Crossing the Quantum Chasm: From NISQ to Fault Tolerance

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John Preskill

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INSTITUTE FOR QUANTUM INFORMATION AND MATTER

@preskill

The Likely Road to Quantum Value:

Fault-Tolerant Quantum Computing

Status of NISQ applications

What we have now. NISQ is valuable for scientific exploration. But there is no proposed application of NISQ computing with *commercial* value for which quantum advantage has been demonstrated *when compared to the best classical hardware running the best algorithms for solving the same problems*.

What we can reasonably foresee. Nor are there persuasive theoretical arguments indicating that commercially viable applications will be found that do *not* use quantum error-correcting codes and fault-tolerant quantum computing.

Quantum algorithms:

A survey of applications and end-to-end complexities

Alexander M. Dalzell*[1], Sam McArdle*[1], Mario Berta[1,2,3], Przemyslaw Bienias[1], Chi-Fang Chen[1,4], András Gilyén[5], Connor T. Hann[1], Michael J. Kastoryano[1,6], Emil T. Khabiboulline[1,7], Aleksander Kubica[1], Grant Salton[1,4,8], Samson Wang[1,3] and Fernando G. S. L. Brandão[1,4]

[1] *AWS Center for Quantum Computing, Pasadena, CA, USA*
[2] *Institute for Quantum Information, RWTH Aachen University, Aachen, Germany*
[3] *Imperial College London, London, UK*
[4] *Institute for Quantum Information and Matter, Caltech, Pasadena, CA, USA*
[5] *Alfréd Rényi Institute of Mathematics, Budapest, Hungary*
[6] *IT University of Copenhagen, Copenhagen, Denmark*
[7] *Department of Physics, Harvard University, Cambridge, MA, USA*
[8] *Amazon Quantum Solutions Lab, Seattle, WA, USA*

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Applications: Looking ahead

Optimization, finance, and machine learning. Typical quantum speedups are at best quadratic. Quantum advantage kicks in for very large problem instances and deep circuits.

Quantum many-body physics: Chemistry and materials. Hundreds of logical qubits, hundreds of millions of logical gates or more.

Quantum fault tolerance needed to run these applications. High cost in physical qubits and gates.

Logical gate speed is also important. Run time on the wall clock.

Overcoming noise in quantum devices

Quantum error mitigation. Used effectively in current processors. Asymptotic overhead cost scales exponentially.

Quantum error correction. Asymptotic overhead cost scales polylogarithmically. Not yet effective in current processors.

What we need. Better two-qubit gate fidelities, *many* more physical qubits, and the ability to control them. Also fast gates, mid-circuit readout, feed-forward, reset.

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 $P_{\text{physical}} = 10^{-4}$.)

Progress toward QEC

Erasure conversion. Dominant errors occur at known locations, hence easier to correct.

Biased noise. Physical suppression of bit flips, error-correcting codes for the phase flips.

More efficient codes. But geometrically nonlocal syndrome measurements required.

Co-design. Adapt the coding to the hardware, adapt the hardware to the code.

Erasure conversion

Dominant errors are heralded, occur at known circuit locations, hence easier to correct.

By design, dominant errors exit the computational space of the qubit, and can be detected without disturbing the coherence of undamaged qubits.

Alkaline earth Rydberg atoms [*Princeton, Caltech*].
$|1\rangle \to |g\rangle$, not $|1\rangle \to |0\rangle$.

Dual-rail superconducting qubit [*Yale, AWS*]. $|01\rangle, |10\rangle \to |00\rangle$
Encode using two transmons or two resonators.

Biased noise

Physically suppress the bit flips, use coding to suppress the phase flips. Gates must preserve bias.

Outer code: Repetition code or asymmetric surface code.

Example: the repetition cat code [*Yale, Alice & Bob, AWS*].

Code states $|0\rangle$, $|1\rangle$ are coherent states, well separated in phase space. Bit flips suppressed exponentially as mean photon number n increases.

