

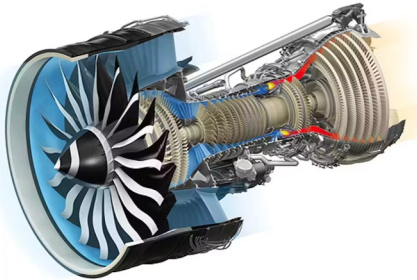
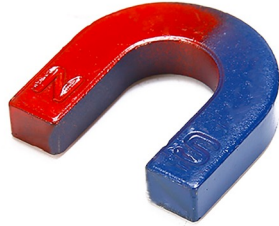


Prospects, applications and challenges for industrial AI's impact of quantum computing

Ryan Babbush
Head of Quantum Algorithms (Google)
Stanford EE392b
May 23, 23



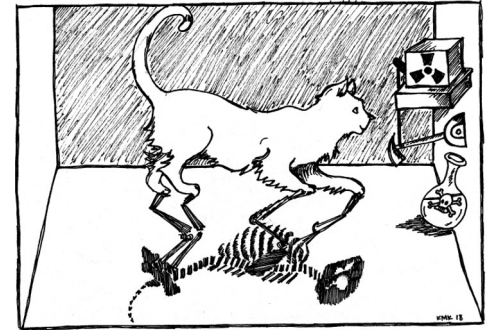
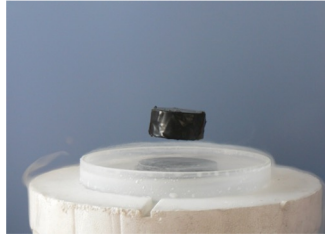
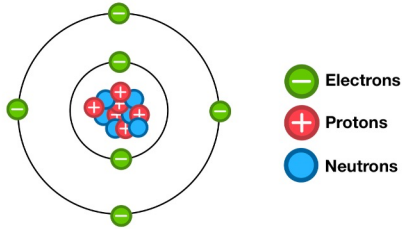
Classical physics



$$F = ma$$

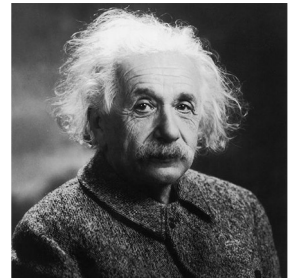
Quantum physics

Quantum things are very small or very cold, or both



The weird physics describing quantum systems has been settled for ~100 years, and is among the most tested and accurate scientific achievements

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$



Simulating “quantum” on “classical” computers is hard



10 CPU ns

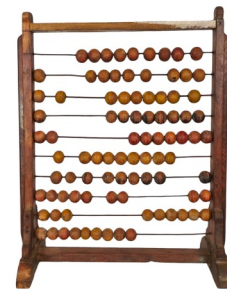


25 CPU ns

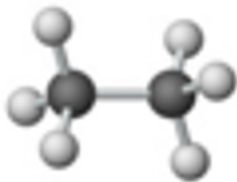


45 CPU ns

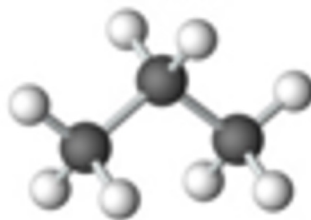
$O(\text{poly}(n))$
e.g. n^2



CPU seconds



CPU minutes



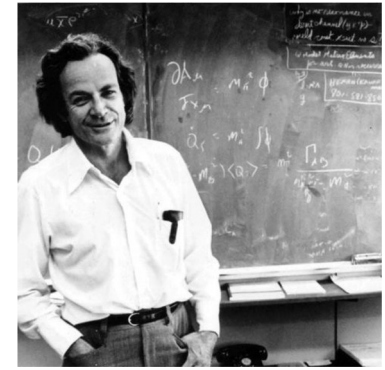
CPU days

$O(\text{exp}(n))$
e.g. 2^n



“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical.”

- **Richard Feynman, 1982**



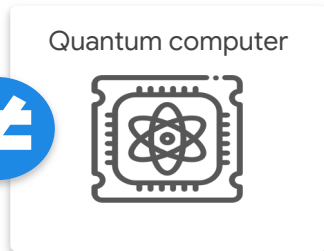
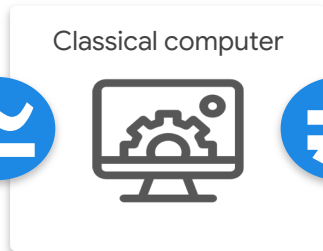
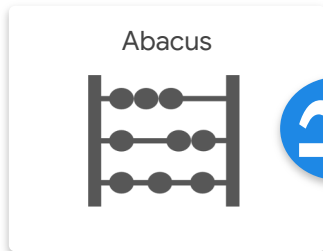
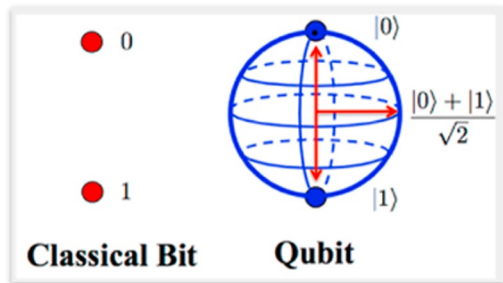
Quantum computing: rather than surrender to the complexity of quantum mechanics, harness it as a resource!

1994: Peter Shor proves quantum computers can efficiently find prime factors, breaking most widely used public key encryption



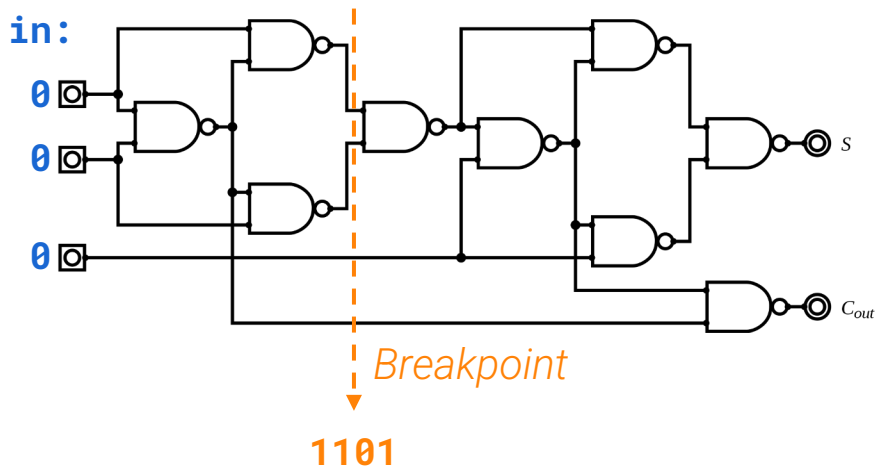
Quantum computers replace Boolean logic with the laws of quantum mechanics

