# CPEN 400Q Lecture 24
# Noisy, intermediate-scale quantum computing

Wednesday 10 April 2024

# Announcements

- Last class today!
  - Please fill out student experience survey on Canvas
  - If you have specific / more direct feedback, especially about improving hands-on content, please reach out with your ideas!
- Literacy assignment 3 due tonight at 23:59
- Final project due Friday 12 April at 23:59
  - To submit, enable access for @glassnotes to your group’s GitHub repository
  - If you want me to review weekly surveys, please let me know by Monday 15 Apr.

# Last time

We learned about a more general quantum operations called **quantum channels** that can turn pure states into mixed states.

$$\rho \to \rho' = \Phi(\rho)$$

Channels are completely positive trace-preserving maps defined by **Kraus operators**,

$$\Phi(\rho) = \sum_i K_i \rho K_i^\dagger, \quad \sum_i K_i^\dagger K_i = I$$

# Last time

*Example*: unitary channel.

$$\Phi(\rho) = U\rho U^\dagger$$

*Example*: bit flip channel (bit flip with probability *p*)

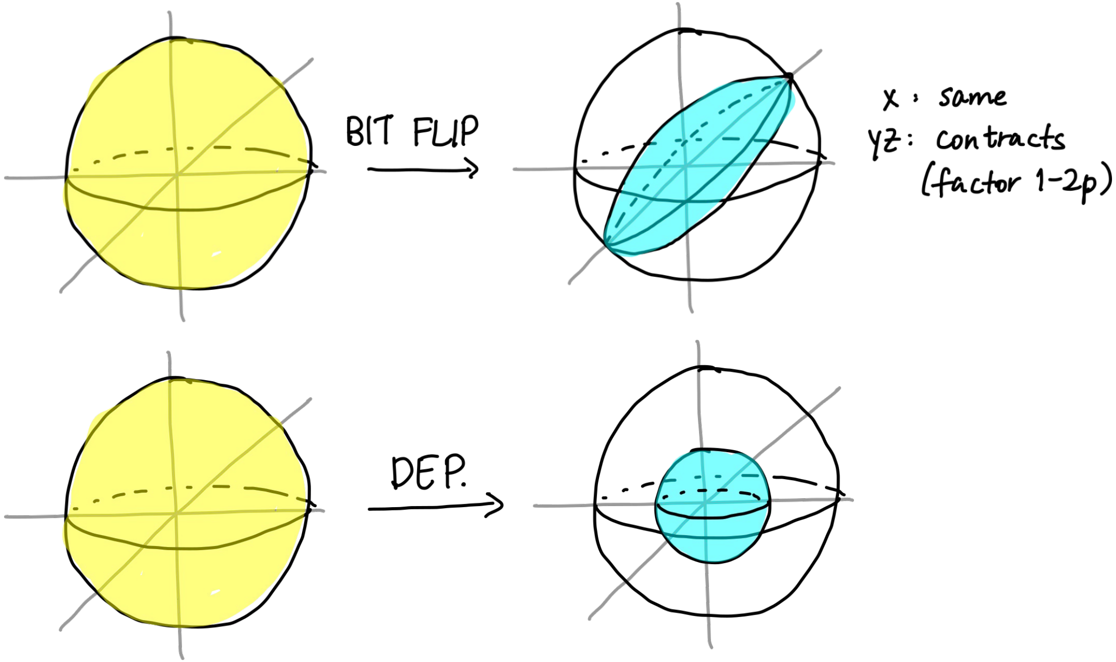
$$\Phi(\rho) = (1-p)\rho + pX\rho X$$

*Example*: depolarizing channel

$$\Phi(\rho) = (1-p)\rho + \frac{p}{3}X\rho X + \frac{p}{3}Y\rho Y + \frac{p}{3}Z\rho Z$$

# Last time

We can visualize the effect of noise processes by analyzing distortion of the Bloch sphere.



# Last time

We discussed two ways to compare density matrices:

Trace distance

$$T(\rho,\sigma) = \frac{1}{2}||\rho-\sigma||_1 = \frac{1}{2}\mathrm{Tr}\left(\sqrt{(\rho-\sigma)^\dagger(\rho-\sigma)}\right), \quad 0 \leq T(\rho,\sigma) \leq 1$$

Fidelity

$$F(\rho,\sigma) = \left(\mathrm{Tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)^2, \quad 0 \leq F(\rho,\sigma) \leq 1$$

# Last time

We did a noisy simulation of solving the deuteron problem with VQE.
The results were… not good.

# Learning outcomes

- Describe key metrics and processes for quantifying quality at the qubit-, gate-, and system-level
- Define “quantum advantage”
- Outline near- and long-term strategies for performing quantum computing in the presence of noise

# The NISQ era

Quantum
the open journal for quantum science

Quantum Computing in the NISQ era and beyond

John Preskill

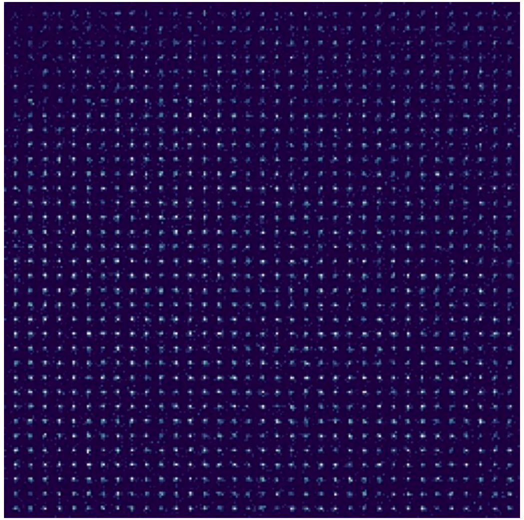

## Abstract

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away - we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.


John Preskill (2018) *Quantum Computing in the NISQ era and beyond*. Quantum 2, 79.

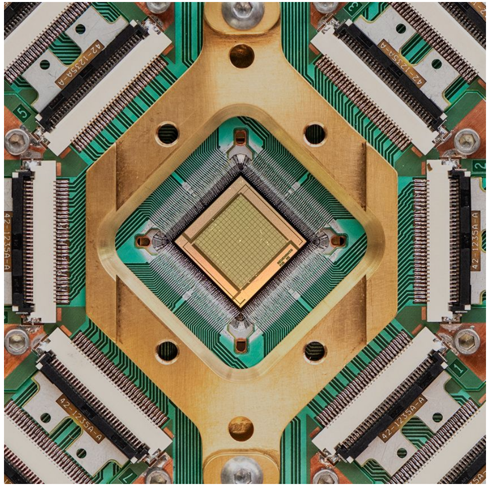
# Quantum processors today

The largest ones have over 1000 operational qubits.