Photon loss induces phase errors, at rate increasing linearly with n.

More efficient codes

Constant-rate qLDPC (quantum low-density parity-check) codes exist, including “good” codes with constant relative distance.

High accuracy thresholds, efficient decoders, schemes for executing fault-tolerant gates.

But syndrome extraction requires geometrically nonlocal operations, e.g. movable qubits or long-range coupling.

Example [*IBM*]: [[144 physical qubits, 12 logical qubits, distance 12]]

Co-design

Adapt the coding to the hardware.

Adapt the hardware to the code.

An exciting time for Rydberg atom arrays!

May lead the progress in quantum error correction for the next few years, if two-qubit gate fidelities continue to improve.

Thousands of qubits, and movement of atoms enables geometrically nonlocal operations and syndrome measurements [*Harvard/MIT*].

Further improvement from erasure conversion.

Repeated syndrome measurement yet to be demonstrated.

Continuous loading of fresh atoms will be needed.

Atomic movement and readout are relatively slow.

Movable qubits

Schemes involving moveable atomic qubits have advantages in the short run.

But in the long run, movement imposes serious limitations on clock speed, unless much faster movement can be achieved.

Fast readout and reset are also important.

Cosmic rays!

Potential limitation for superconducting qubits.

Go deep underground?

Concatenated codes?

Hardening processor against ionizing radiation?