- “Qubits” are quantum bits
- A **richer set of operations** becomes available using generalized logic and probability
- Certain computations can be performed **exponentially faster**
- Quantum processors are **co-processors** that accelerate some calculations but not others



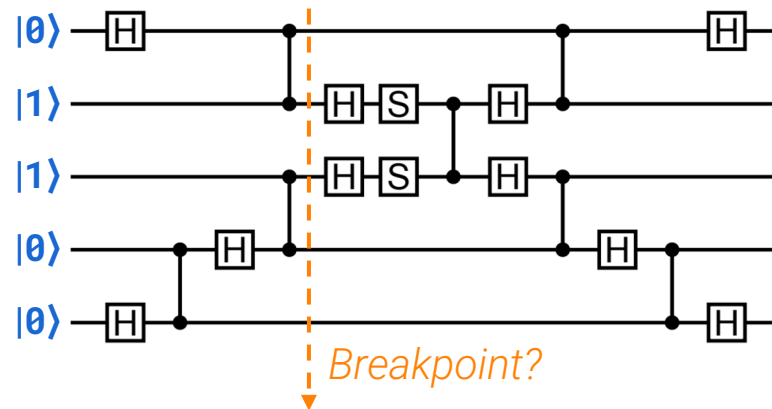
Quantum circuits, briefly

“Classical” digital logic



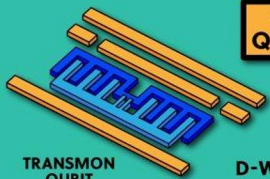
Quantum logic

in:



$$|01100\rangle + |01101\rangle - |01110\rangle - |01111\rangle - |11100\rangle - |11101\rangle + |11110\rangle + |11111\rangle$$

SUPERCONDUCTING QUANTUM COMPUTERS



TRANSMON QUBIT

IBM 127

GOOGLE 53

UST OF CHINA 56

D-WAVE (QUANTUM ANNEALING) 5760

INTEL 49

QUTECH

ALIBABA QUANTUM LABORATORY 11

RIGETTI 80

QUANTUM CIRCUITS

BLEXIMO

SEEQC

OXFORD QUANTUM CIRCUITS

ALICE & BOB

QUANTWARE

ORIGIN QUANTUM

IQM QUANTUM COMPUTERS

AMAZON

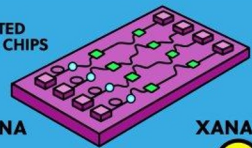
NORTHROP GRUMMAN

RAYTHEON BBN

COMPANY QUBIT COUNTS JAN 2022

UNIVERSAL QC / NOT UNIVERSAL QC

OPTICAL QUANTUM COMPUTERS



INTEGRATED PHOTONICS CHIPS

UST OF CHINA 113 (NUMBER OF PHOTONS IN A BOSON SAMPLER)

XANADU 40

PSIQUANTUM

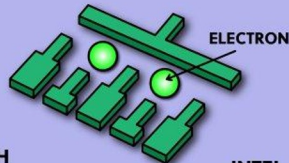
QUIX QUANTUM

ORCA COMPUTING

QUANDELA

QUANTUM DOT QUANTUM COMPUTERS

ALSO SILICON SPIN QUANTUM COMPUTERS



ELECTRONS

QUTECH

CEA-LETI

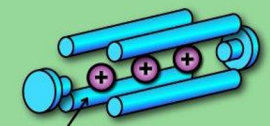
HRL LABORATORIES

RIKEN CENTER FOR QUANTUM COMPUTING

INTEL

PHOTONIC QUANTUM MOTION

TRAPPED ION QUANTUM COMPUTERS



IONISED ATOMS TRAPPED IN ELECTRIC FIELDS

QUANTINUM 12

IONQ 32

OXIONICS

ALPINE QUANTUM TECHNOLOGIES 24

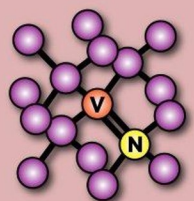
UNIVERSAL QUANTUM

INFINEON

OXFORD IONICS

QSCOUT

COLOUR CENTRE QUANTUM COMPUTERS



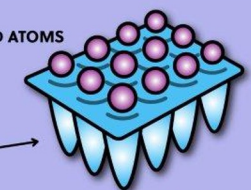
QUTECH

SQC

QUANTUM BRILLIANCE 2

INTERNATIONAL IBERIAN NANOTECH LAB

NEUTRAL ATOMS IN OPTICAL TWEezer ARRAY



TRAPPED ATOMS

TWEezer ARRAYS

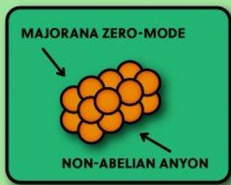
COLDQUANTA 100

ATOM COMPUTING 100

PASQAL 200 (QUANTUM SIMULATOR NUMBER OF ATOMS)

QUERA 256 (QUANTUM SIMULATOR NUMBER OF ATOMS)

TOPOLOGICAL QUANTUM COMPUTERS




MAJORANA ZERO-MODE

NON-ABELIAN ANYON

MICROSOFT

QUTECH

ELECTRON-ON-HELIUM QUANTUM COMPUTERS



EEROQ 1

QISKIT (IBM)

CIRQ (GOOGLE QUANTUM AI)

Q# (MICROSOFT)

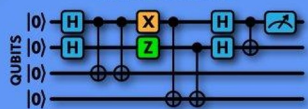
PENNYLANE (XANADU)

SOFTWARE PACKAGES

PYQUIL (RIGETTI)

