On the Road to Quantum Advantage

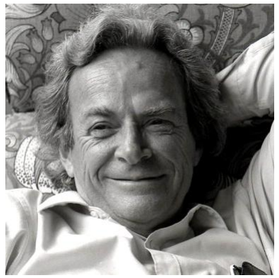

Image generated using Midjourney

INSTITUTE FOR QUANTUM INFORMATION AND MATTER

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Quantum World Congress
25 September 2026

Oratomic

From NISQ to FASQ

What we have now:

-- *Noisy Intermediate-Scale Quantum (NISQ) machines*.

-- Capable of performing thousands of two-qubit operations.

-- Becoming useful for scientific exploration.

-- Limited commercial value.

What we want to have:

-- *Fault-Tolerant Application-Scale Quantum (FASQ) machines*.

-- Capable of performing billions or trillions of two-qubit operations.

-- Opening a wide variety of scientific and commercial applications.

-- Need to improve error rates by many orders of magnitude!

-- Quantum error correction is essential for crossing from NISQ to FASQ.

Some recent highlights

Applications:

Simulations of quantum dynamics

Hardware:

Advancement of superconducting and atomic processors

Error correction:

Advantages from long-range connectivity

Algorithms:

Reduced cost for Shor’s algorithm

Quantum machines for science

Quantinuum Helios: 98 qubits, 2Q gate F=.9992 (MS, all pairs)

IBM Heron: 156 qubits, 2Q gate F=.9988 (median CNOT)

Google Willow: 105 qubits, 2Q gate F=.9988 (mean CZ)

Harvard/QuEra/MIT: 442 qubits, 2Q gate F=.9985 (CZ, low depth)

More than 5K 2Q gates for correlated dynamics, mitigated.

Higher fidelity and nonlocal connectivity vs. more shots.

Correlated fermions in 2D (digital)

Phasecraft / Google Willow (superconducting): Fermi-Hubbard dynamics on 6 x 6 lattice, 2 qubits per site, compare with free fermions for mitigation. 72 qubits, 4372 2Q gates.

Quantinuum Helios (ions): Fermi-Hubbard pairing correlations on 6 x 6 lattice + 18 ancillas, local fermion encoding. 90 qubits, 3439 2Q gates.

Harvard (neutral atoms): Non-abelian spin liquid and Fermi-Hubbard quench dynamics. 72-qubit honeycomb + 32 ancillas, 104 qubits, low depth circuits.

Analog simulations (neutral fermionic atoms in optical lattices): Thousands of lattice sites, but digital provides more flexible initial states, output observables and tunable Hamiltonians.

Floquet dynamics in quantum spin systems

Floquet Ising dynamics: Up to 74 qubits on heavy-hex ladders.

Qedma's advanced error mitigation on an IBM Heron device.

Beyond the reach of classical tensor-network and Pauli-path methods.

Cross-platform corroboration using Quantinuum Helios.

Physics insight: Surprisingly persistent prethermal oscillations.

arXiv:2607.24937

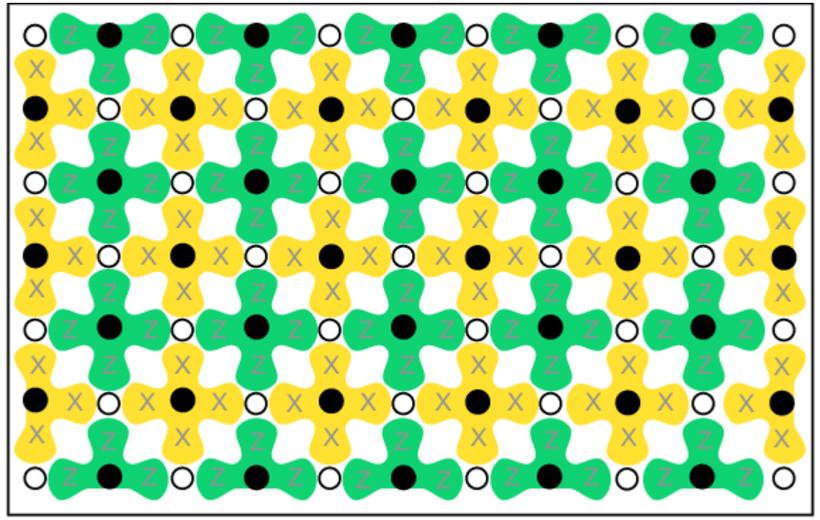
Overhead cost of fault tolerance

$$P_{\text{logical}} \approx C\left(P_{\text{physical}} / P_{\text{threshold}}\right)^{(d+1)/2}$$