Big Question

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

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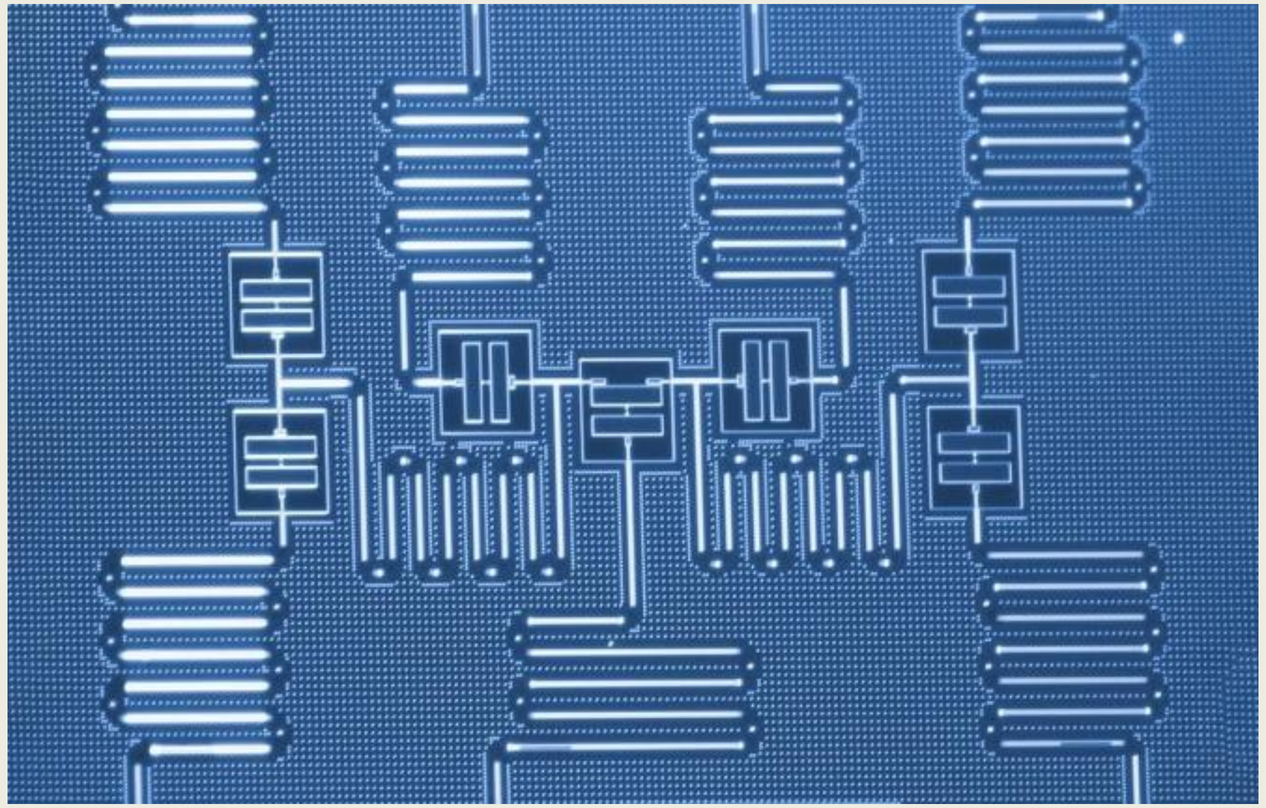
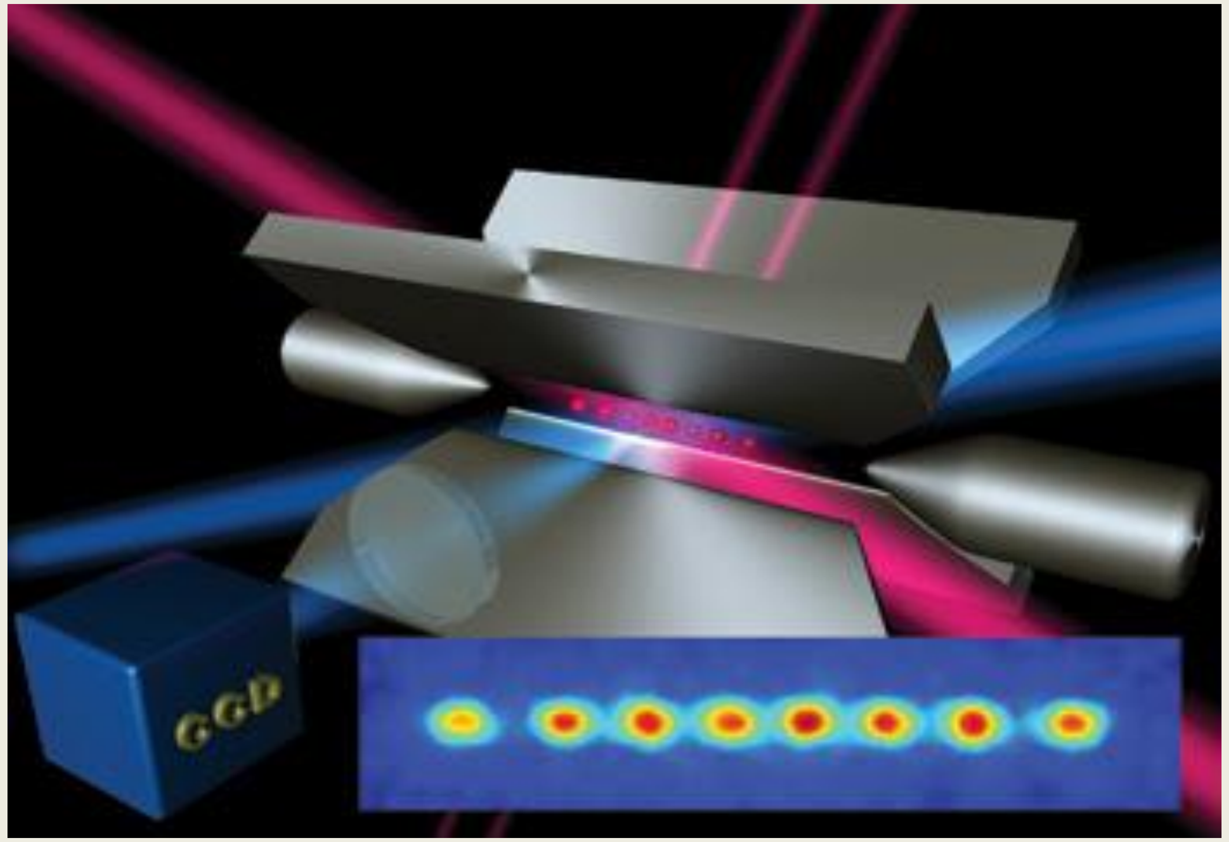
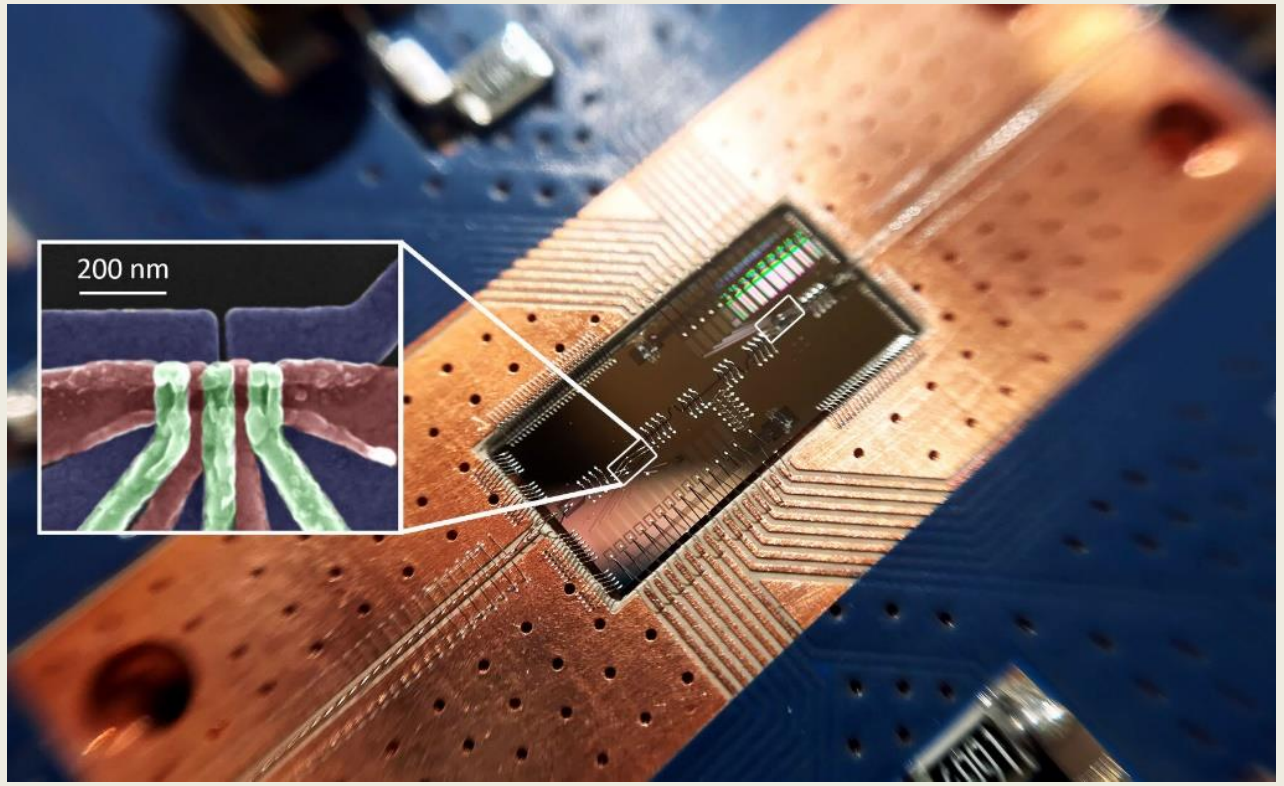
We don’t know yet!