NON-HARDWARE QUANTUM COMPANIES

SOFTWARE TOOLS, RESEARCH AND APPLICATIONS



QUBITS

QUANTINUM

RIVERLANE

MULTIVERSE COMPUTING

HEISENBERG QUANTUM SIMULATIONS

BLUEQAT

BAIDU

PHASECRAFT

QU & CO

CLASSIQ

ZAPATA COMPUTING

1QUBIT

QSIMULATE

KEYSIGHT Q

QUBITOR LABS

HORIZON

QUNASYS

QC WARE

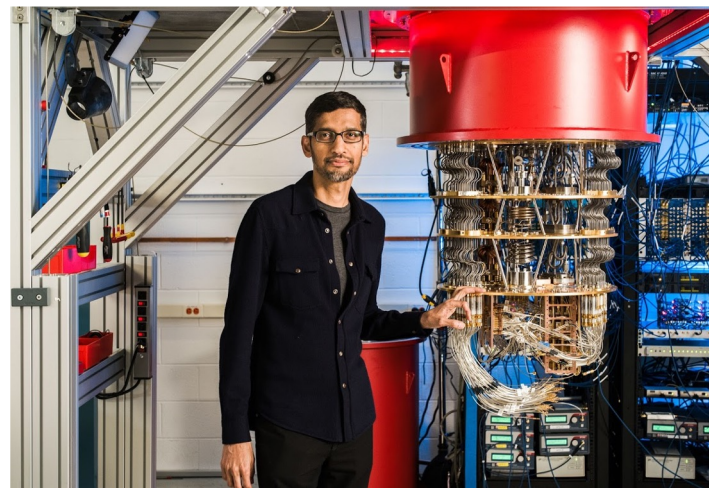
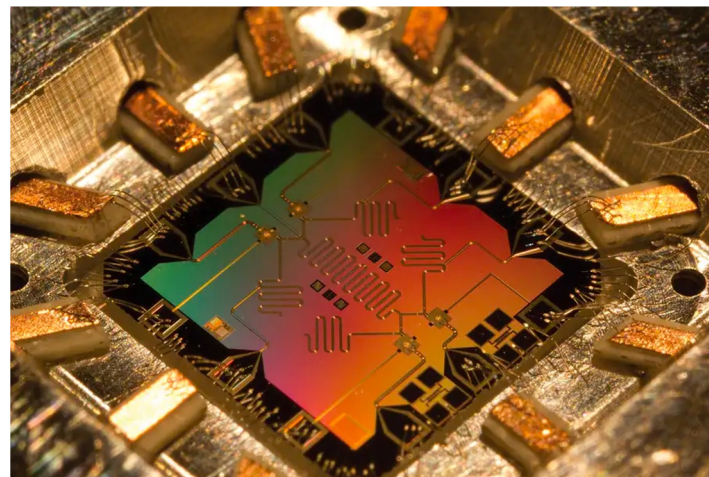
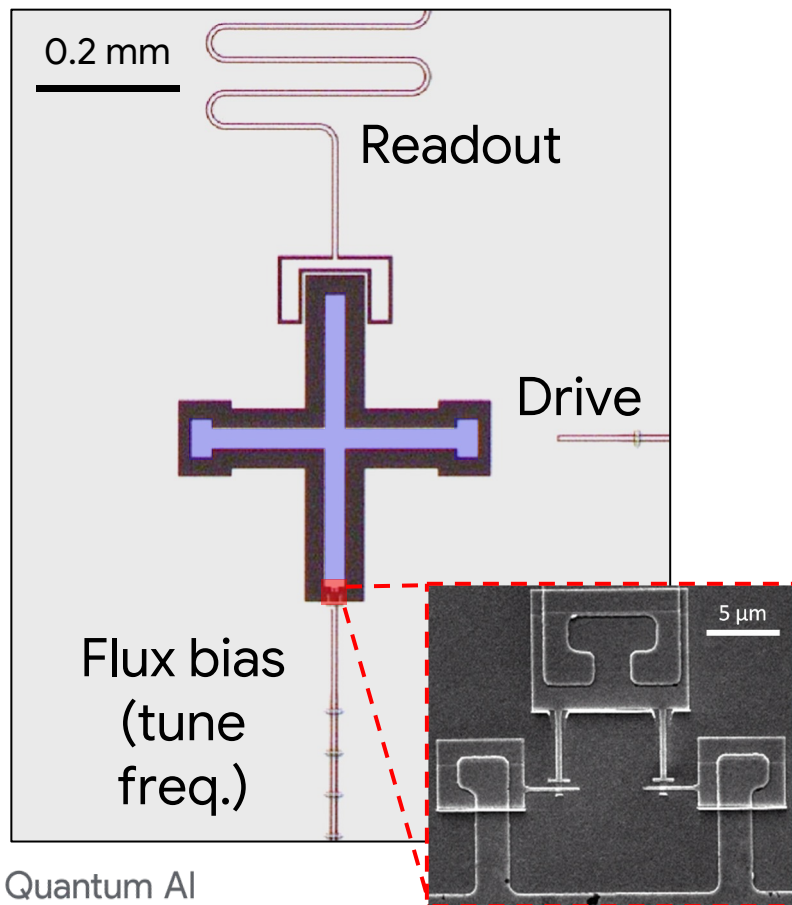
ENTROPICA LABS