1180 neutral atom qubits
Atom Computing


1121 superconducting qubits
IBM



5000+ superconducting qubits
D-Wave

https://arstechnica.com/science/2023/10/atom-computing-is-the-first-to-announce-a-1000-qubit-quantum-computer/

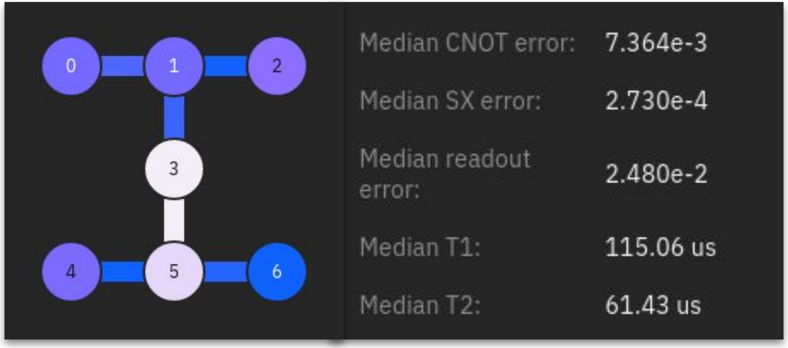
https://arstechnica.com/science/2023/12/ibm-adds-error-correction-to-updated-quantum-computing-roadmap/

https://www.dwavesys.com/solutions-and-products/systems/

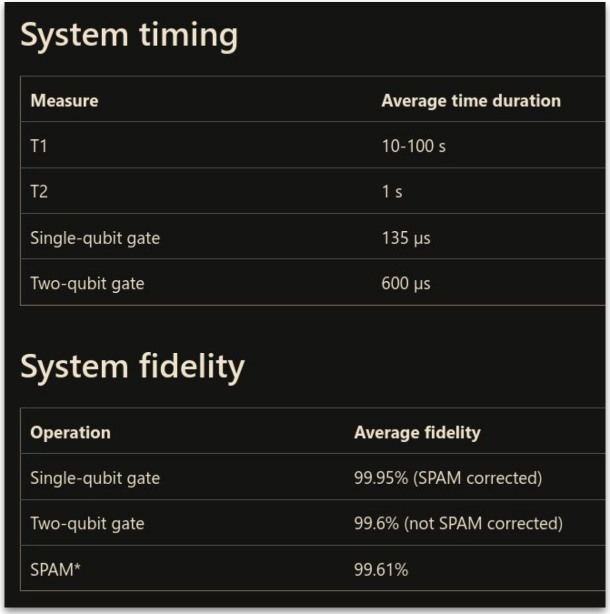
# Benchmarking quantum computers

Need a way to quantify:

- Quality: gate and readout errors
- Time: gate times, coherence times
- Other factors: connectivity, software




IBM Q Nairobi
(captured 2023-10-27, IBM Quantum Platform)



## System timing

| Measure | Average time duration |
|---|---|
| T1 | 10-100 s |
| T2 | 1 s |
| Single-qubit gate | 135 μs |
| Two-qubit gate | 600 μs |

## System fidelity

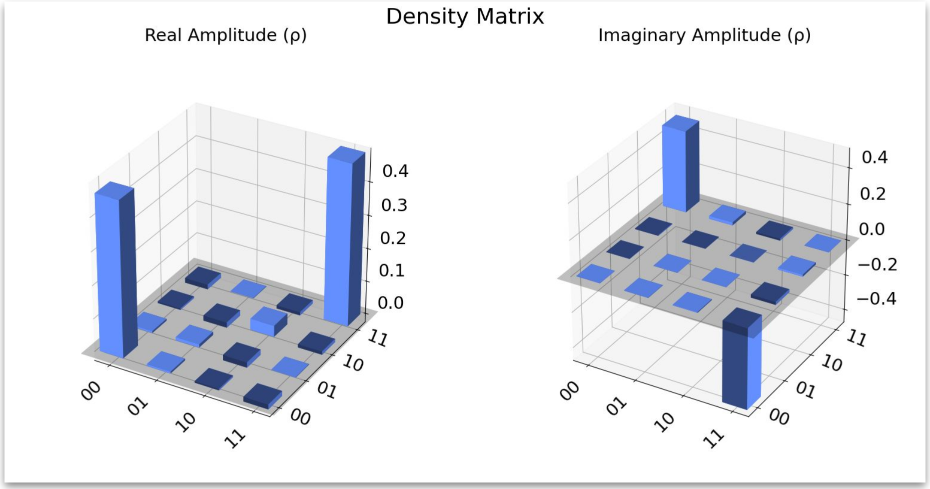
| Operation | Average fidelity |
|---|---|
| Single-qubit gate | 99.95% (SPAM corrected) |
| Two-qubit gate | 99.6% (not SPAM corrected) |
| SPAM* | 99.61% |

IonQ Aria
(captured 2023-10-27, Azure Quantum docs)

# Benchmarking quantum computers

## Quantum tomography

Reconstruct a quantum state or process based on measurement data.




Issue: full characterization with no prior knowledge requires an exponential number of measurements!

Recall for 1 qubit,

$$\rho = \frac{1}{2}I + \frac{\langle X \rangle}{2}X + \frac{\langle Y \rangle}{2}Y + \frac{\langle Z \rangle}{2}Z$$

For $n$ qubits,

$$\rho = \sum_{i=0}^{4^n-1} c_i P_i$$

Image: https://qiskit-extensions.github.io/qiskit-experiments/manuals/verification/state_tomography.html#

# Benchmarking quantum computers

**Randomized benchmarking**

Perform increasingly-long random experiments with Clifford gates and fit survival probability to estimate an average gate fidelity.

Many variations on the protocol; can be challenging to interpret, requires assumptions about error model, representation of process matrices, etc.