$$d = \sqrt{n}, \quad C \approx 0.1, \quad P_{\text{threshold}} \approx .01$$

surface code

Suppose $P_{\text{physical}} = .001, P_{\text{logical}} = 10^{-11}$
$\Rightarrow d = 19, n = 361$ physical qubits per logical qubit,
plus a comparable number of ancilla qubits for syndrome measurement. (Improves to $d = 9$ for $P_{\text{physical}} = 10^{-4}$.)



white = data
black = check

Quantum low-density parity-check codes

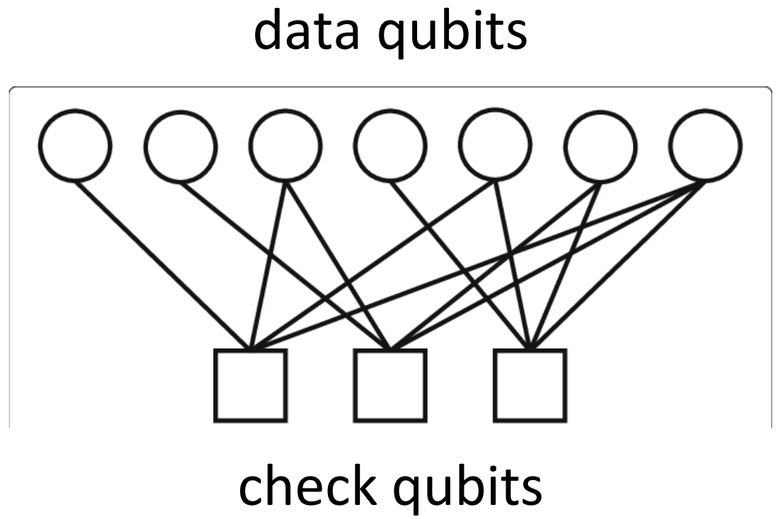
The n physical qubits obey n-k constraints ("checks"), leaving k "logical" qubits.

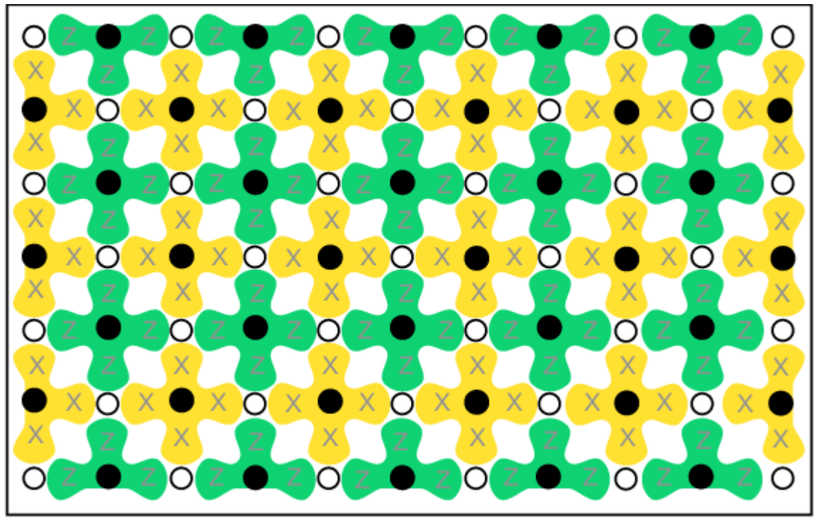
Each logical operator acts on at least d physical qubits ("distance" d).

Each constraint acts on few physical qubits, and each physical qubit is involved in few constraints.

Surface code: checks are geometrically local in 2 dimensions. k=1 logical qubits per block.

High-rate codes: large k and d via nonlocal connectivity.





surface code

The joy of nonlocal connectivity

Long-range connections might require complex fabrication in solid state devices.

More natural for movable qubits in ion traps and neutral atom arrays.

Higher encoding rates with quantum low-density parity-check (qLDPC) codes. Reduced number of physical qubits, high threshold, feasible decoders.