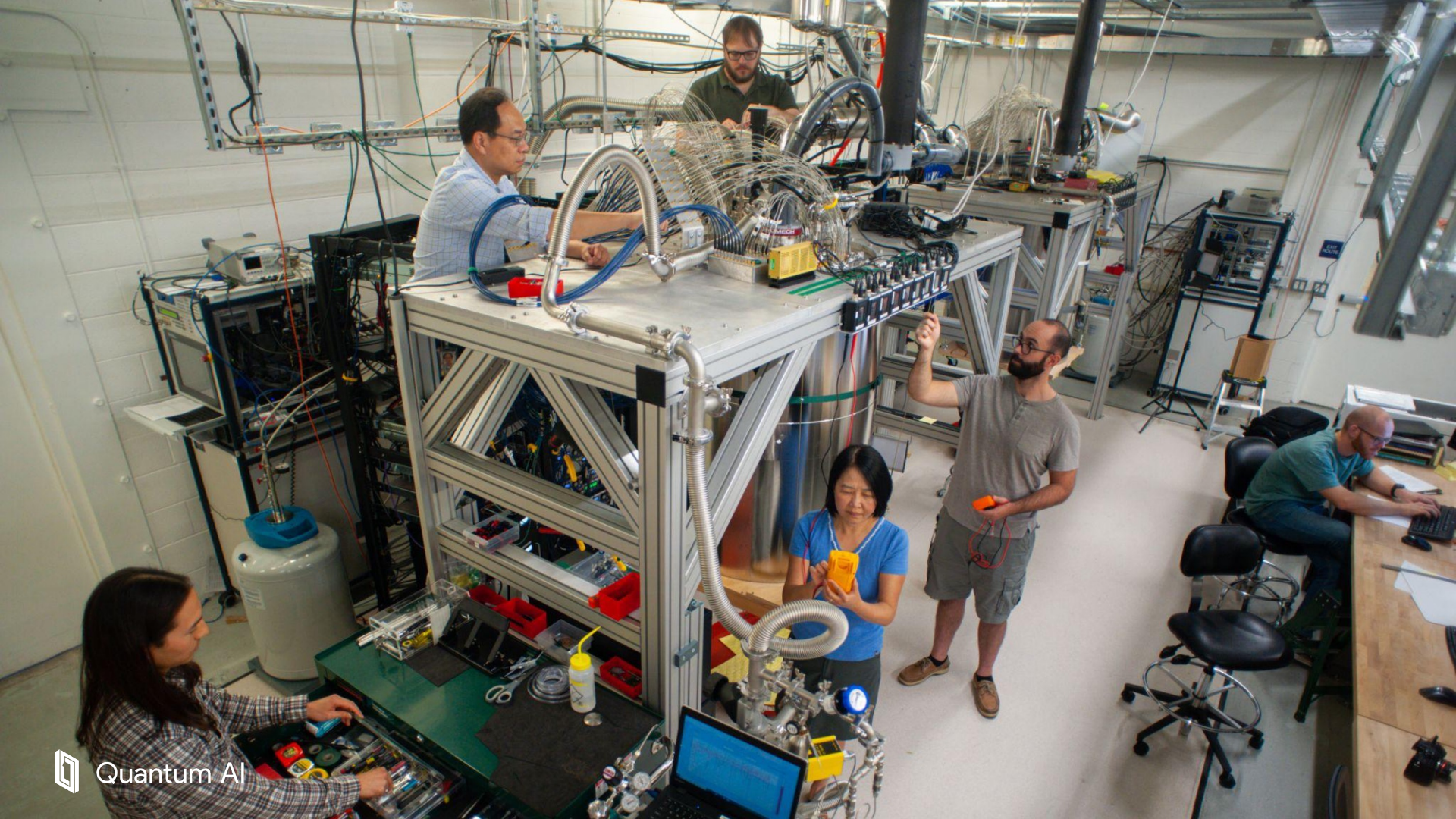
STRANGEWORKS

ATOS

PARITY QC

Google's qubits, briefly





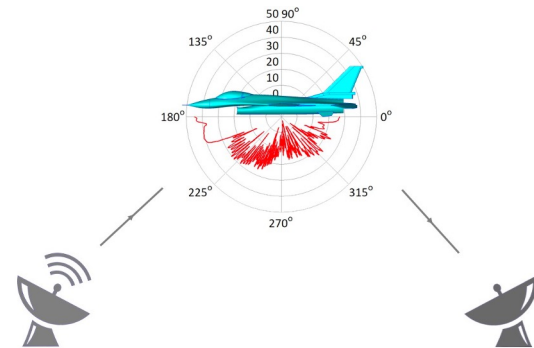
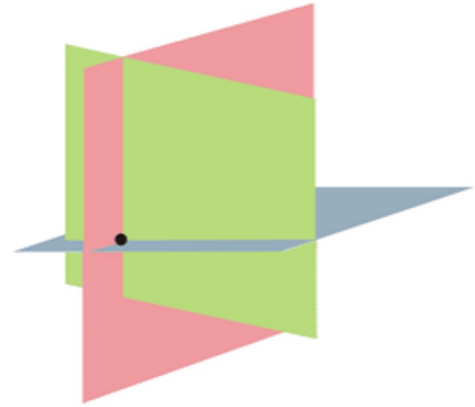
Exponential quantum speedups are not generic

- Quantum computers can perform computation on all possible inputs to a problem at once (quantum parallelism)
- But reading out the result of all those computations would take exponential time!
- The art of quantum algorithms is to take advantage of some special structure in the problem to engineer interference which amplifies the solution
- Otherwise only quadratic speedup possible
- Shor's algorithm factors N by finding "period" of $f(x) = x^r \bmod N$ - a "wavelike property"



Quantum linear algebra and the I/O problem

- Quantum computers can solve systems of N linear equations ($A \mathbf{x} = \mathbf{b}$) “querying” A only $O(\log(N))$ times 😊
- But sometimes each query to A takes time $O(\text{poly}(N))$ 😞
- Focus on problems where linear system has underlying structure, e.g., physically inspired linear differential equations
- Promising applications include mechanical engineering models, acoustic or electromagnetic scattering, fluid dynamics, electrical grid modeling
- **I/O problem severely limits quantum speedups for “big data”; instead focus on easy-to-specify yet hard-to-solve problems**



Two paradigms: NISQ vs fault-tolerance

Every quantum gate fails with a fixed probability such that even the best devices today can only execute quantum circuits comprised of a few thousand gates

Using these devices today is called NISQ: “noisy intermediate scale quantum”