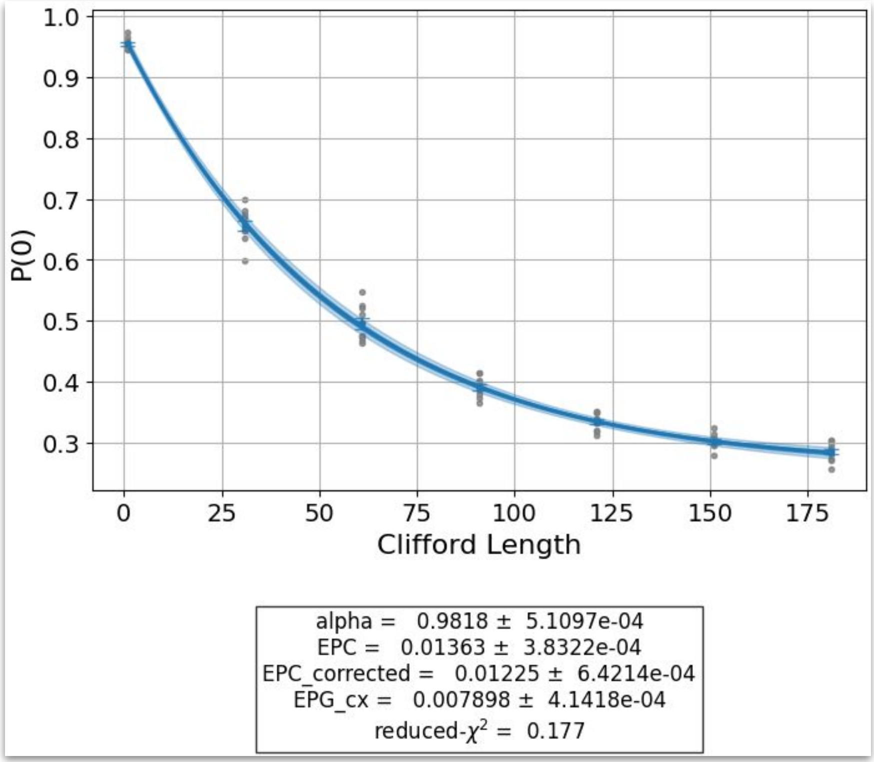



Image: https://qiskit-extensions.github.io/qiskit-experiments/manuals/verification/randomized_benchmarking.html

# Benchmarking quantum computers

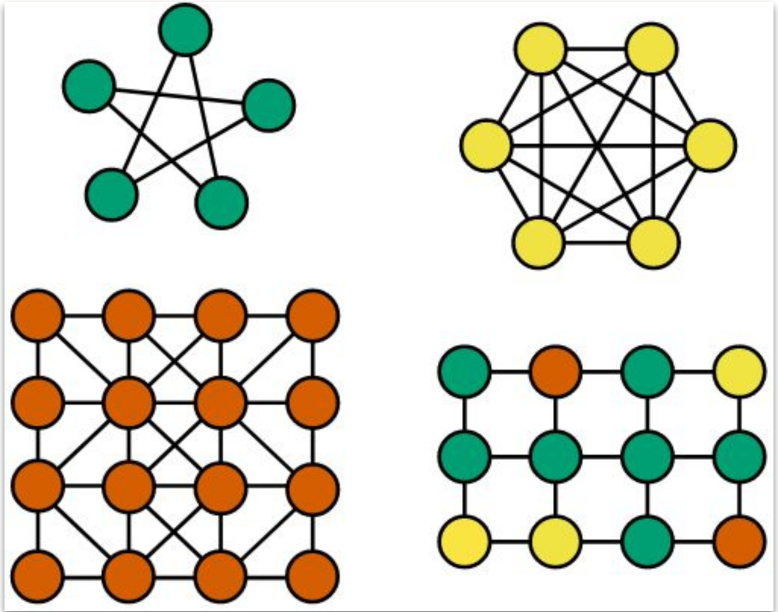


Image: https://pennylane.ai/qml/demos/quantum_volume/

# Benchmarking classical computers

TOP500 ranking

- Single-number (ish)
- Quantify speed for a specific task (LINPACK benchmark)
- List updated 2x/year

## TOP10 System - November 2023

$R_{max}$ and $R_{peak}$ values are in PFlop/s. For more details about other fields, check the TOP500 description.

$R_{peak}$ values are calculated using the advertised clock rate of the CPU. For the efficiency of the systems you should take into account the Turbo CPU clock rate where it applies.

| Rank | System | Cores | Rmax (PFlop/s) | Rpeak (PFlop/s) | Power (kW) |
|---|---|---|---|---|---|
| 1 | **Frontier** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE<br>DOE/SC/Oak Ridge National Laboratory<br>United States | 8,699,904 | 1,194.00 | 1,679.82 | 22,703 |
| 2 | **Aurora** - HPE Cray EX - Intel Exascale Compute Blade, Xeon CPU Max 9470 52C 2.4GHz, Intel Data Center GPU Max, Slingshot-11, Intel<br>DOE/SC/Argonne National Laboratory<br>United States | 4,742,808 | 585.34 | 1,059.33 | 24,687 |
| 3 | **Eagle** - Microsoft NDv5, Xeon Platinum 8480C 48C 2GHz, NVIDIA H100, NVIDIA Infiniband NDR, Microsoft<br>Microsoft Azure<br>United States | 1,123,200 | 561.20 | 846.84 | |

Image: https://www.top500.org/lists/top500/2023/11/

# Quantum volume

A **single-number** metric developed by IBM to quantify the quality of a full stack. Based on successful execution of random “square” circuits

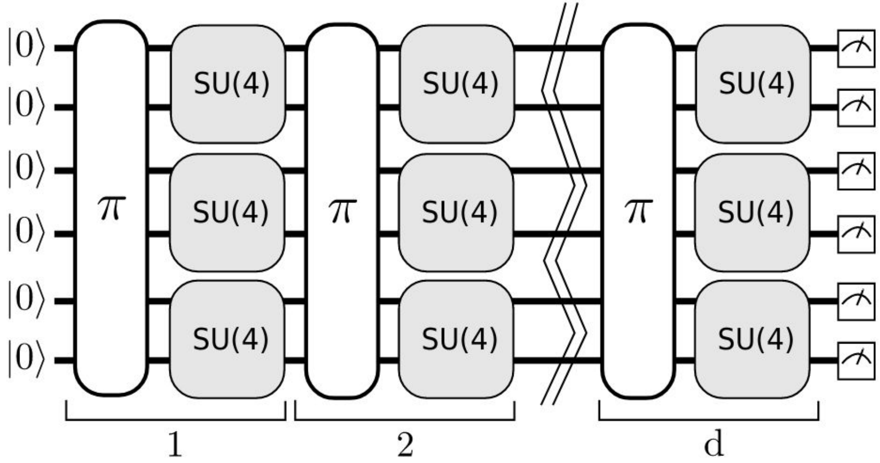



Image: Cross, A. W., Bishop, L. S., Sheldon, S., Nation, P. D., & Gambetta, J. M., Validating quantum computers using randomized model circuits, Physical Review A, 100(3), (2019).

