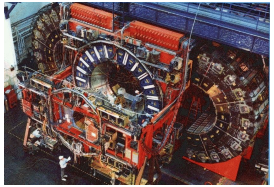
Google AI
Quantum

Google's quantum computer and pursuit of quantum supremacy

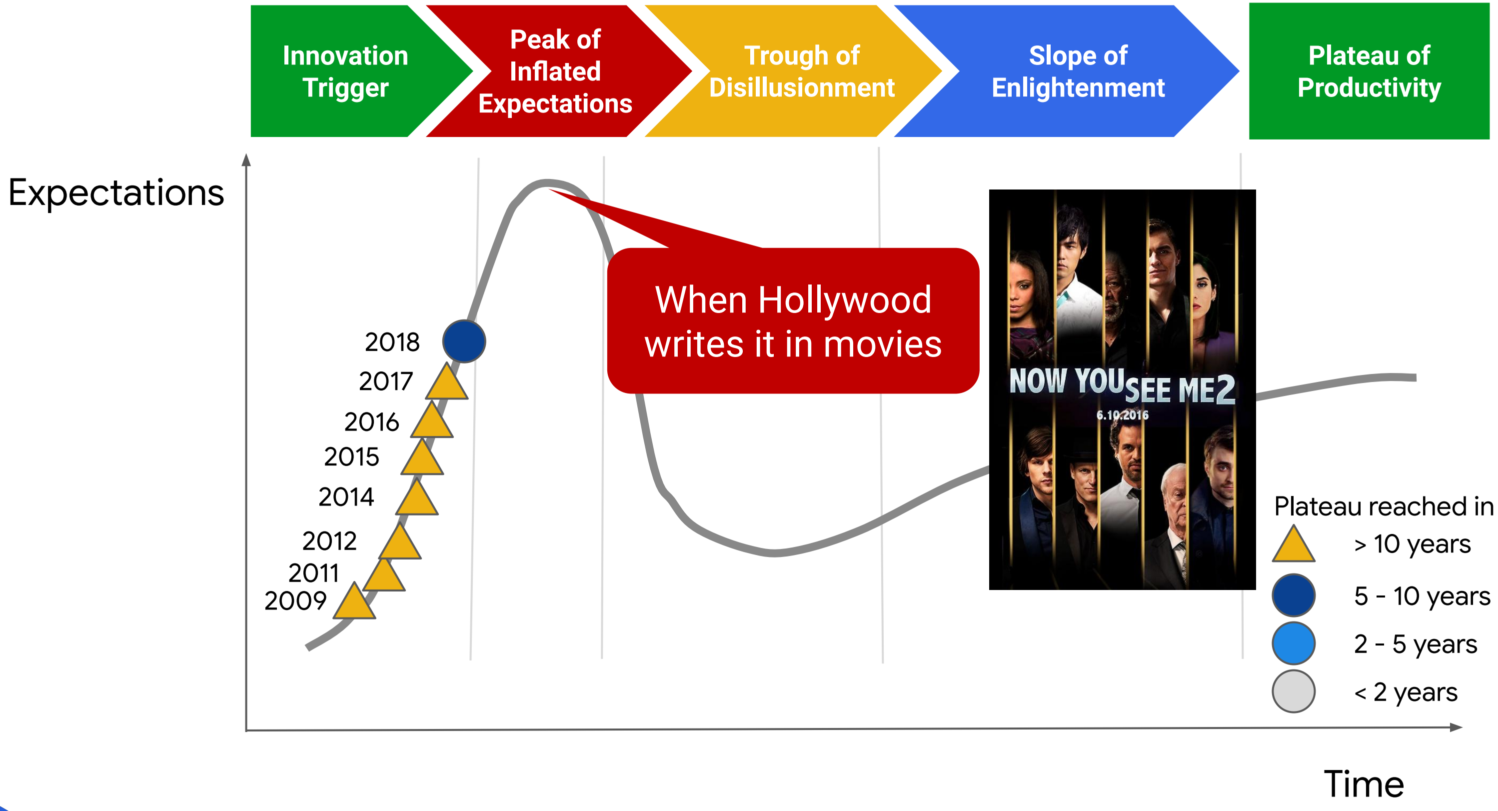
Ping Yeh (pingyeh@google.com)
Google Santa Barbara
KEK, 2019-09-26

About me

Collider Detector at Fermilab (CDF) 	Thesis: "Measurement of Top Quark Mass from Dilepton Events using Invariant Mass of Lepton and b-jet in p-pbar collisions at sqrt(s) = 1.8 TeV" Data production design for CDF-2 upgrade
Alpha Magnetic Spectrometer	Onboard data acquisition software in assembly for Sharc DSP Particle back-tracing in geo-magnetic field, for identifying cosmic rays (signals) from geo-trapped particles (backgrounds)
Belle B factory	eta' meson
oogle	Search quality, iGoogle (personalized homepage), Google Analytics & Adwords, Cross-device ads attribution, 2 cancelled "start up" projects, and now quantum computing.

Google AI Quantum

Quantum computing on Gartner's hype curve



Goal & timeline set by physicists

Quantum Computing Roadmap v1 (2002) and v2 (2004)
https://qist.lanl.gov/pdfs/qc_roadmap.pdf

> "The ten-year (2012) goal would extend QC into the "architectural / algorithmic" regime, involving a quantum system of such complexity that it is beyond the capability of classical computers to simulate."

Coined by John Preskill as "Quantum Supremacy" in 2012.

Not yet achieved

Quantum control

Also in the roadmap:

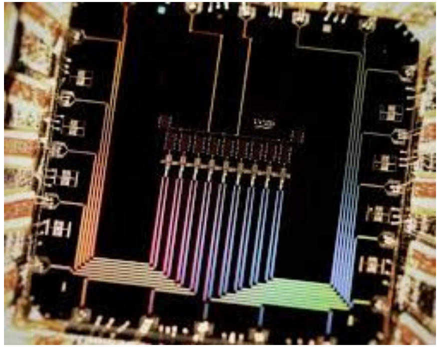
> “Quantum systems of ***unprecedented complexity*** will be created and ***controlled***, potentially leading to greater fundamental understanding of how classical physics emerges from a quantum world, which is as perplexing and as important a question today as it was when quantum mechanics was invented.”