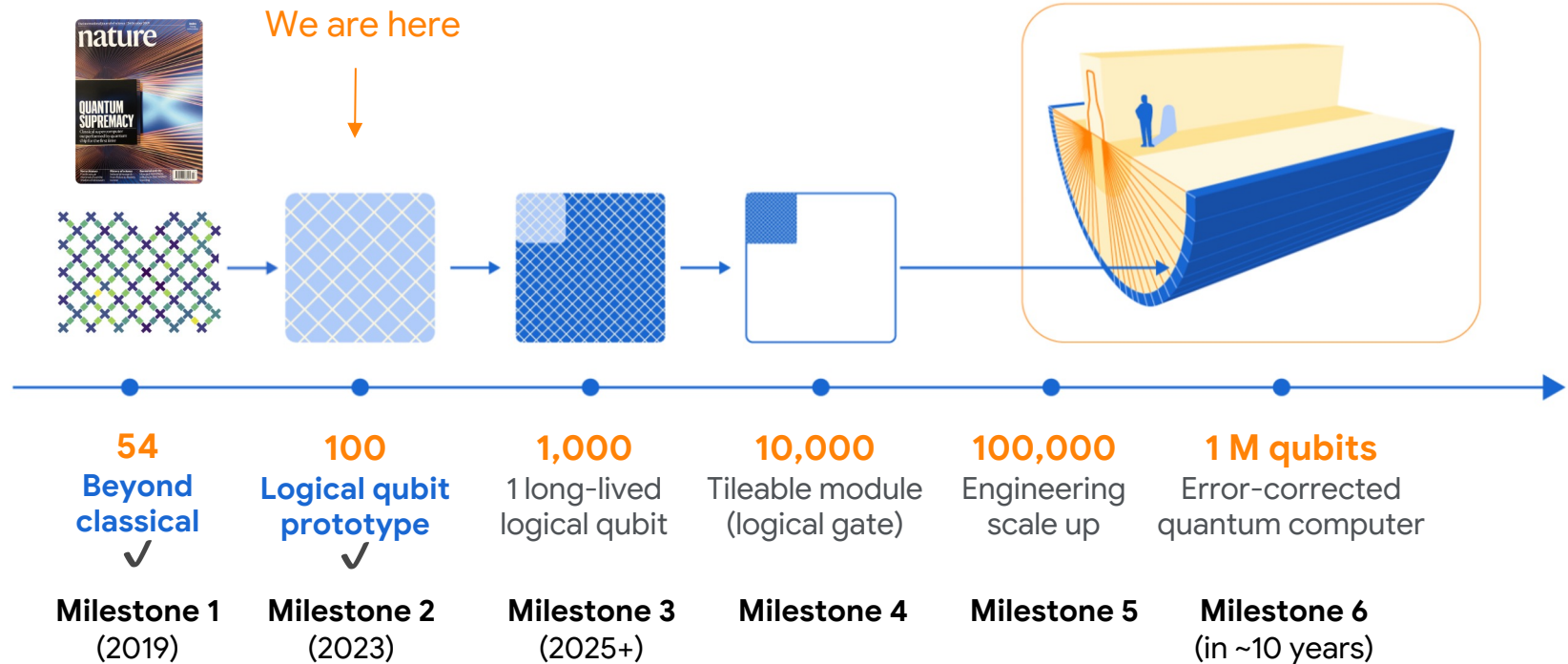
Most quantum algorithms with provable exponential speedup on valuable problems have millions or billions of gates, require “fault-tolerance”

At today’s error rates, about 1k “physical qubits” required for each “logical qubit”

Most NISQ algorithms, like most modern ML algorithms, are heuristics

Most heuristics are honed empirically, not proven with pencil/paper

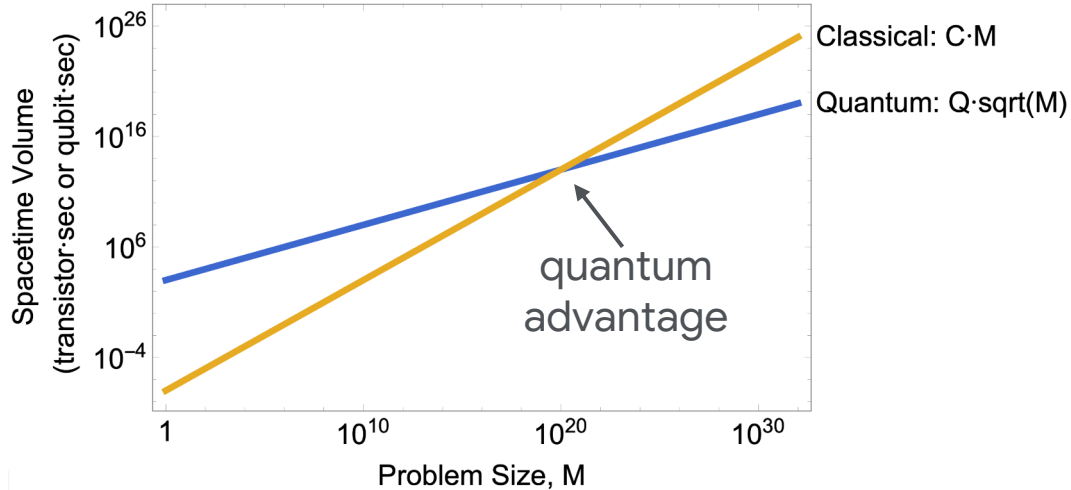
Google's roadmap towards practical quantum computing



Quadratic speedups not practical due to QEC overhead

There are a huge number of possible applications with quadratic speed up: unstructured search, optimization, mean-value estimation, sampling, etc.

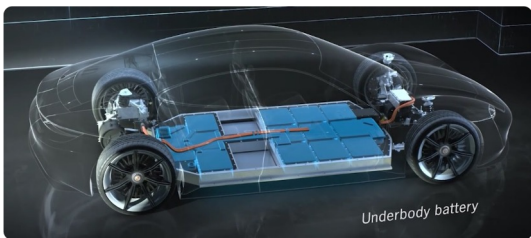
classical scales as $C * M$
quantum scales as $Q * \text{sqrt}(M)$
for QEC assume $Q / C \sim 10^{10}$



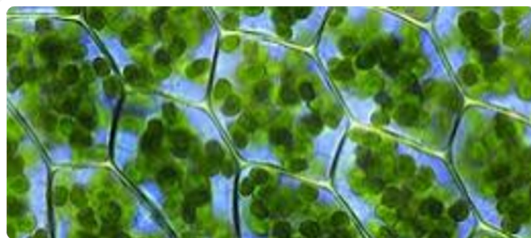
- for exponential speedups constant factor slowdown is easily overcome but for small (e.g., quadratic) polynomial speedups, it is not
- this suggests that practical quantum advantage is likely to happen only for problems with super-quadratic speedups in the next couple decades

Efficient quantum simulation promises significant industrial impact

Many valuable scientific problems come down to classically intractable quantum simulations