# Quantum volume

Sampling from the distribution produced by random circuits must pass statistical test for “heavy output generation”.

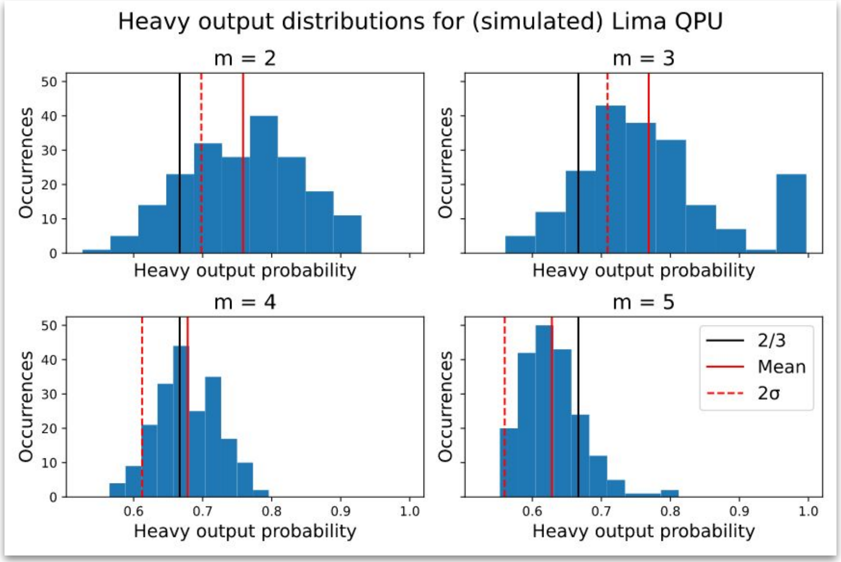
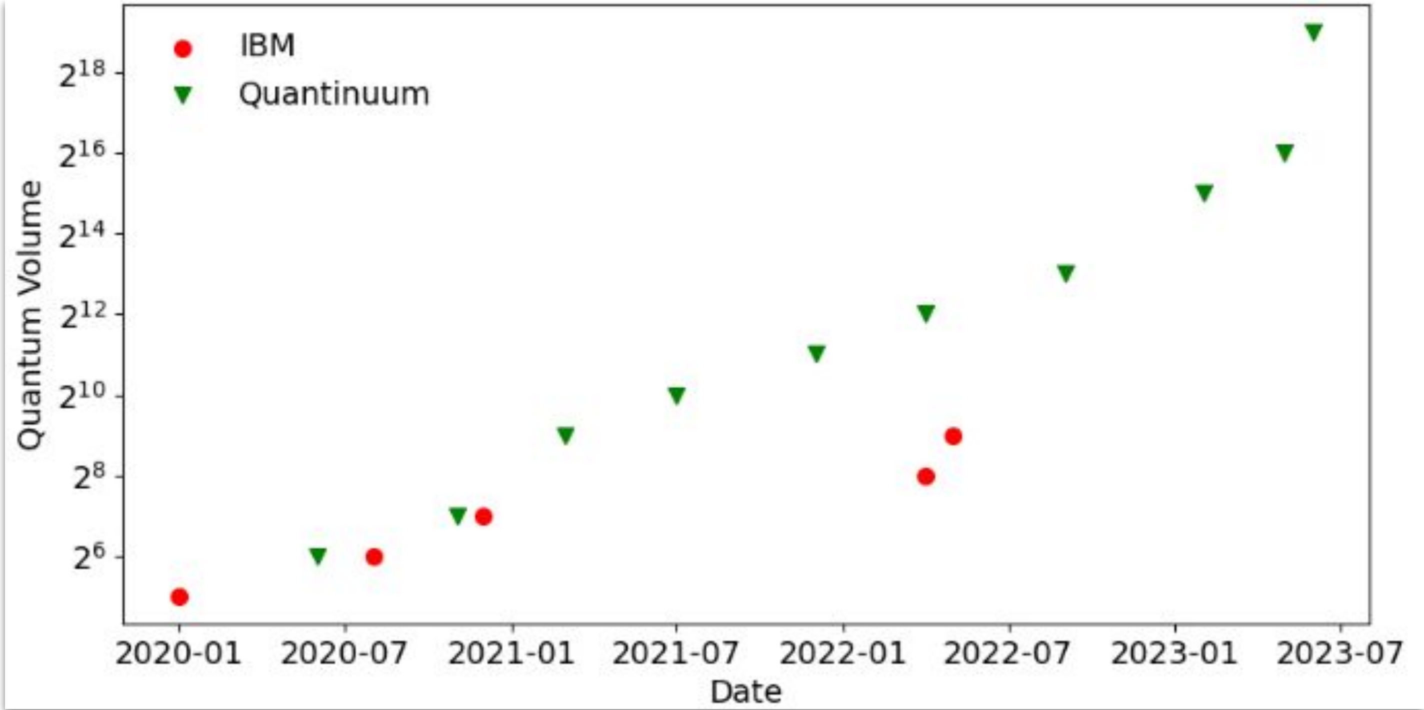



Image: https://pennylane.ai/qml/demos/quantum_volume/

# Quantum volume




Data source: https://en.wikipedia.org/wiki/Quantum_volume#Achievement_history.

