Beyond NISQ: The Megaquop Machine

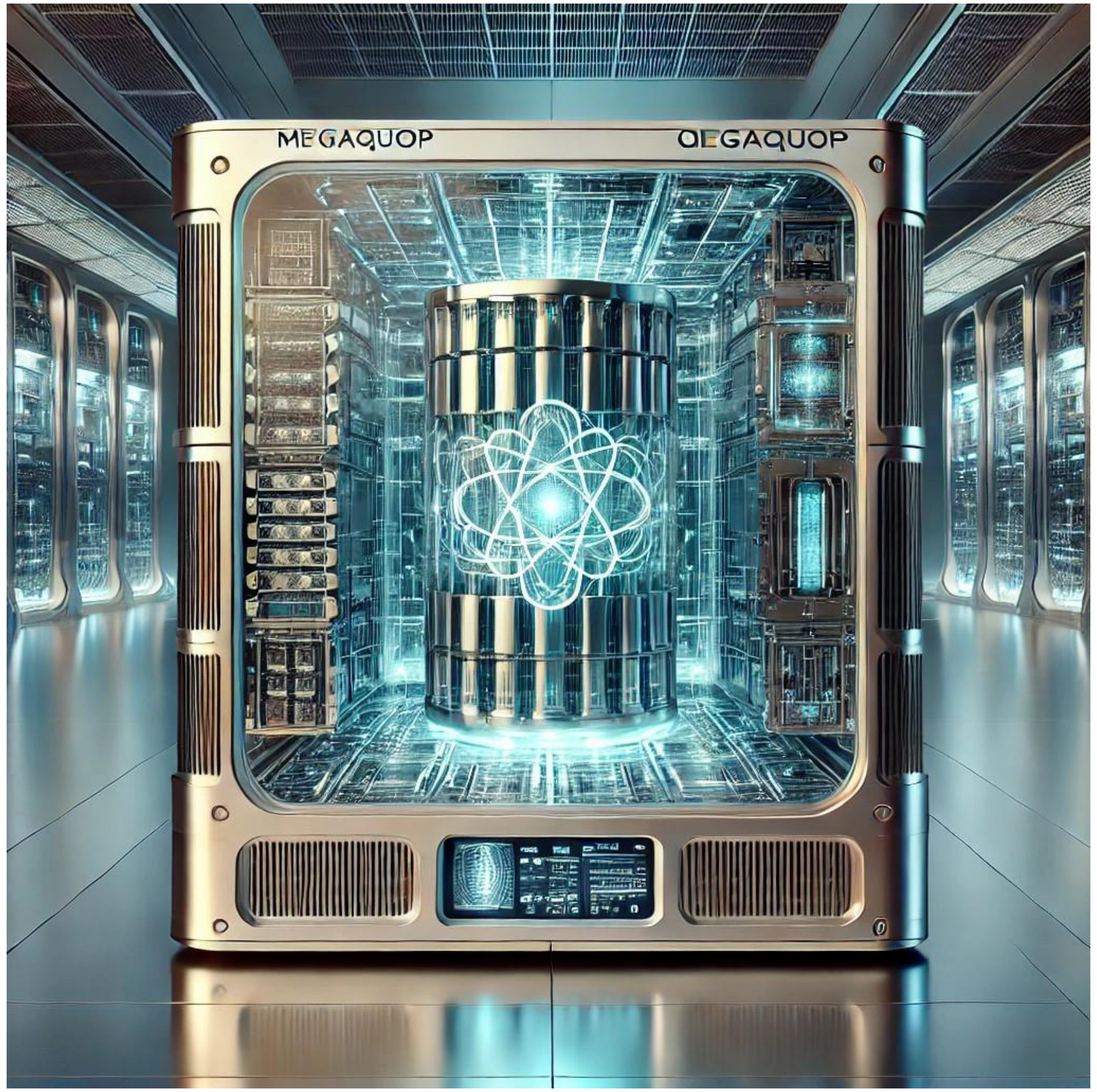

Image generated by ChatGPT

AWS

IQIM
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill

Q2B 2024 Silicon Valley

11 December 2023

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

@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.

Beyond NISQ

NISQ: Noisy Intermediate-Scale Quantum

FASQ: Fault-tolerant Application-Scale Quantum*

ISQ: Intermediate-Scale Quantum**

LISQ: Logical Intermediate-Scale Quantum***

MISQ, GISQ, TISQ, etc.: Mega-Instruction-Scale Quantum, etc.****

Megaquop, Gigaquop, Teraquop, etc.

* A. Landahl (2020)　　**J. M. Arrazola (2023)
*** S. Severini (2023)　　**** D. Bacon (2024)

Megaquop Machine

Logical gate error rate ~ 10^{-6}. Not achievable without QEC.

