryptography. Peter Shor showed that a sufficiently capable quantum computer could factor large integers far more efficiently than known classical methods, potentially undermining RSA and related cryptographic systems.[6]

In 2020, we wrote that a perfectly functioning quantum computer with roughly 4,100 qubits could theoretically break RSA-2048. Those were effectively perfect logical qubits, not today's noisy physical qubits.[1] A 2021 study estimated that the calculation could require 20 million noisy physical qubits under specified assumptions; a 2025 Google Quantum AI preprint reduced the estimate to fewer than one million, largely through improvements in algorithms, arithmetic, logical-qubit storage, and error correction.[7,8]

The day on which a quantum computer can break widely used public-key cryptography is commonly called **Q-Day**. Its timing remains uncertain, but the threat has moved into institutional planning horizons. Google has set 2029 as the deadline for completing its migration to post-quantum cryptography, while NIST finalized its first principal post-quantum cryptography standards in 2024 and says organizations should begin applying them now.[9,10] "Store now, decrypt later" attacks make the issue relevant before Q-Day because intercepted data may remain valuable long enough to be decrypted by a future machine.[9]

Why It's Disruptive

Cryptography is the best-understood application of quantum computing, but potentially not the most valuable. The larger case rests on simulation. Quantum systems naturally represent other quantum systems, creating the possibility of modeling molecules and materials that become extremely difficult for classical computers. Our original paper highlighted catalysts, batteries, pharmaceuticals, solar materials, fertilizers, and superconductors as candidates.[1]

Early evidence points in that direction without yet establishing commercial usefulness. Infleqtion used two logical qubits in a prototype materials-science calculation.[3] Google's "Quantum Echoes" experiment ran a set of circuits roughly 13,000 times faster than its estimate for the best classical algorithm on the Frontier supercomputer, and a companion experiment applied the method to molecular-structure analysis.[11] Neither result represents a commercial application, and neither is yet a demonstration of economic value.

Optimization, finance, and machine learning are more contingent because any advantage must survive data preparation, repeated sampling, verification, and continuing improvement in classical methods. A realistic path to commercial value may therefore be narrow: a quantum processor need not replace an entire workflow if it can accelerate one economically consequential step that classical systems handle poorly.

The Quantum-Classical Model

Quantum computers are unlikely to replace classical computers. They are more likely to function as specialized accelerators inside classical computing environments. A quantum processing unit, or QPU, may perform the portion of a calculation for which quantum mechanics provides an advantage, while CPUs and GPUs prepare data, control the hardware, decode error signals, and complete the work before and after the quantum calculation. Large-scale error correction may itself require substantial low-latency classical computing.[12]

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5 IonQ, "Industry-Leading Roadmap," company technology roadmap, accessed August 27, 2026.

6 Peter W. Shor, "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," SIAM Journal on Computing 26, no. 5 (1997): 1484–1509, DOI: 10.1137/S0097539795293172. Originally presented at FOCS 1994.

7 Craig Gidney and Martin Ekerå, "How to Factor 2048-Bit RSA Integers in 8 Hours Using 20 Million Noisy Qubits," Quantum 5, 433 (2021), DOI: 10.22331/q-2021-04-15-433.

8 Craig Gidney, "How to Factor 2048-Bit RSA Integers with Less Than a Million Noisy Qubits," arXiv:2505.15917 (2025). Preprint; not peer reviewed.

9 Heather Adkins and Sophie Schmieg, "Google's Timeline for PQC Migration," Google, March 25, 2026; Kent Walker and Hartmut Neven, "The Quantum Era Is Coming. Are We Ready to Secure It?" Google, February 6, 2026; both accessed August 29, 2026.

10 National Institute of Standards and Technology, "Post-Quantum Cryptography," including the 2024 publication of FIPS 203, FIPS 204, and FIPS 205 and the transition framework described in NIST IR 8547, accessed August 29, 2026.

11 Google Quantum AI and Collaborators, "Observation of Constructive Interference at the Edge of Quantum Ergodicity," Nature 646, 825–830 (2025), DOI: 10.1038/s41586-025-09526-6; "Quantum Computation of Molecular Geometry via Many-Body Nuclear Spin Echoes," arXiv:2510.19550 (2025), preprint; Google Quantum AI, "A Verifiable Quantum Advantage," October 22, 2025, accessed August 29, 2026. The 13,000-times figure is Google's estimate of the classical cost.

12 NVIDIA, "NVIDIA Introduces NVQLink, Connecting Quantum and GPU Computing," October 2025, accessed August 29, 2026; "Platform Architecture for Tight Coupling of High-Performance Computing with Quantum Processors," arXiv:2510.25213 (2025), preprint.