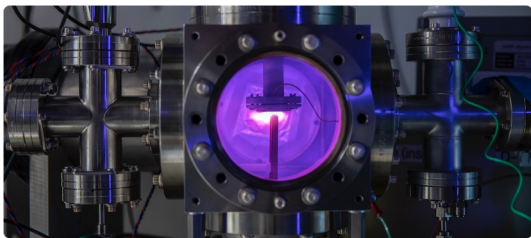
Lightweight batteries



Efficient solar cells



Low-loss power transmission



Nuclear fusion



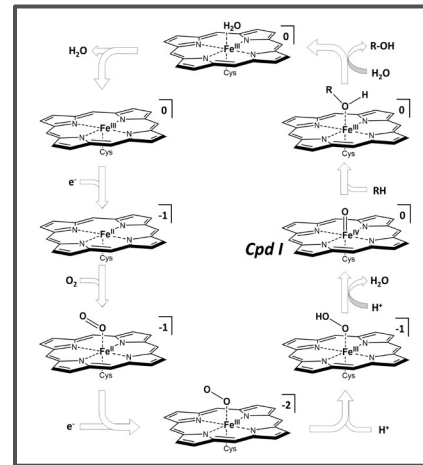
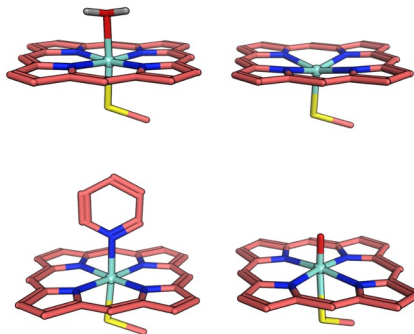
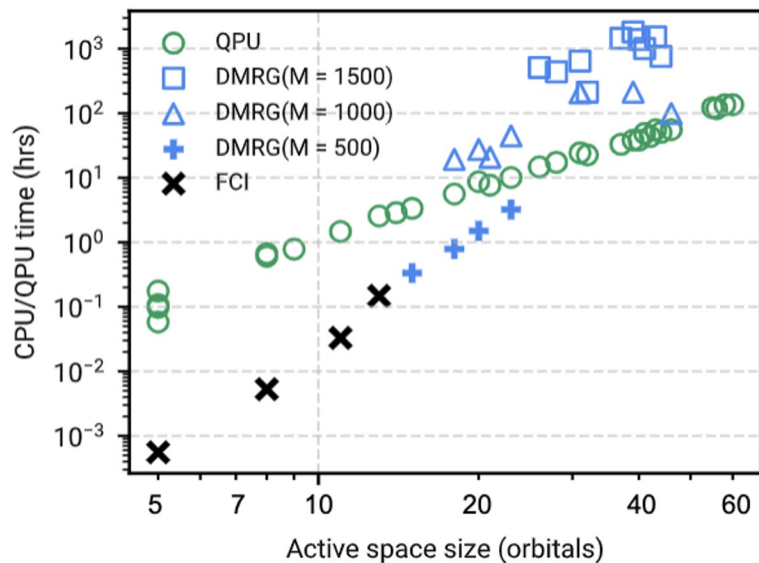
Industrial catalysts



Efficient fertilizer production

Assessing quantum/classical boundary for P450

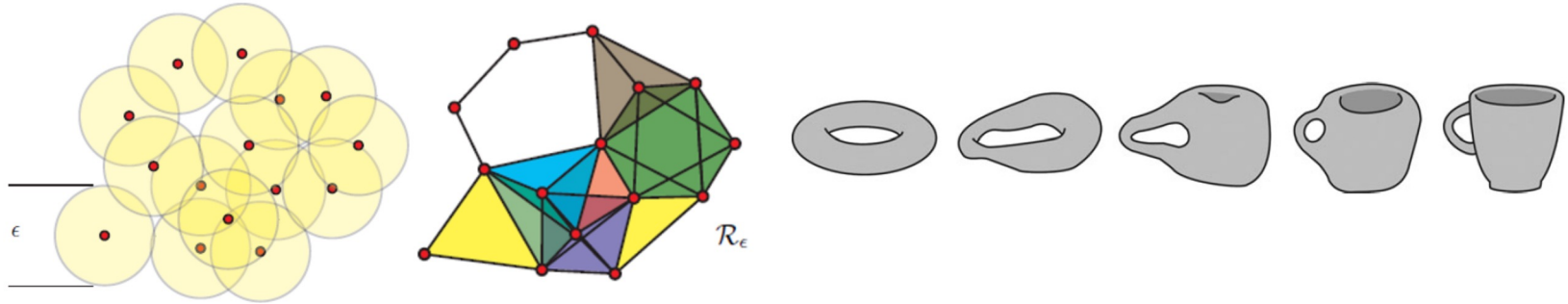
P450 is notoriously difficult-to-simulate
classical drug anti-target



We observe onset of quantum advantage for
active space sizes near 80 qubits

Example fault-tolerant application: topological data analysis

- Topological features (especially in high dimensions) are considered “fundamental” global properties, believed to be robust to high amounts of noise in the data set
- Given n data points, make a graph G with data points as nodes, with edges between points wherever the points are within some distance ϵ

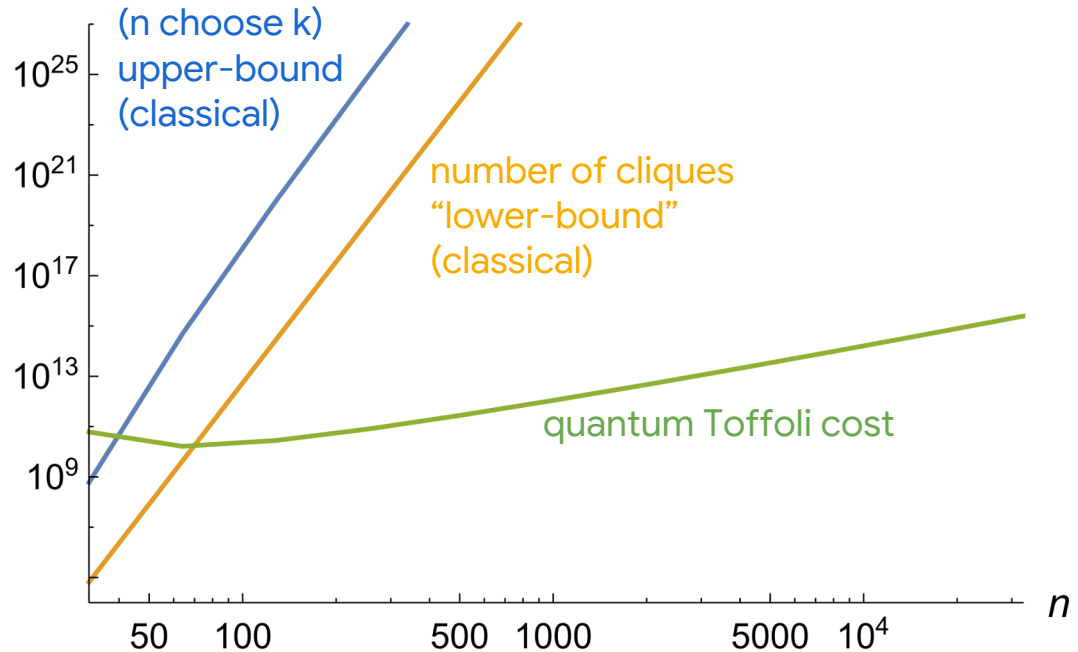


- The k^{th} order Betti number (β_k) is the number of k -dimensional holes in the simplicial complex
- Real world applications of this in neuroscience, epidemiology, genetics, finance, even physics