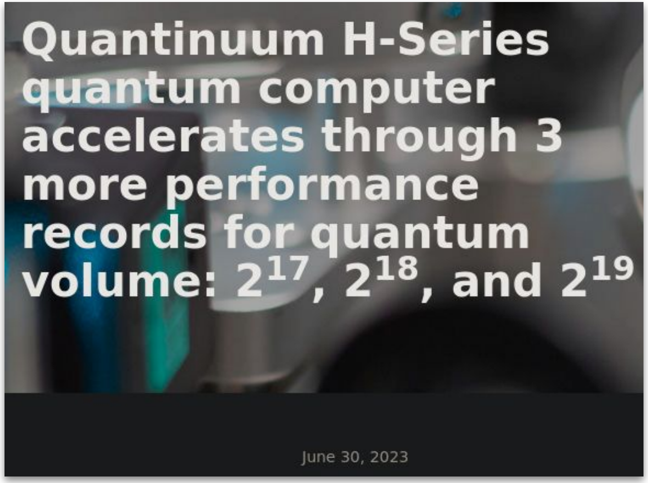
# Quantum volume

Pros:

- Captures software and compiler quality
- Established enough to be reported by multiple hardware types and providers*

Cons:

- Considers only “square” circuits
- Requires classical verification
- Circuits have no application-specific meaning




Headline: https://www.quantinuum.com/news/quantinuum-h-series-quantum-computer-accelerates-through-3-more-performance-records-for-quantum-volume-217-218-and-219

*See: https://en.wikipedia.org/wiki/Quantum_volume#Achievement_history

# Volumetric benchmarks

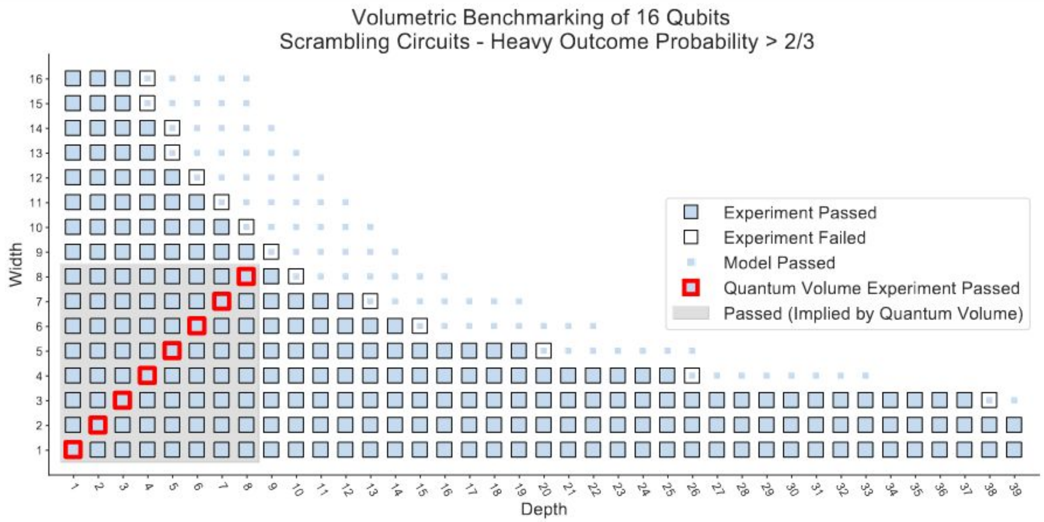



Figure 8(a). Volumetric benchmarking of a 16 qubit device using scrambling circuits. If at least 2/3 of the measurement results are heavy for a given width/depth pair, then the pair passes the test and is marked with a large, solid blue box. Using linear axes, the quantum volume experiments appear along the diagonal and are outlined with heavy, red lines. For this example, $\log_2(V_Q) = 8$. It is expected that scrambling circuits with both width and depth less than or equal to the quantum volume should succeed, and we highlight these with a gray background.

Image: R. Blume-Kohout and K. C. Young (2020) *A volumetric framework for quantum computer benchmarks*. Quantum 4, 362.

# Volumetric benchmarks: #AQ

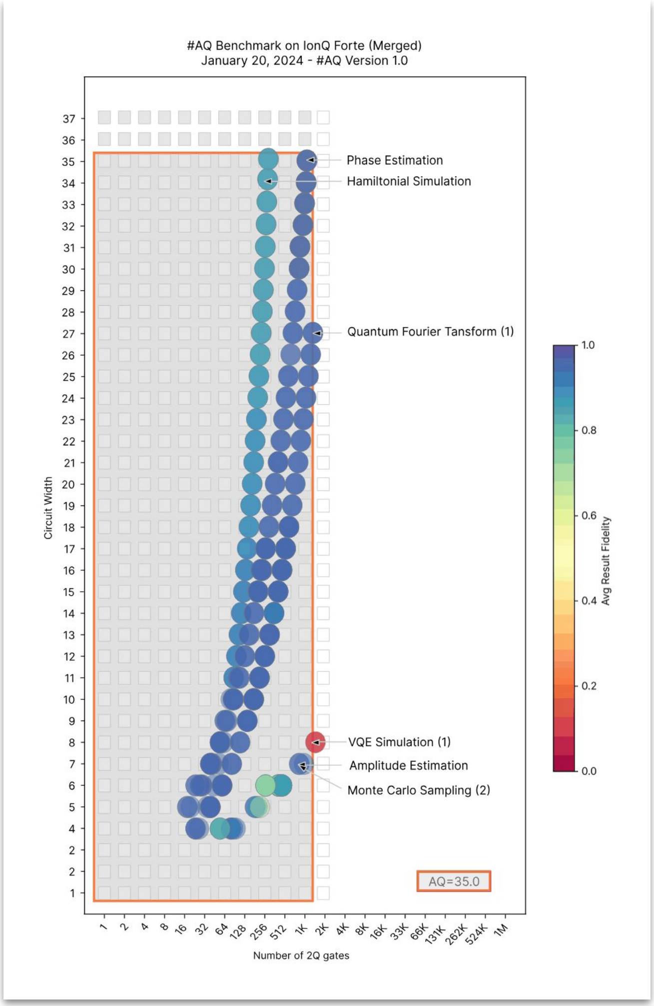
“Algorithmic qubits” proposed by IonQ based on application-specific benchmark suite developed by QED-C.

- Current record is 35 (IonQ)
- Recent jump from 29 -> 35 attributed to more (better) qubits *and compiler quality*

https://github.com/SRI-International/QC-App-Oriented-Benchmarks

https://ionq.com/algorithmic-qubits

Image: https://www.hpcwire.com/off-the-wire/ionq-surpasses-milestone-achieves-35-algorithmic-qubits-ahead-of-schedule/



# Other metrics

- Q-Score (size; based on solving MaxCut problem)
- CLOPS / QUOPS (speed)
- Layer fidelity (quality)
- Error-per-layered-gate (quality)
- …

Even if these numbers look high,

- Is the QC doing something *better* than a classical one?
- Is the QC doing something better that is also *useful*?
- How do we even quantify “better”?