superconducting qubits



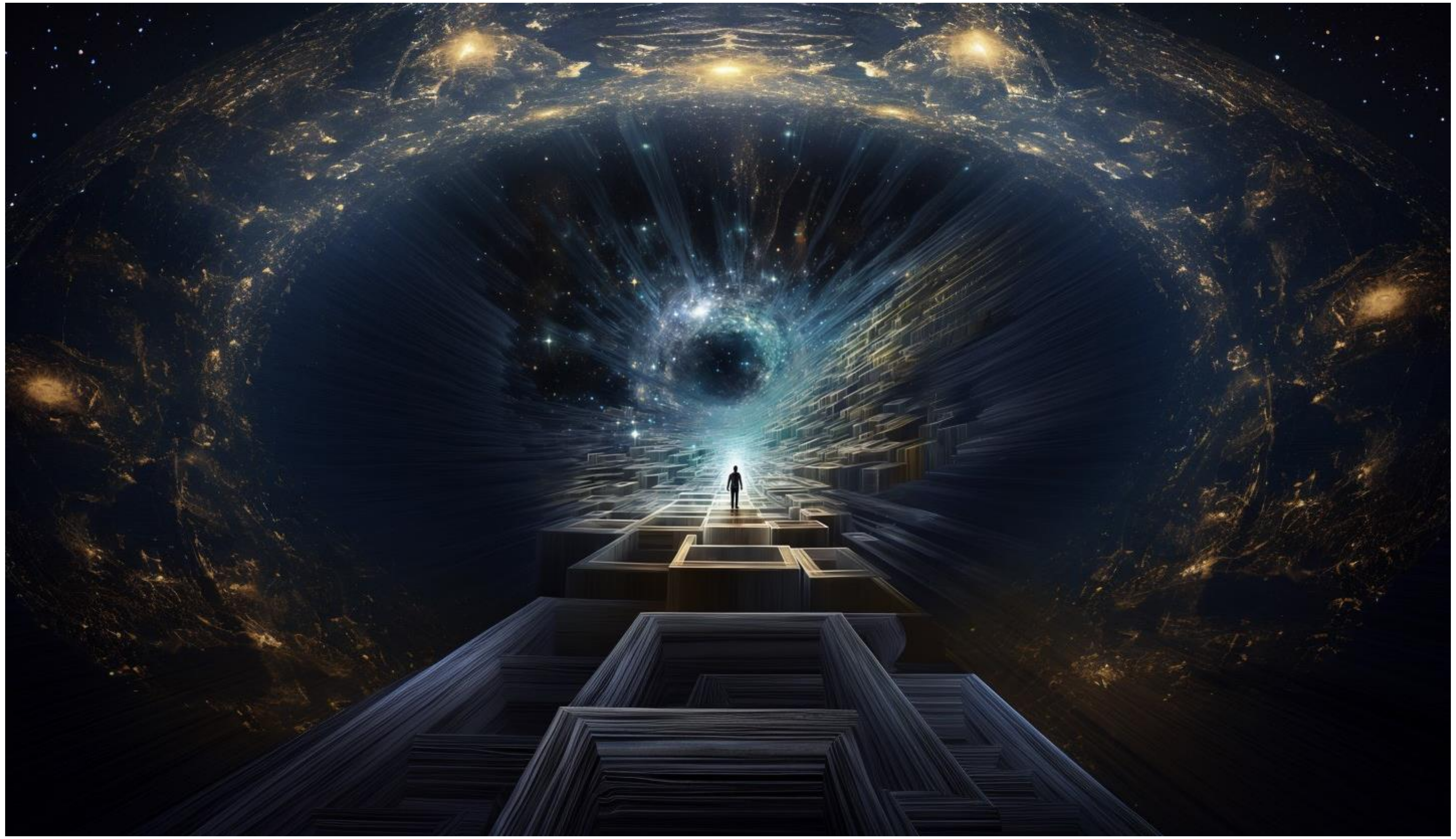
trapped atoms/ions



spin qubits

photonics

To attain quantum value, we must follow the road to fault tolerance.



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