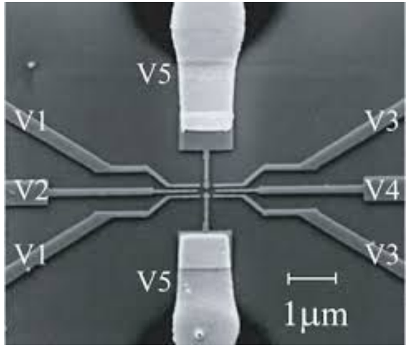
What is Quantum Computing?

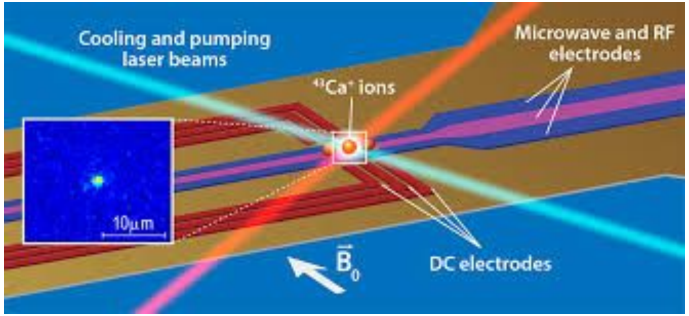
Using **2-state quantum systems** to perform computational tasks.

Some 2-state quantum systems:

- Photons
- Nuclear spins
- Trapped Ions
- Neutral Atoms
- Molecular spins
- Quantum dots
- Superconducting circuits



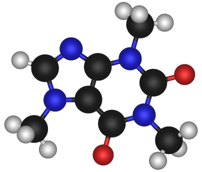


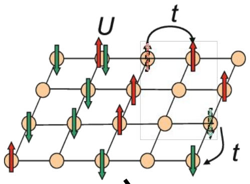


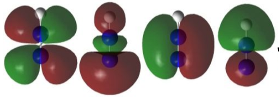
Why build a quantum computer?

Quantum simulation

Feynman's initial idea

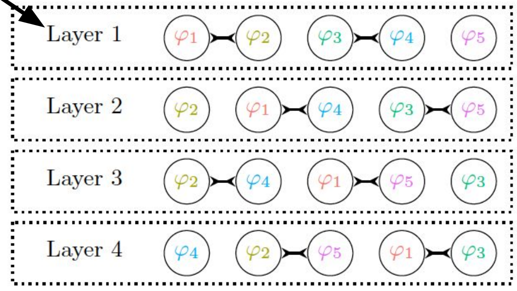


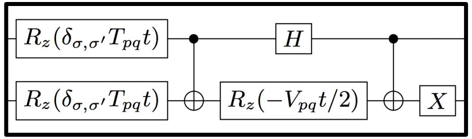




$$H = \sum_{ij} h_{ij} a_i^\dagger a_j + \frac{1}{2} \sum_{ijkl} h_{ijkl} a_i^\dagger a_j^\dagger a_k a_l$$

$$H = \sum_{p \neq q} \tilde{T}_{pq} \left(X_p Z_{p+1} \cdots Z_{q-1} X_q + Y_p Z_{p+1} \cdots Z_{q-1} Y_q \right) + \sum_{p \neq q} \tilde{V}_{pq} Z_p Z_q + \sum_p \tilde{U}_p Z_p$$

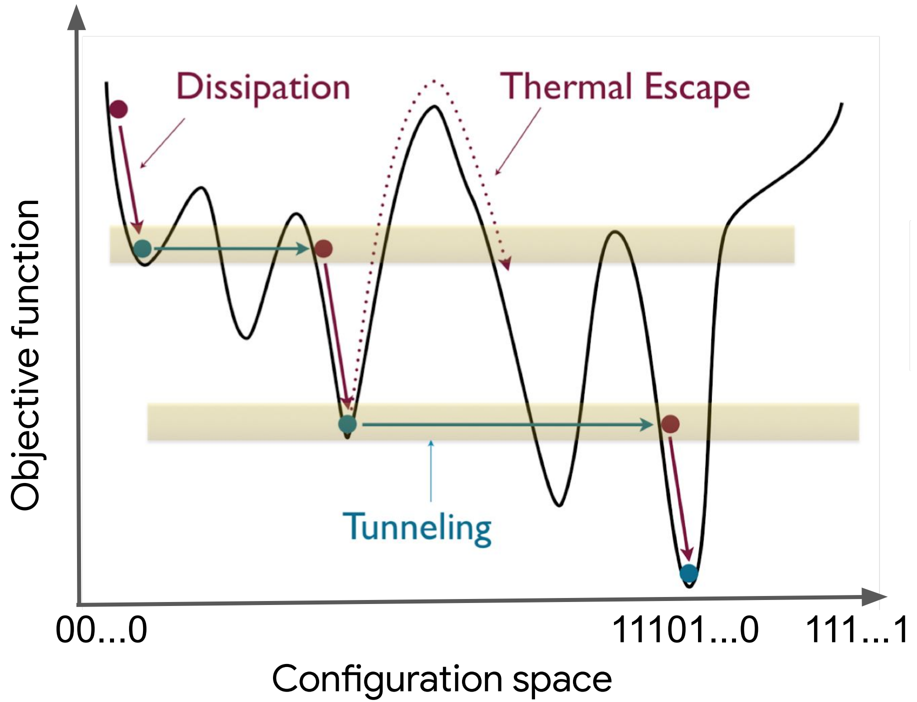




Why build a quantum computer?

Quantum simulation

Optimization



Why build a quantum computer?