# Quantum advantage

Article | Published: 23 October 2019

## Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, ... John M. Martinis + Show authors

*Nature* **574**, 505–510 (2019) | Cite this article

Article | Open access | Published: 01 June 2022

## Quantum computational advantage with a programmable photonic processor

Lars S. Madsen, Fabian Laudenbach, Mohsen Falamarzi. Askarani, Fabien Rortais, Trevor Vincent, Jacob F. F. Bulmer, Filippo M. Miatto, Leonhard Neuhaus, Lukas G. Helt, Matthew J. Collins, Adriana E. Lita, Thomas Gerrits, Sae Woo Nam, Varun D. Vaidya, Matteo Menotti, Ish Dhand, Zachary Vernon, Nicolás Quesada & Jonathan Lavoie

*Nature* **606**, 75–81 (2022) | Cite this article

## Quantum computational advantage using photons

HAN-SEN ZHONG, HUI WANG, YU-HAO DENG, MING-CHENG CHEN, LI-CHAO PENG, YI-HAN LUO, JIAN QIN, DIAN WU, XING DING, YI HU, PENG HU, XIAO-YAN YANG, WEI-JUN ZHANG, HAO LI, YUXUAN LI, XIAO JIANG, LIN GAN, GUANGWEN YANG, LIXING YOU, ZHEN WANG, LI LI, NAI-LE LIU, CHAO-YANG LU, AND JIAN-WEI PAN fewer Authors Info & Affiliations

SCIENCE • 3 Dec 2020 • Vol 370, Issue 6523 • pp. 1460-1463 • DOI: 10.1126/science.abe8770

Article | Open access | Published: 14 June 2023

## Evidence for the utility of quantum computing before fault tolerance

Youngseok Kim, Andrew Eddins, Sajant Anand, Ken Xuan Wei, Ewout van den Berg, Sami Rosenblatt, Hasan Nayfeh, Yantao Wu, Michael Zaletel, Kristan Temme & Abhinav Kandala

*Nature* **618**, 500–505 (2023) | Cite this article

# Moving target…

Article | Open access | Published: 14 June 2023

**Evidence for the utility of quantum computing before fault tolerance**

Youngseok Kim, Andrew Eddins, Sajant Anand, Ken Xuan Wei, Ewout van den Berg, Sami Rosenblatt, Hasan Nayfeh, Yantao Wu, Michael Zaletel, Kristan Temme & Abhinav Kandala

*Nature* **618**, 500–505 (2023) | Cite this article

**Fast and converged classical simulations of evidence for the utility of quantum computing before fault tolerance**

TOMISLAV BEGUŠIĆ, JOHNNIE GRAY, AND GARNET KIN-LIC CHAN Authors Info & Affiliations

*SCIENCE ADVANCES* · 17 Jan 2024 · Vol 10, Issue 3 · DOI: 10.1126/sciadv.adk4321

# Terminology

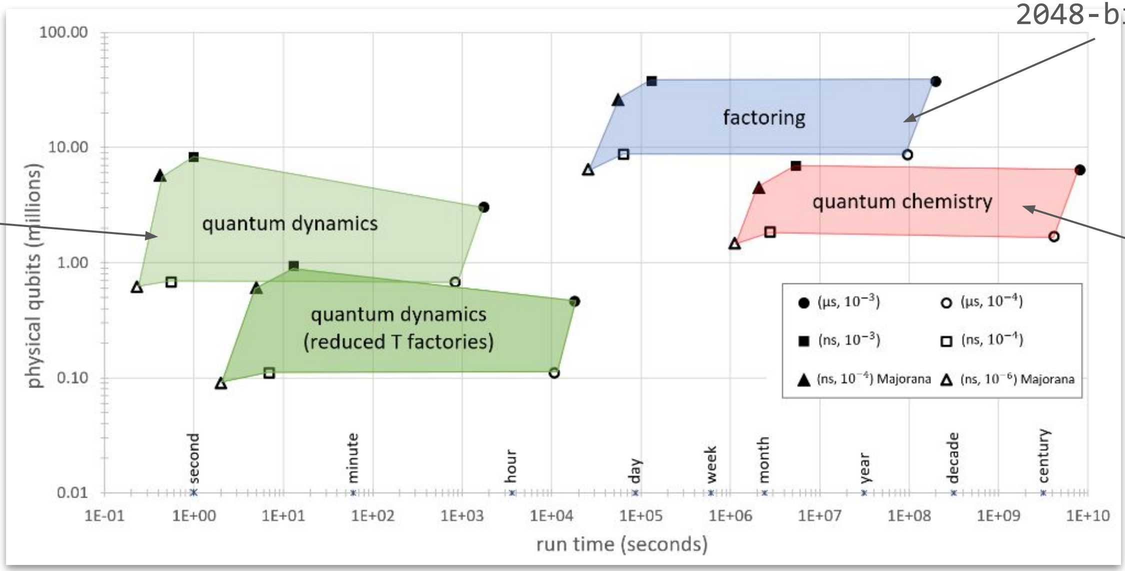
Quantum computational advantage

Practical quantum advantage

Quantum utility

# Resource estimates

2D Ising model, 100 spins, 10 timesteps 4th-order Trotter




2048-bit integer

energy of ruthenium-based catalyst for carbon fixation (qubitization)

Image (Microsoft Quantum team): M. E. Beverland et al., *Assessing requirements to scale to practical quantum advantage*. arXiv 2211.07629 [quant-ph].

# Error-correction and fault-tolerance

Need **error correction** to perform computations reliably even with noisy qubits.

- Many physical qubits work together as a **logical qubit**
- Huge overhead
- Starting to see small demonstrations
- New software challenges