Speedup of quantum topological data analysis

- We are able to show examples of the problem where quantum has superpolynomial speedup
- Random instances (perhaps evocative of real applications) have quartic speedup
- More work required to say how impactful this will really be

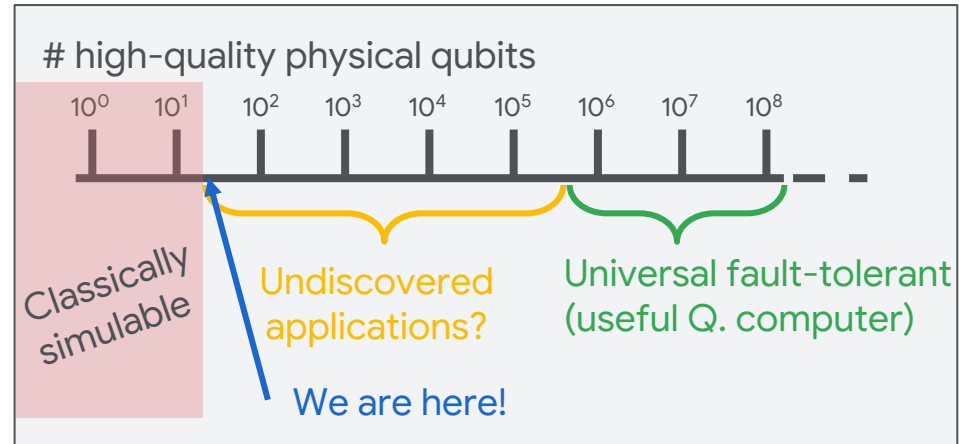
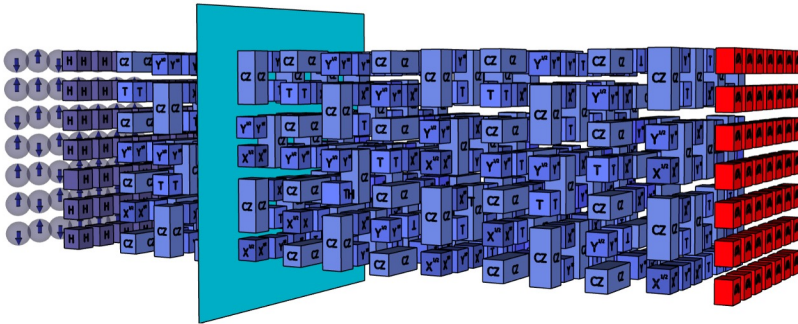


Quantum computers today

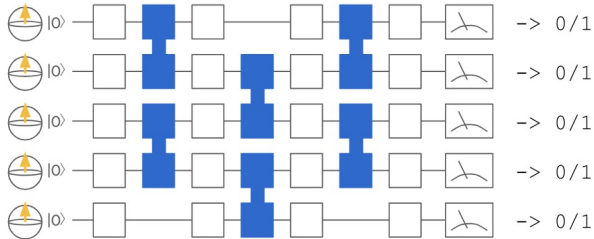
We are in the age of noisy intermediate scale (NISQ) quantum devices

We can run circuits on 50-100 qubits but errors severely limit circuit size

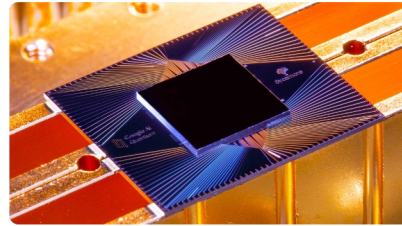
In 2019 Google team demonstrated beyond classical computation i.e., we used our 54 qubit quantum computer to perform a well defined computational task that (was then) intractable on a classical computer



A computational race



**Benchmark
computational task**



Quantum processor



**200
seconds**



Classic supercomputer



**10,000
years**

Realistic runtime estimates (arXiv:2304.11119)

Exp.	1 amp.	1 million noisy samples		
	FLOPs	FLOPs	XEB fid.	Time
SYC-53 [1]	$6.44 \cdot 10^{17}$	$1.12 \cdot 10^{18}$	$2.24 \cdot 10^{-3}$	26.5 s
ZCZ-56 [12]	$1.6 \cdot 10^{19}$	$1.37 \cdot 10^{20}$	$6.62 \cdot 10^{-4}$	54.1 min
ZCZ-60 [13]	$6.3 \cdot 10^{20}$	$9.92 \cdot 10^{22}$	$3.66 \cdot 10^{-4}$	27.3 days
This work	$4.8 \cdot 10^{23}$	$8.97 \cdot 10^{26}$	$1.68 \cdot 10^{-3}$	676 yr

Frontier (DOE):

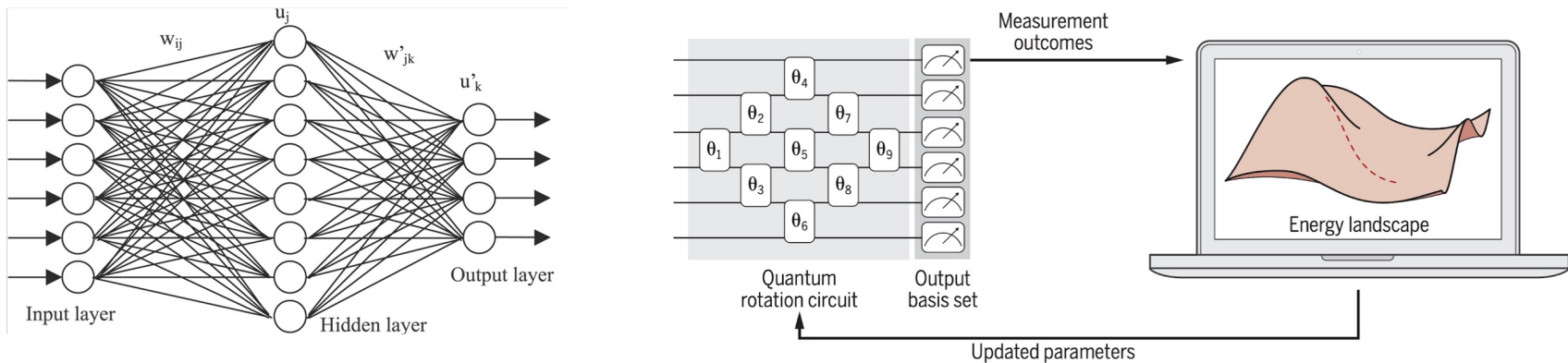
- Exascale GPU supercomputers $> 10^{18}$ FLOPS
- 20% FLOP efficiency