Universal gate gadgets for qLDPC codes with reduced spacetime cost.

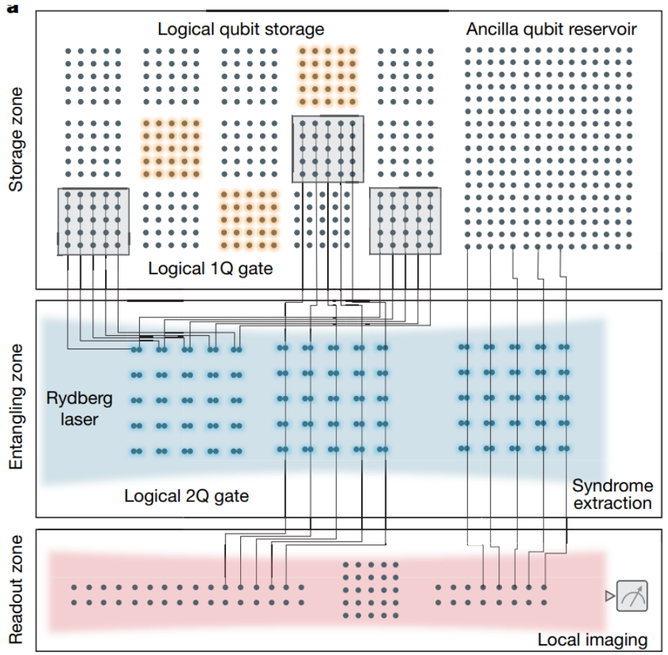
These advantages partially compensate for the slow clock speed.

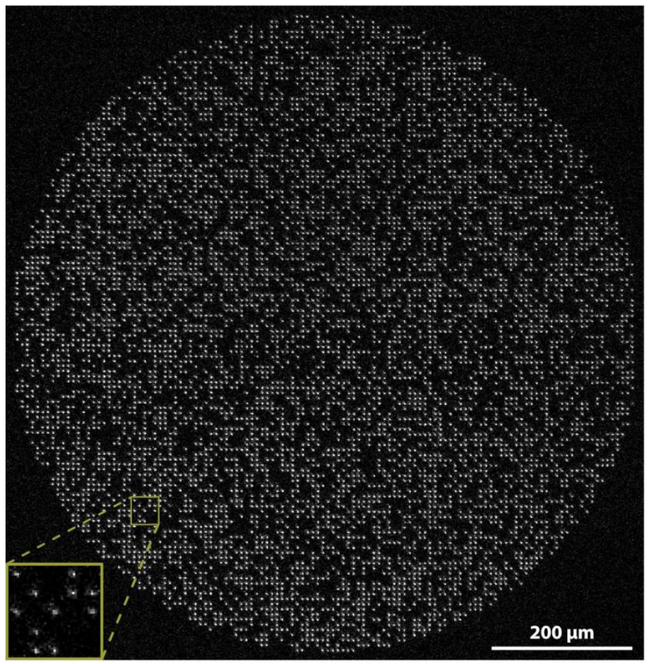
Neutral atoms in optical tweezer arrays

Traveling qubits for measuring nonlocal check operators.
Efficient logical operations on high-rate code blocks.
Pursued by companies, but so far universities have been leading innovation.
Likely to be the leading near-term quantum computing architecture.

Logical processor based on reconfigurable atoms arrays

Lukin Lab (Harvard)
Nature 2024





Tweezer array with 6100 highly coherent atomic qubits

Endres Lab (Caltech)
Nature 2025

Toward scalable control

Wiring bottleneck. Cryo-CMOS reduces requirements for connecting to room-temperature control.

HRL 2026. CMOS controller at 4K, connected by superconducting ribbon cable to 18 qubits (54 Si quantum dots) at 150 mK. Programs running autonomously inside the cryostat.

IBM 2026. Cryo-CMOS control chips connected to 156-qubit Heron QPU. 2Q gate fidelities comparable to using room-temperature control.

Desired: further reduction of power per qubit.

Also possible: ultra-low-power superconducting classical logic inside the dil fridge [SEEQC 2025, Northrop-Grumman 2026].

Toward cryptanalytic relevance

Factor 2048 bits in a few days using fewer than 1M physical qubits (assuming 10^{-3} 2Q error rate and 2D processing) [Gidney 2025].