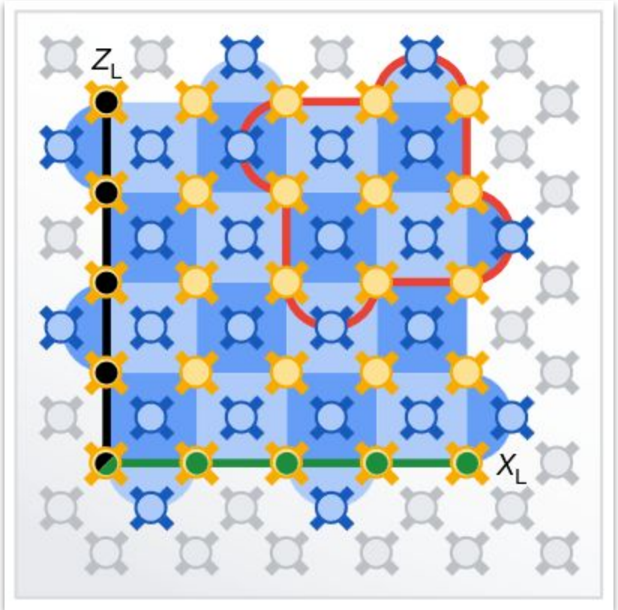
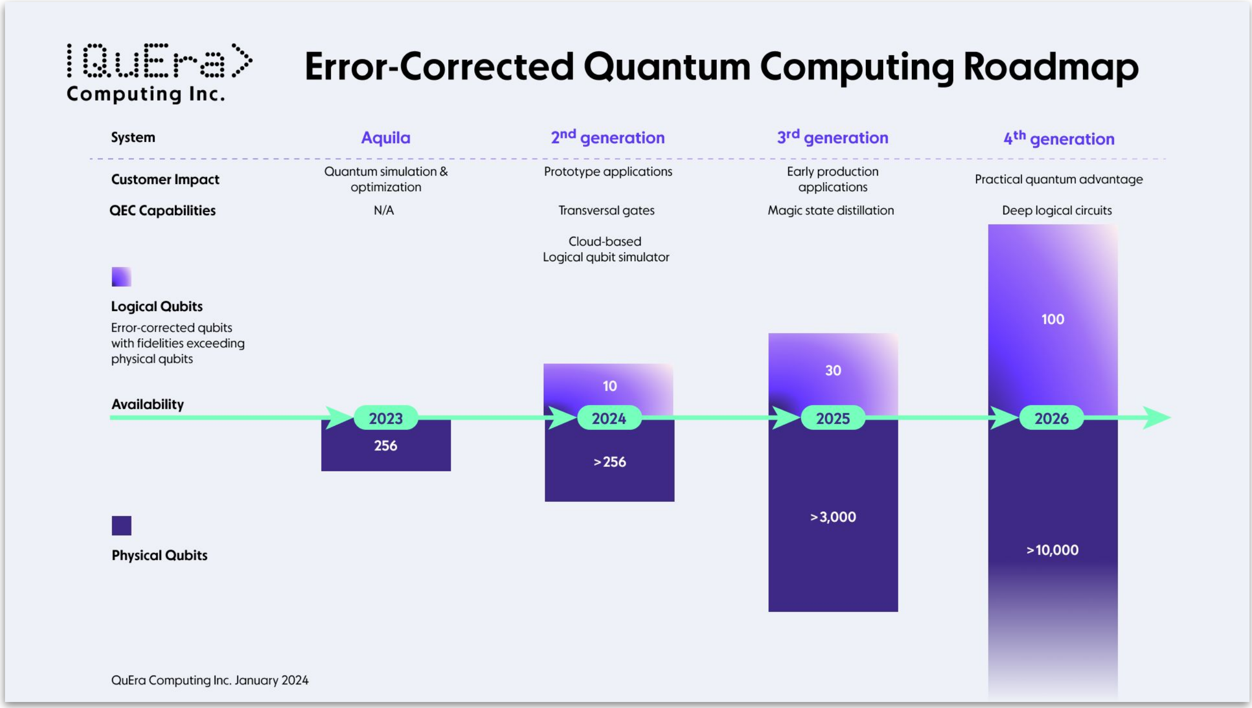


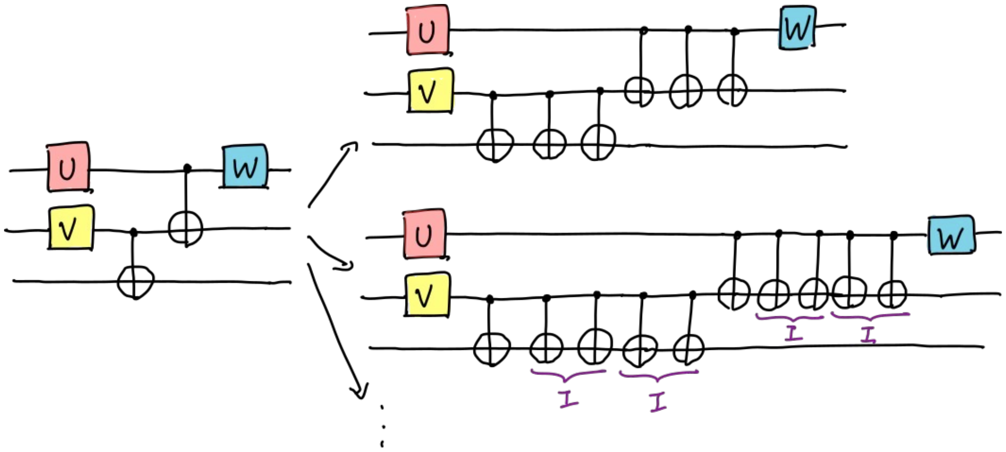

Image: Google Quantum AI, *Suppressing quantum errors by scaling a surface code logical qubit*. Nature 614, 6760681 (2023).