Error mitigation will continue to be useful in the Megaquop era and beyond.

Beyond classical, NISQ, or analog. E.g., depth 10K and 100 (logical) qubits.

Tens of thousands of high-quality physical qubits.

When will we have it? Less than 5 years? What modality? Rydberg atoms?

What will we do with it? Quantum dynamics?

Commercial as well as scientific applications?

Quantum error correction: What we want

Repeated rounds of accurate error syndrome measurement.

Quantum memory times that improve sharply as codes increase in size.

Accurate *real-time* decoding of error syndromes, scalable control.

Scalable efficient logical universal gates with (much) higher fidelity than physical gates.

Logical gate fidelities that improve sharply as codes increase in size.

Acceptable overhead cost in space and time.

Speed matters! (Superconducting ~1000 time faster than ions.)

Quantum error correction below the surface-code threshold

[*Google 2024*]

105 qubit Willow processor. Improved transmon lifetime, measurement error, leakage correction.

Millions of rounds of surface-code error syndrome measurement, each lasting ~1 microseconds (600 nanosecond measurement time).

Logical error rate for quantum memory improves by $\Lambda \approx 2$ when code distance increases by 2 (from 3 to 5 to 7).

Accurate *real-time* decoding of error syndromes for distance 3 and 5.

Repetition code: $\Lambda \approx 8.4$ up to d = 29.

Looking ahead: Better Λ, larger codes, high-fidelity logical two-qubit gates.

Resilience against ionizing radiation

[Google 2024]

Potential limitation for superconducting qubits.

Go deep underground? Concatenated codes?

Gap engineering: Large superconducting gap suppresses quasiparticle tunneling across Josephson junction.

Error floor improves from 10^{-6} to 10^{-10} per round (from seconds to hours).

What other rare events should we worry about?

Is real-time decoding scalable?

Needed for universal logical gates. A serious challenge for superconducting circuits (maybe less of an issue for slower modalities).

Google decoding latency for distance d=5: ~ 63 + 10 microseconds.

Riverlane + Rigetti 2024: FPGAs integrated into control system improve latency for small codes.

Google DeepMind 2024: Better decoding performance from reinforcement learning, but training gets hard at large code distance.

"Correlated decoding" across multiple code blocks can reduce circuit depth overhead [*Harvard + QuEra 2024*], but increases complexity of decoding.

Trading simplicity for performance

Cat qubits with highly biased noise [*Yale, ENS, Alice & Bob, AWS*].

Dual-rail qubits for erasure detection [*Yale + QCI, AWS*].

GKP qubits/qutrits/ququarts in resonators, well protected against loss, providing soft information [*Yale, Nord Quantique, ETH*].

Fluxonium for strong anharmonicity and high fidelity: 2Q fidelity > .999 [*MIT + Atlantic Quantum*].

Other error correction progress

Movable qubits for all-to-all coupling.

Harvard + MIT + QuEra: Circuit sampling with 48 logical qubits on a 280-qubit device. CCZ gates within an [[8,3,2]] code block.

Atom Computing + Microsoft: Bernstein-Vazirani algorithm with 28 logical qubits in a 256-qubit device. [[4,1,2]] subsystem code.

Quantinuum + Microsoft. Preparation of a cat state with 12 logical qubits on a 56-qubit device. CNOT within a [[16,4,4]] block and transversal between blocks.

Caveats: Few rounds of syndrome measurement and unscalable postselection.

Can movement be much faster?

Toward the Megaquop Machine

High-rate codes, e.g. Bivariate Bicycle (BB) codes [*IBM 2024*]. Nonlocal connectivity.

Logical error mitigation making use of error syndrome information boosts the simulable circuit volume [*Qedma*].

T state "cultivation" (rather than distillation) to reduce cost [*Google 2024*].

Chemistry: Fewer qubits, higher circuit depth.

Materials: More qubits, lower circuit depth. Translation invariance → parallel operation. Circuit optimizations [*Phasecraft 2024*].

Post-NISQ quantum dynamics, e.g. in 2D. Classical algorithms for quantum simulation are a moving target.

Megaquop Machine: A reachable near-term goal?

Advances in hardware, control, algorithms, error correction, error mitigation, etc. are bringing us closer to a machine that can reliably execute circuits with of order a million quantum operations.

What are the potential uses for a megaquop machine? A compelling challenge for the quantum community.

Progress hinges on innovation at all levels of the stack. An opportunity for co-design. Advances in basic science and systems engineering are needed.

What we learn in the megaquop era will guide our path to gigaquops, teraquops, and beyond.