Quantum simulation

Optimization

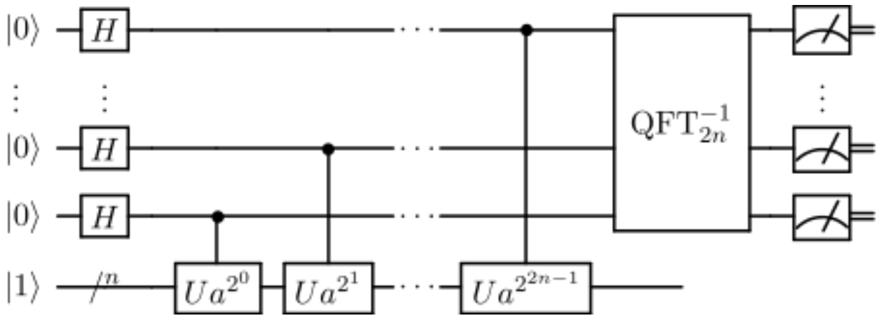
Factoring

age of universe vs. < 1 day

for n = 2048.

Classical algorithm $O\left(e^{1.9\, n^{1/3} (\log n)^{2/3}}\right)$

Shor's algorithm $O\left(n^2 (\log n)(\log \log n)\right)$



Factoring

$$15 = 5 \times 3$$

Why build a quantum computer?

Quantum simulation

Optimization

Factoring

???

OpenFermion

+

Cirq

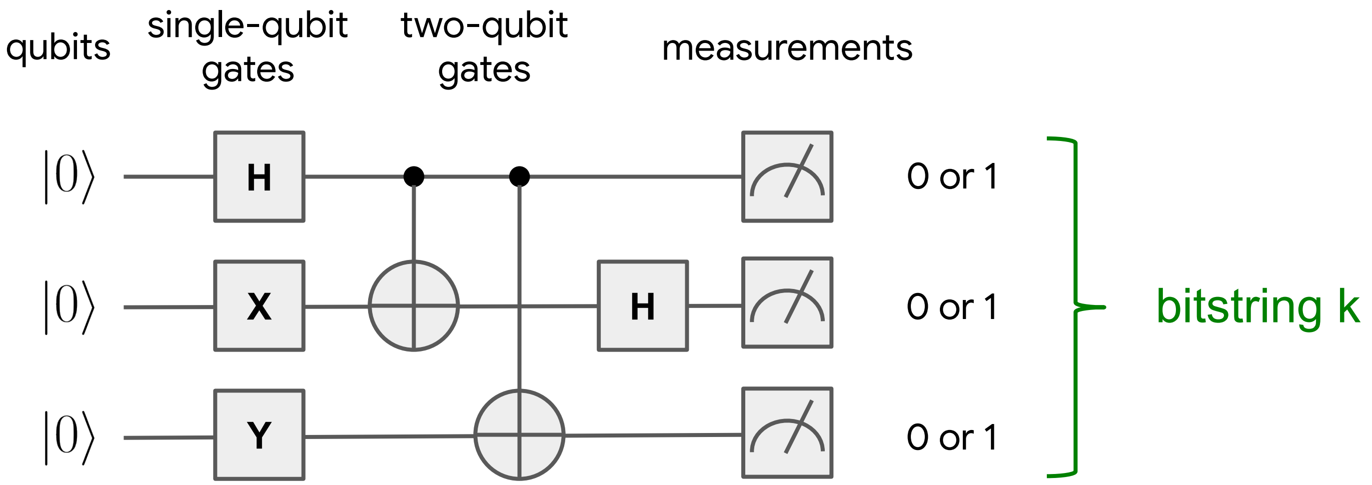
https://www.openfermion.org/

https://github.com/quantumlib/cirq

The computation model

Turing machine → Quantum Turing machine

Alternatively: Quantum circuit



Other models: quantum annealing, adiabatic quantum computing.

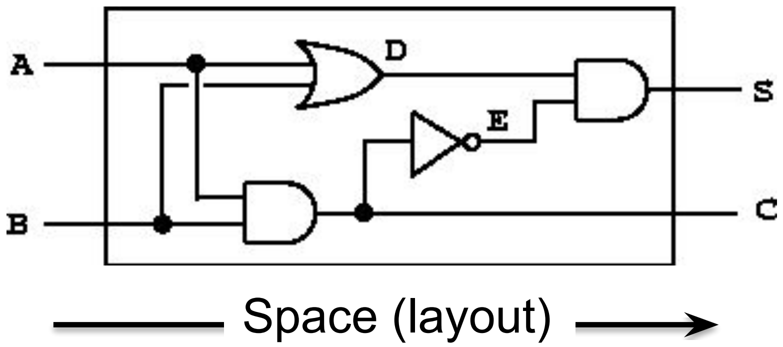
Logic and quantum circuits

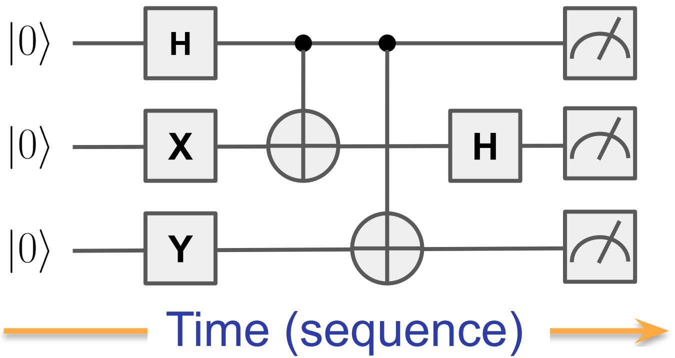
Classical logic circuit

- Deterministic
- Wiring fan-out
- Universal: 1 bit NOT + 2 bit AND

Quantum circuit

- Probabilistic
- No clone theorem
- Universal: 1 qubit rotation + 2 qubit CNOT





State of a qubit: Bloch sphere representation

Bloch sphere representation of a qubit:

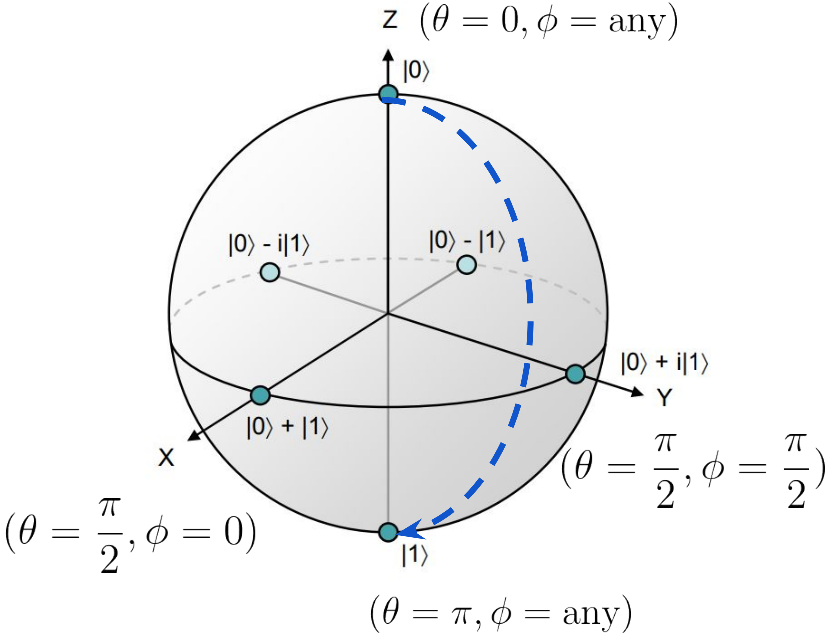
$$
\begin{aligned}
|\psi\rangle &= c_0|0\rangle + c_1|1\rangle \\
&= \cos\frac{\theta}{2}\,|0\rangle + \sin\frac{\theta}{2}\,e^{i\phi}\,|1\rangle
\end{aligned}
$$

(Global phase discarded)

A gate operation: $(\theta, \phi) \longrightarrow (\theta', \phi')$

- can be modeled as a rotation on Bloch sphere
- NOT gate = rotate around x-axis by π
- What about $\frac{\pi}{2}$ rotation?

Spherical angular coordinates (θ, ϕ)



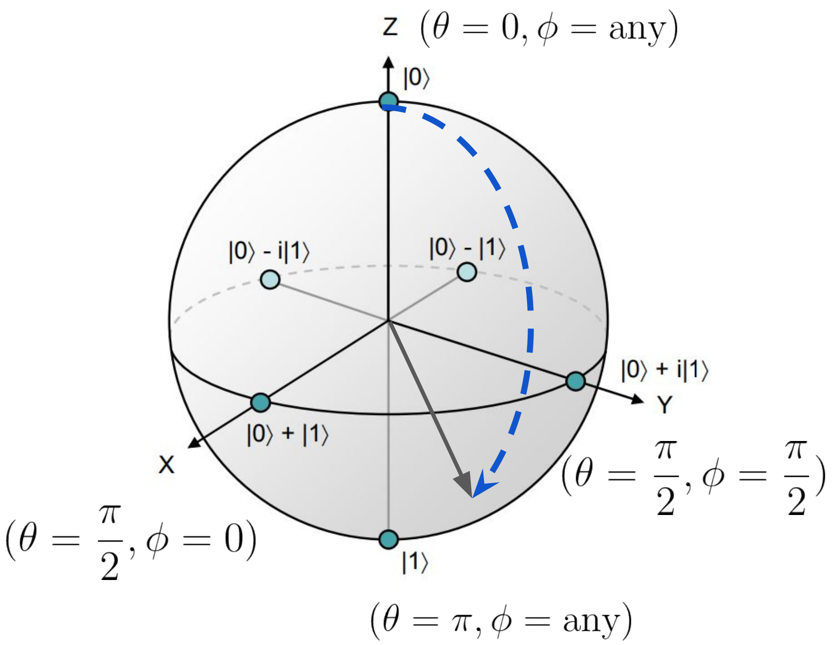
Challenge: Controlling a qubit

Analog control errors: over/under rotation, deviation of the rotation axis

Decoherence (environmental) errors: random bit flips / phase changes

Qubit error mechanisms inform nearly all design decisions

Spherical angular coordinates (θ, ϕ)