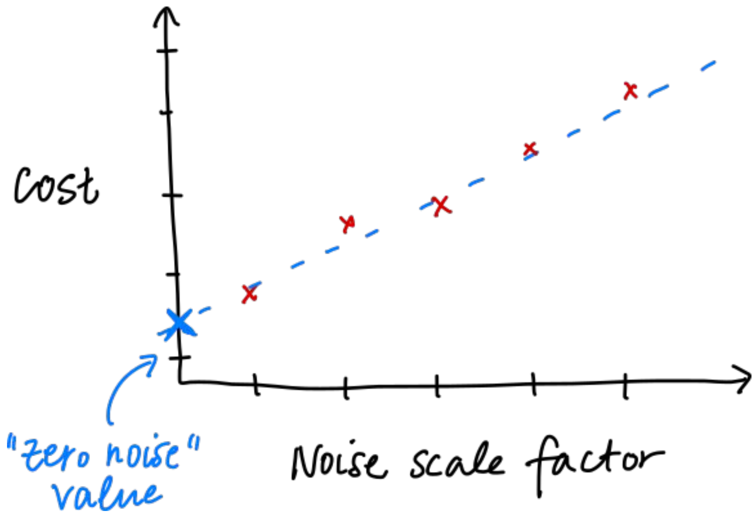
# Error-correction and fault-tolerance



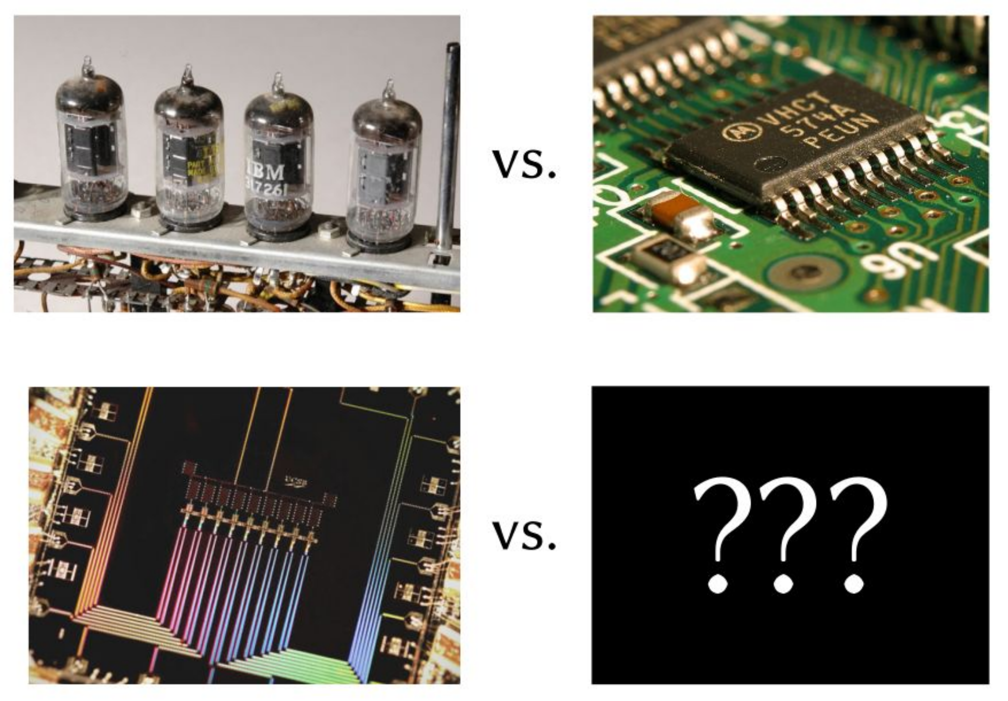
# Near-term solution: error mitigation

Example: Zero-noise extrapolation (ZNE). Also adds overhead, but of a different nature.



# Early days




Images:
https://hubpages.com/business/What-Is-a-Transistor-and-Why-is-it-Important
https://en.wikipedia.org/wiki/Solid-state_electronics
https://physicsworld.com/a/google-gains-new-ground-on-universal-quantum-computer/ (Google 9-qubit processor)

# Early days

ENIAC

(ca. 1945)

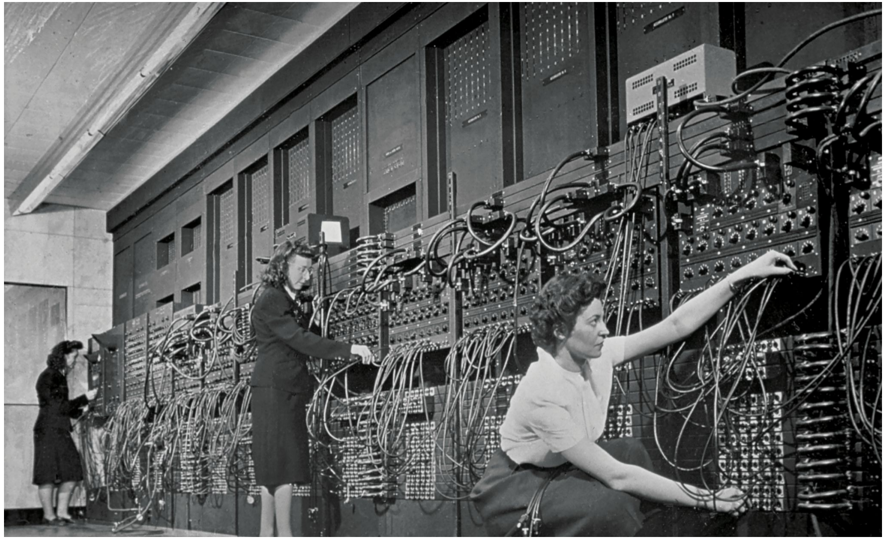


Image:

https://www.nytimes.com/2019/02/13/magazine/women-coding-computer-programming.html

IBM Q System One

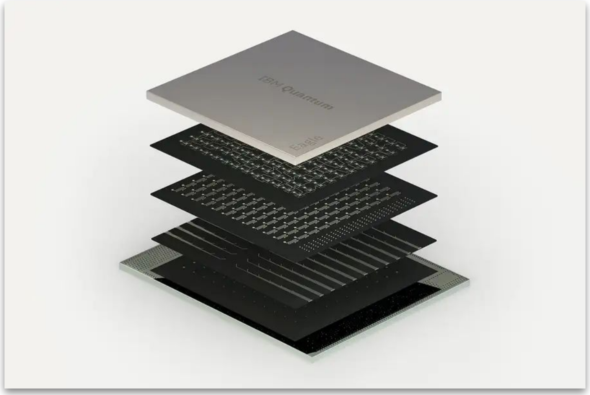
(ca. 2019)


Image: IBM Research

https://spectrum.ieee.org/when-will-quantum-computing-have-real-commercial-value

# Final thoughts

- It is an exciting time in quantum computing!
- We are starting to see demonstrations of fault-tolerance and simulations thought classically intractable
- **There is a lot of work to do improving hardware AND software**



```python
def ansatz_180_custom(params):
    qml.PauliX(wires=0)
    qml.PauliX(wires=1)

    qml.RY(params[0], wires=3)

    for param_idx, init_wire in enumerate(range(3, 10, 2)):
        qml.RY(-params[param_idx+1]/2, wires=init_wire+2)
        qml.CNOT(wires=[init_wire, init_wire+2])
        qml.CNOT(wires=[init_wire, init_wire-1])
        qml.RY(params[param_idx+1]/2, wires=init_wire+2)
        qml.CNOT(wires=[init_wire, init_wire+2])

    qml.CNOT(wires=[11, 10])

    for qubit_idx in range(2, 12):
        qml.CNOT(wires=[qubit_idx, qubit_idx-2])
```

Image: IBM Eagle quantum processor.
https://www.newscientist.com/article/2378229-ibm-quantum-computer-beat-a-supercomputer-in-a-head-to-head-test/