This model broadens the ecosystem. Useful systems will require not only quantum processors but also control electronics, cryogenics or photonics depending on the architecture, software, networking, real-time decoding, and conventional high-performance computing. The QPU may therefore enter the data center as an additional processor optimized for a distinct class of problems, much as the GPU did.[12]

Competing Architectures

There is still no standardized quantum equivalent of the transistor. Several architectures are advancing in parallel, each with different strengths and engineering challenges. The comparison below is intentionally simplified; performance depends on the specific implementation and continues to change quickly.[1,13]

What This Means for Investors

For investors, the key question is shifting from whether quantum mechanics can support scalable computation to when sufficiently reliable systems will solve economically valuable problems, which architectures will do so, and where in the ecosystem the resulting value will accrue.

The eventual winners may not be limited to the companies building quantum processors. The quantum-classical model creates potential opportunities across control electronics, photonics, cryogenics, software, networking, real-time decoding, and high-performance computing—even before broadly useful fault-tolerant systems arrive.[12]

We believe three indicators deserve particular attention: **the number of reliable logical qubits, the logical error rate, and evidence of economically useful advantage over classical alternatives.** The first two measure whether the technology is becoming technically capable; the third will determine whether that capability creates commercial value.

Architecture remains an important uncertainty. DARPA is explicitly evaluating multiple approaches in its Quantum Benchmarking Initiative rather than assuming a single winner.[14] For investors, that argues for focusing less on headline physical-qubit counts and more on demonstrated logical performance, scalability, system economics, and evidence of useful applications.

Reasons for Caution

The history of quantum computing rewards caution. Google's 2019 Sycamore experiment was presented as a calculation that would take a classical supercomputer 10,000 years; three years later, researchers generated one million uncorrelated samples from the same circuit in roughly 15 hours on 512 GPUs.[15] Classical methods have improved in response to nearly every quantum-advantage claim so far.

The error-correction results are also narrower than the headlines can suggest. Willow demonstrated below-threshold scaling for a quantum memory rather than a large set of logical gates, which is the harder problem.[2] The best demonstrations remain far below roadmaps calling for thousands of logical qubits and cryptographic estimates on the order of a million physical qubits.[4,5,8]

APPROACH	BASIC IDEA	POTENTIAL ADVANTAGE	KEY CHALLENGE
Superconducting	Artificial circuits cooled near absolute zero	Fast operations; leverages chip-fabrication techniques	Shorter-lived quantum states, error correction, and cryogenic scaling
Trapped ions	Charged atoms held in electromagnetic traps	High-fidelity operations and naturally uniform qubits	Slower operations and engineering large interconnected systems
Neutral atoms	Uncharged atoms positioned and controlled with lasers	Large, reconfigurable arrays and long coherence	Control fidelity, atom loss, and fault-tolerant scaling
Photonic	Quantum information encoded in particles of light	Networking, connectivity, and potential modularity	Photon loss and resource overhead for error correction
Silicon spins	Electron or nuclear spins controlled in semiconductor devices	Potential compatibility with semiconductor manufacturing	Uniform fabrication, control, and scaling beyond small devices

Sources: NIST; Nature Electronics; Nature Materials; DARPA.[13]

[13] National Institute of Standards and Technology, "Quantum Computing Explained," accessed September 3, 2026; Nature Electronics, "Betting on Qubits," 2025; Nature Materials, "The Photonic Path to Quantum Advantage," November 26, 2025; Nature Materials, "Tweezer Arrays Advance Quantum Computing," November 21, 2025; Defense Advanced Research Projects Agency, Quantum Benchmarking Initiative materials. These sources describe the principal hardware approaches and their broad engineering tradeoffs.

[14] Defense Advanced Research Projects Agency, "Quantum Benchmarking Initiative"; "Quantum Benchmarking Initiative Expands Quest to Separate Hype from Reality," March 10, 2026; Stage B selection materials, accessed September 3, 2026.

[15] Frank Arute et al., "Quantum Supremacy Using a Programmable Superconducting Processor," Nature 574, 505–510 (2019), DOI: 10.1038/s41586-019-1666-5; Feng Pan, Keyang Chen, and Pan Zhang, "Solving the Sampling Problem of the Sycamore Quantum Circuits," Physical Review Letters 129, 090502 (2022), DOI: 10.1103/PhysRevLett.129.090502.

Several questions still need to be answered:

- Can below-threshold error suppression continue at much larger code sizes and across logical gates?
- Can logical-error metrics become comparable enough to evaluate vendors on a common basis?
- Which applications justify the full cost of the quantum and classical infrastructure required to run them?
- Will one architecture dominate, or will the market support several specialized approaches?

Conclusion

The case that quantum computing could become a foundational technology is stronger than it was in 2020. The biggest change is error correction. Researchers have now demonstrated the scaling behavior on which fault-tolerant quantum computing depends: under the right conditions, a quantum system can become more reliable as its error-correcting code becomes larger.[2]

That result does not complete the path to a useful quantum computer, but it changes the nature of the challenge.

A central scientific proposition is increasingly becoming an engineering and systems problem. Logical error rates will help determine how quickly the industry progresses from short experiments to deep, useful calculations. Declining estimates for cryptographic workloads, late-decade hardware roadmaps, and the global transition to post-quantum security suggest that quantum computing is entering a more consequential phase—even as the timing, winning architectures, and ultimate commercial applications remain uncertain.

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