End Goal: Universal Fault-Tolerant QC

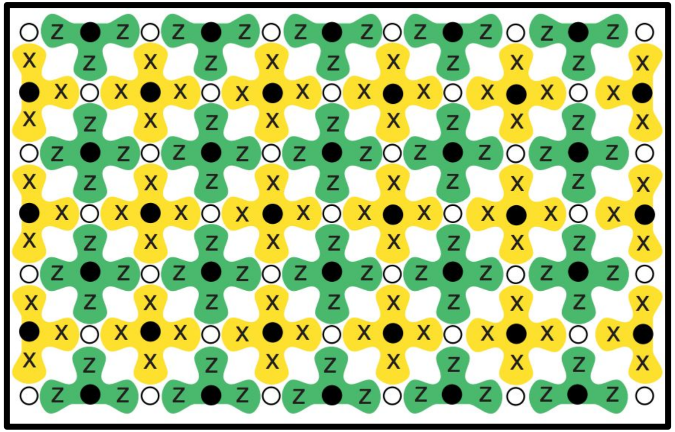
Fault tolerance via error correction

1 **logical qubit** from many **physical qubits**

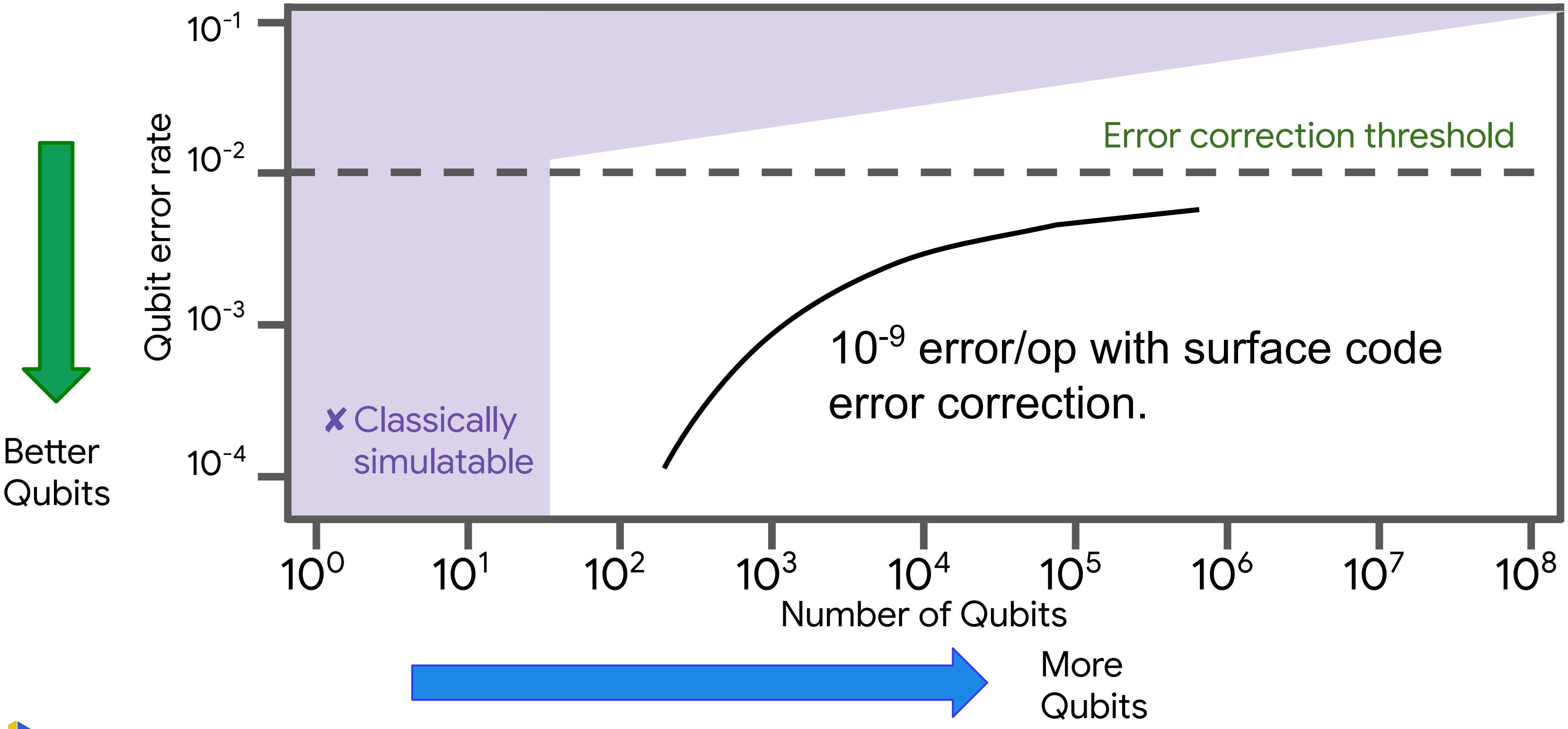
Universal QC requires error/op ~10^{-10}

Surface code error correction:

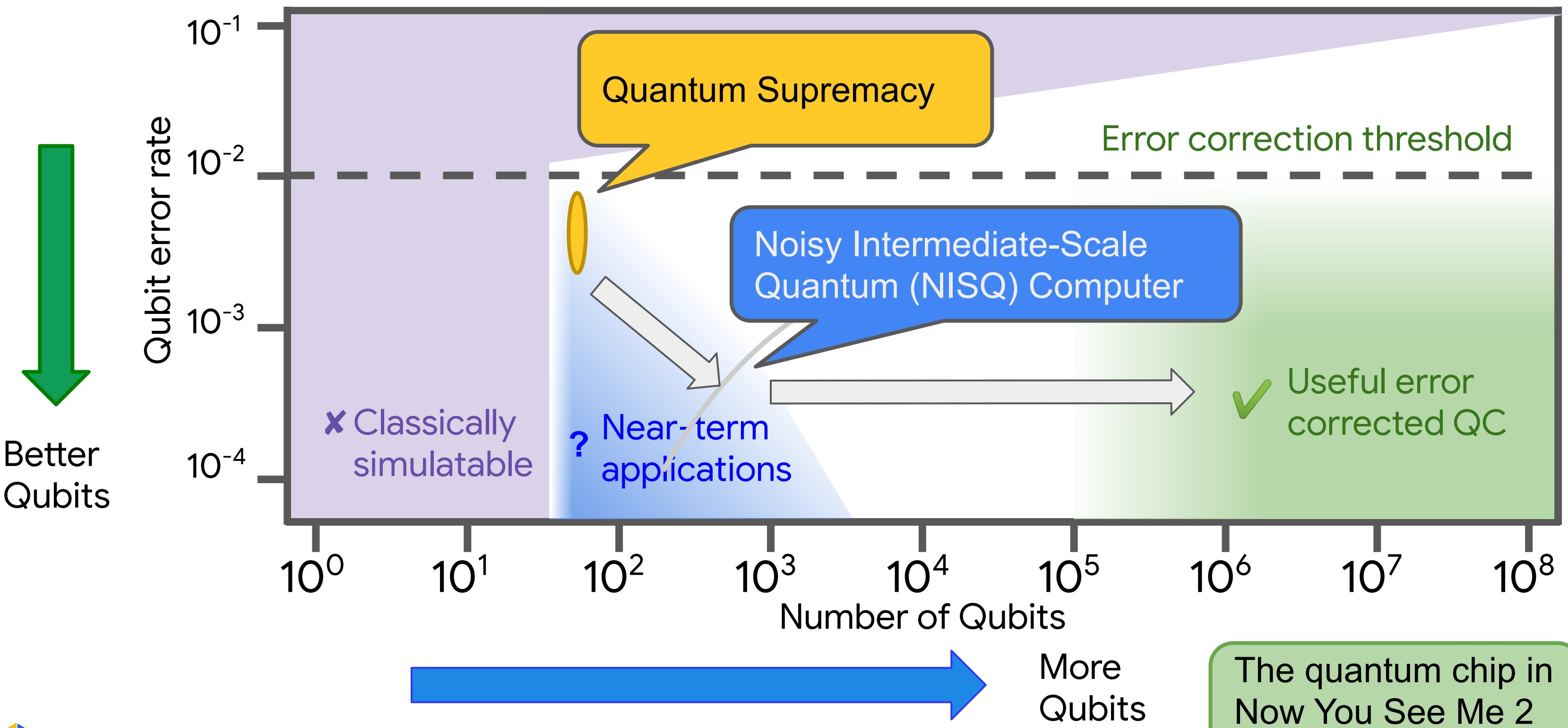
- 2D qubit array, nearest-neighbor coupling
- Error/op (physical): 10^{-2} threshold, 10^{-3} target
- Useful at 10^5-10^6 physical qubits



When is a Quantum Computer Useful?