Breaking ECC-256 with fewer than 70 million (logical) Toffoli gates [Google 2026]. Further optimization via AI [ecdsa.fail].

Breaking ECC-256 with tens of thousands of physical qubits via high-rate coding [Oratomic 2026, IonQ 2026].

Accelerating the timeline for migration to post-quantum cryptography. [Google, Cloudflare 2029, US Government 2031].

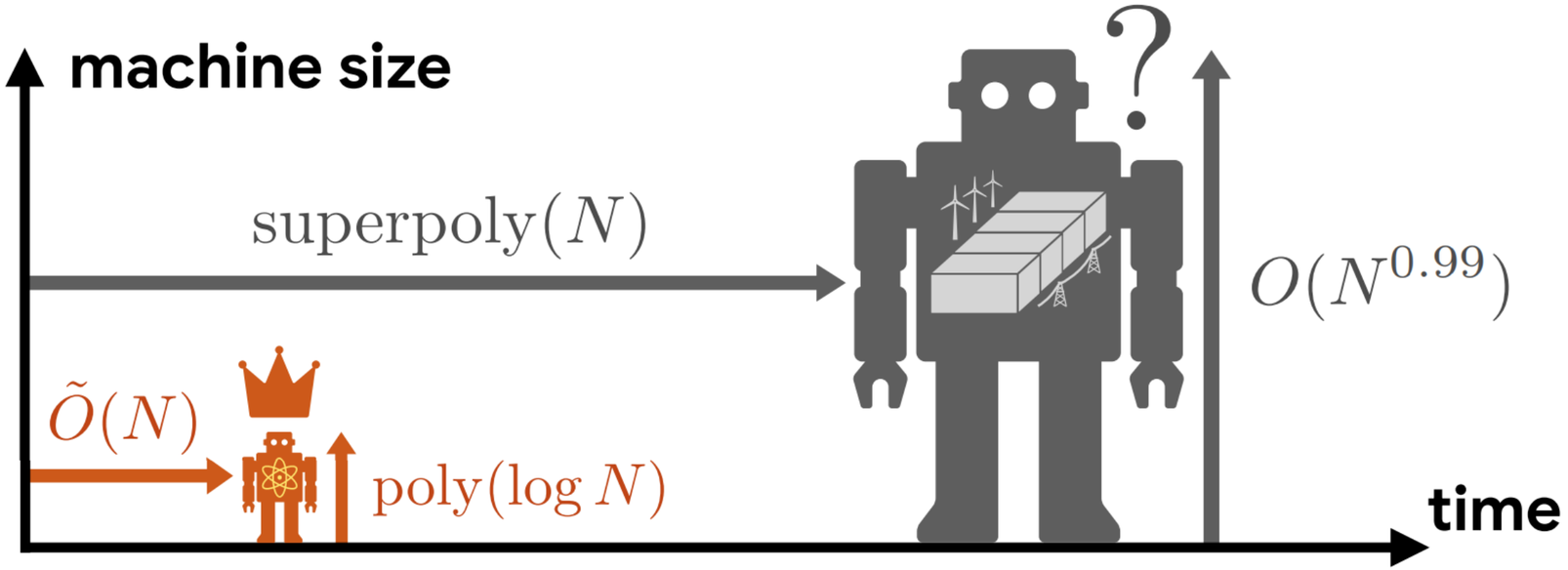
AI / Quantum in 2026

Competition on (quantum) applications.

Indispensable tool, accelerating progress.

Practical applications of quantum + AI?

Processing massive classical data on small quantum computers



Exponential memory advantage for e.g. classification, dimension reduction.

Quantum memory size poly(log *N*) suffices for dimension-*N* task.

Classical machine with size sublinear in *N* requires superpoly(*N*) time.

Exponentially compact classical models possible only with quantum technology.

Zhao, Zlokapa, Neven, Babbush, Preskill, McClean, Huang arXiv:2604.07639

Open Questions

How will we scale up to quantum computing systems that can solve hard problems?

What are the important applications for science and for industry?

Prospects for the next few years

Encouraging progress toward scalable fault-tolerant quantum computing.

Scientific insights enabled by programmable quantum simulators and circuit-based quantum computers.

The most important applications of quantum computing are likely to be ones we have not yet imagined.