Highly optimized, but still exponential scaling with qubits x depth

The prototypical NISQ heuristic: quantum variational algorithms

We can prepare extremely complex quantum states on existing hardware
But how do we make relevant states for an application?

Train parameterized quantum circuits like a neural network



There do exist “classical” functions only a quantum circuit can efficiently represent!

But how easy are these functions to train? How prevalent are they in “classical” datasets?

A new taxonomy for machine learning

classical learning +
classical data

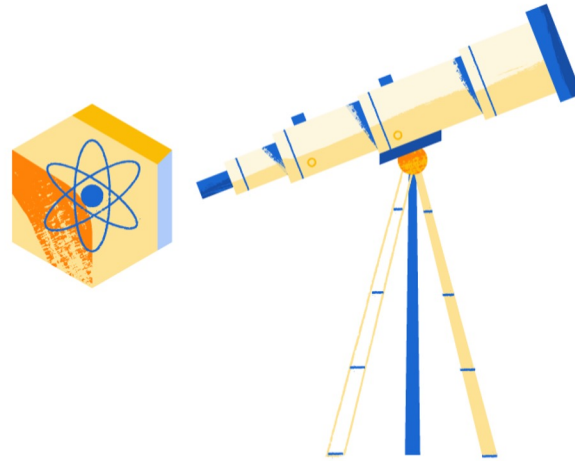
quantum learning +
classical data

classical learning +
quantum data

quantum learning +
quantum data



Classical Data



Quantum Data

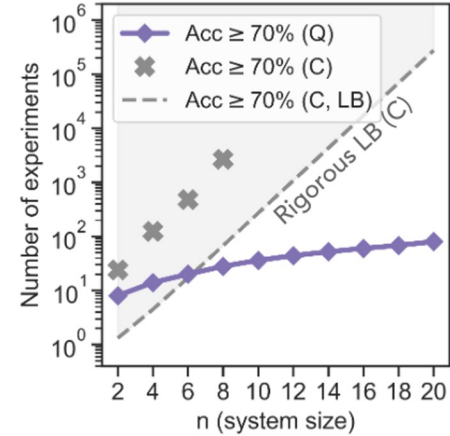
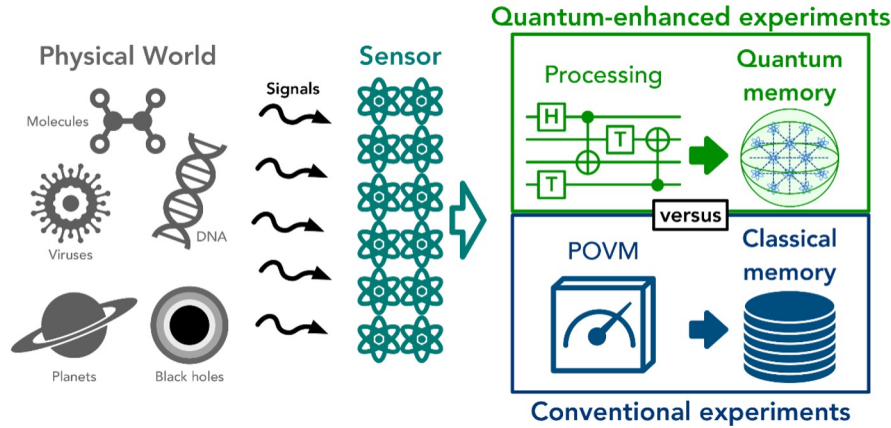
Whether starlight or molecular spectra, thus far science has only used “classical data”

If data is collected by quantum sensor (rapidly progressing technology) and transduced to an error-corrected quantum memory, we can do amazing things with that data

Quantum states output from a quantum simulation (e.g. of chemistry) also constitute quantum data

Quantum enhanced experiments

Science 376, 1182-1186 (2022)



By entangling two copies of N qubit state (e.g. from a sensor), we can learn properties with 2^N fewer queries vs when having access to a single copy or classical data

With limited data, advantage possible with very few qubits; achieved on our chips!

Open source APIs for executing quantum computations

Google open-source frameworks to simulate on classical devices or near-term quantum computers



[Cirq](#) - Open-source quantum framework for NISQ algorithms on near-term quantum processors



[Qsim](#) - Full wave function simulator using gate fusion, AVX/FMA instructions and multi-threading



[OpenFermion](#) - Translate problems in chemistry and materials science into quantum circuits



[TensorFlow Quantum](#) for rapid prototyping of hybrid quantum- classical ML models

```
import cirq

# Step 1: Create Circuit object
circuit = cirq.Circuit()

# Step 2: Define 2 qubits
(q0, q1) = cirq.LineQubit.range(2)

# Step 3: Perform quantum gates on qubits
circuit.append([cirq.H(q0), cirq.CNOT(q0, q1)])

# Step 4: Measure quantum bits
circuit.append([cirq.measure(q0), cirq.measure(q1)])

# Step 5: Perform simulation of the circuit
sim = cirq.Simulator()
results = sim.run(circuit, repetitions=10)
print(results)
```



Key takeaways on quantum ML prospects

Quantum Computing not for all problems...
...for some use cases classical methods are better

ML usually advances through empirically honed heuristics, not exact algorithms with rigorous proofs and so we will need larger devices to probe true potential

We can prove large speedups for some ML applications but those algorithms require quantum error-correction

Quantum ML has clear advantage when learning on quantum data output from sensors or quantum simulations

Quantum is really different, weird, powerful - only beginning to understand its potential