When is a Quantum Computer Useful?



The quantum chip in Now You See Me 2 is off the chart.

DiVincenzo Criteria for Quantum Computers

1. Scalable system of well-characterized qubits
2. Ability to initialize to a fiducial state
3. Long coherence time
4. Universal set of quantum gates
5. Capable of measuring any specific qubit

[D. P. DiVincenzo, NATO ASI Series E, Kluwer Ac. Publ., Dordrecht, 1996]; arXiv:cond-mat/9612126v2.

Two more criteria were added later for quantum communications.

Physical systems for quantum computers (2004)

DiVincenzo Criteria	NMR	Neutral Atom	Cavity QED	Super-conductors	Trapped Ion	Photonic	Solid State
Scalable / well characterized	🔴	🟡	🟡	🟡	🟡	🟡	🟡
State preparation	🟡	🟢	🟢	🟢	🟢	🟡	🟡
Long coherence	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Universal gates	🟢	🟡	🟡	🟡	🟢	🟡	🟡
Random-access measurement	🟡	🟡	🟢	🟡	🟢	🟡	🟡

- 🔴 No viable approach is known
- 🟡 Viable approach proposed, no sufficient proof of principle yet
- 🟢 Viable approach has been sufficiently demonstrated

D. P. DiVincenzo, NATO ASI Series E, Kluwer Ac. Publ., Dordrecht, 1996; arXiv:cond-mat/9612126v2.

QC Roadmap 2.0 (2004)
https://qist.lanl.gov/pdfs/qc_roadmap.pdf

Physical systems for quantum computers (2018)

DiVincenzo Criteria	NMR	Neutral Atom	Cavity QED	Super-conductors	Trapped Ion	Photonic	Solid State
Scalable / well characterized	🔴	🟡	🟡	🟡🟢	🟡	🟡	🟡
State preparation	🟡	🟢	🟢	🟢	🟢	🟡🟢	🟡🟢
Long coherence	🟡	🟡🟢	🟡🟢	🟡🟢	🟡🟢	🟢	🟡🟢
Universal gates	🟢	🟡🟢	🟡	🟡🟢	🟢	🟡🟢	🟡🟢
Random-access measurement	🟡	🟡🟢	🟢	🟡🟢	🟢	🟡🟢	🟡🟢

QC Roadmap 2.0 (2004)

🔴 No viable approach is known

🟡 Viable approach proposed, no sufficient proof of principle yet

🟢 Viable approach has been sufficiently demonstrated

Peter McMahon, Q2B 2018
https://q2b2018.qcware.com/videos-presentations

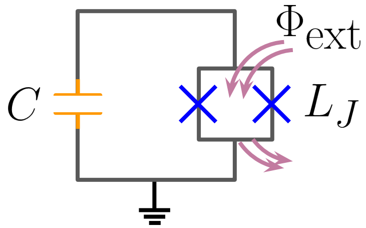
Major commercial players

Company	Qubit technology	#qubits	announcement time
IonQ	trapped ion	79/160	2018-12
Rigetti	superconducting	128	2018-08
Google	superconducting	72	2018-03
Alibaba	superconducting	11	2018-03
Intel	superconducting, silicon spin qubits	49 N/A	2018-01
IBM	superconducting	50	2017-11
D-Wave	superconducting	2000	2017-01
Microsoft	topological	N/A	N/A
Others	...	...	...

quantum annealing machine

Building a Superconducting Quantum Computer

Tunable qubits: LC circuit with SQUID



Josephson junction ~ nonlinear inductor

Hamiltonian

N(Cooper pairs)

effective phase diff across SQUID

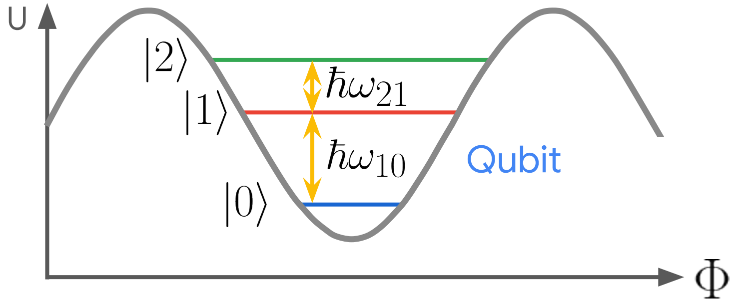
$$H = 4E_c\, n^2 - 2E_J \left|\cos\frac{\pi\Phi_{\text{ext}}}{\Phi_0}\right| \cos\varphi$$

$[\varphi, n] = 1$

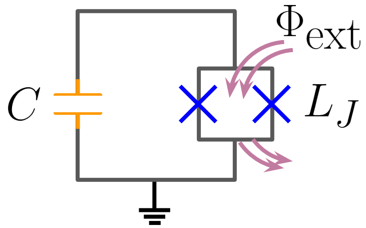
flux qunatum

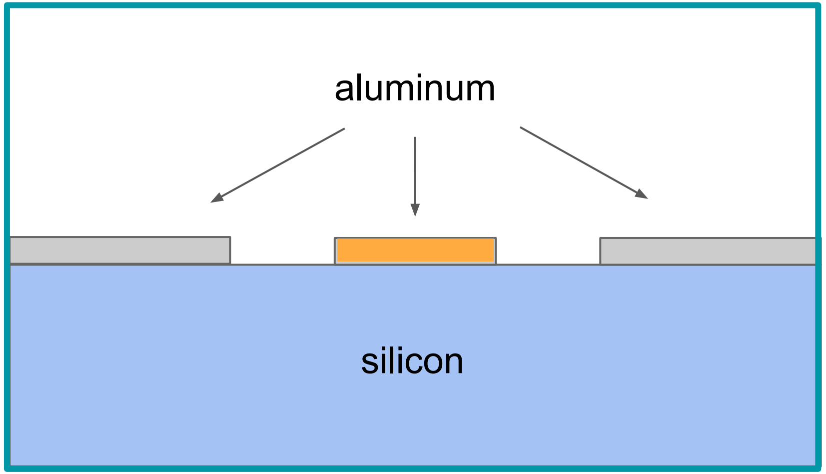
$E_C,\ E_J$: fixed by qubit material and geometry

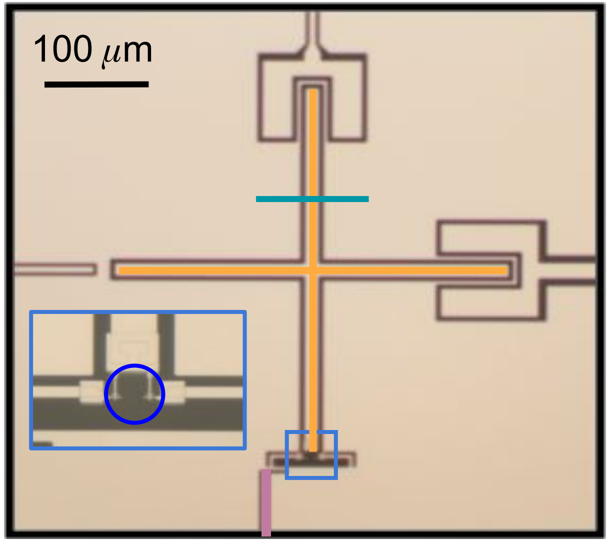
Qubit frequency tunable by Φ_{ext}



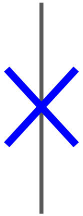
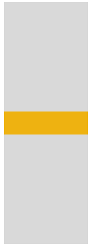
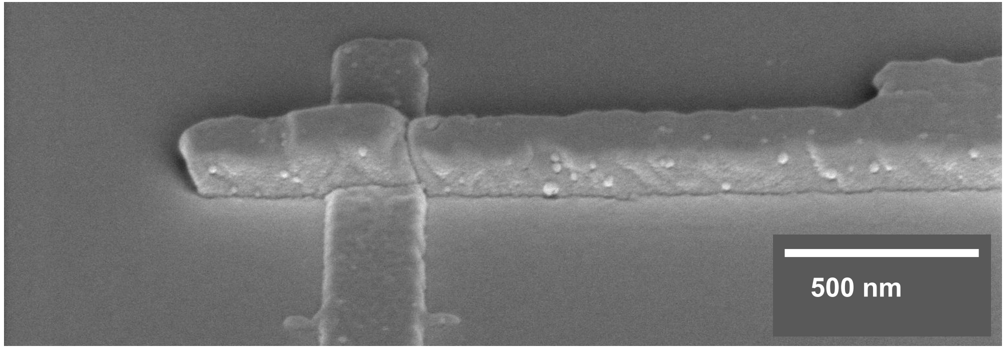
Physical layout of a transmon qubit

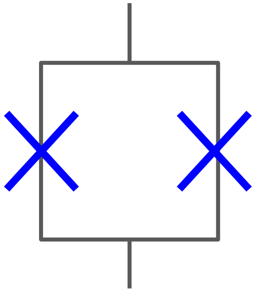


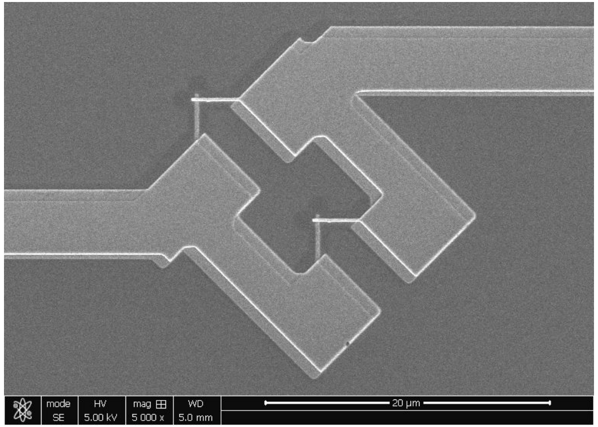




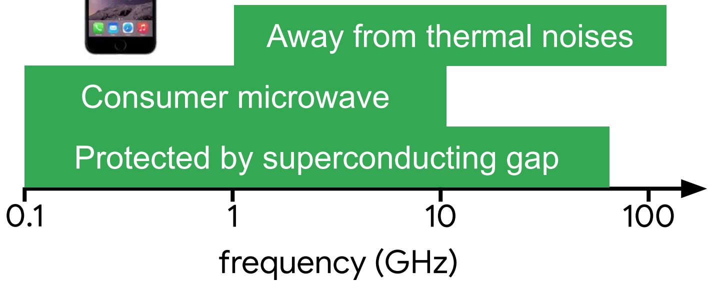
The fabricated Josephson junction





Region of Operation



Energy gap of superconducting aluminum

$$\Delta_{\mathrm{Al}} = 3.4 \times 10^{-4}\ \mathrm{eV} \approx 82\ \mathrm{GHz}$$

Consumer wireless applications (WiFi, LTE, etc.)

> 10 GHz hard/expensive to engineer

Dilution refrigerator cools to < 50 mK

Minimize thermal noises at T ~ 10 mK (~ 0.2 GHz)

Typical values (transmon):

L ≈ 8 nH, C ≈ 80 fF

$$\frac{\omega_{10}}{2\pi} = f_{10} \approx 6\ \mathrm{GHz}$$

Qubit control example: Rabi Oscillation

Driving a qubit on-resonance with a wave:

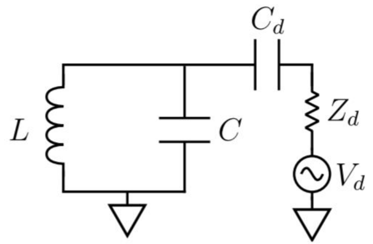
$$V(t) = V_0 \sin(\omega t + \phi)$$

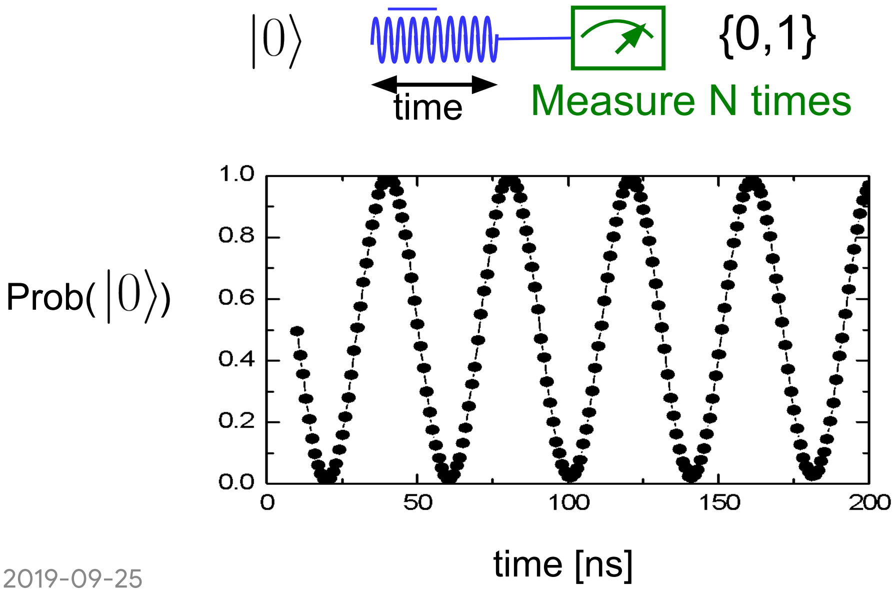
Qubit oscillates

$$|\psi(t)\rangle = \cos(\tfrac{\Omega}{2}t)|0\rangle + ie^{i\phi}\sin(\tfrac{\Omega}{2}t)|1\rangle$$

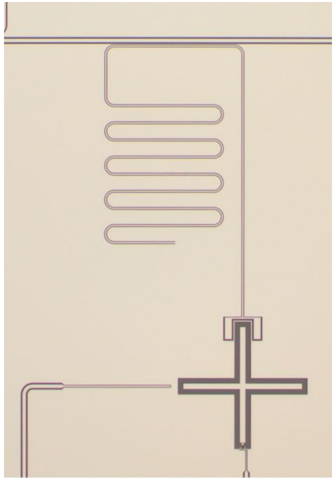
with Rabi frequency

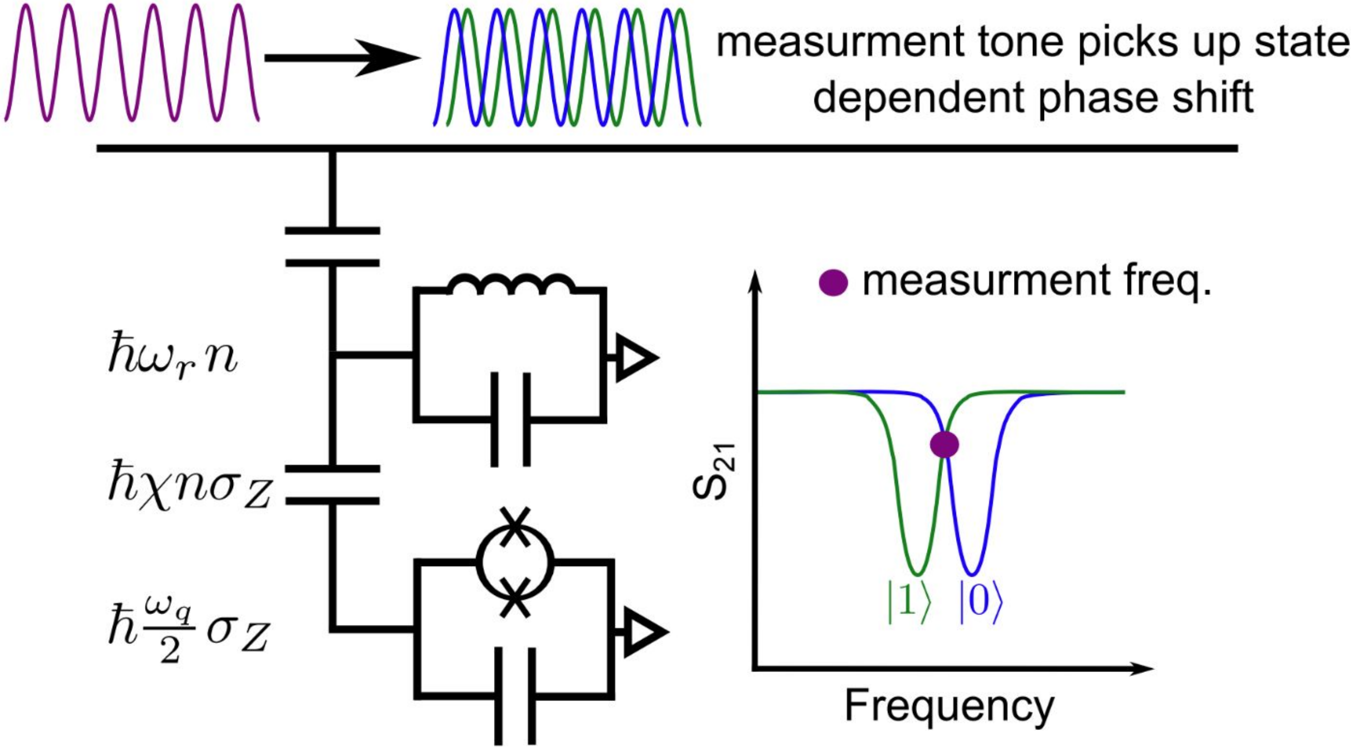
$$\Omega = \frac{C_d}{C + C_d}\frac{V_0}{\hbar}\langle 0|Q^2|0\rangle^{\frac{1}{2}}$$



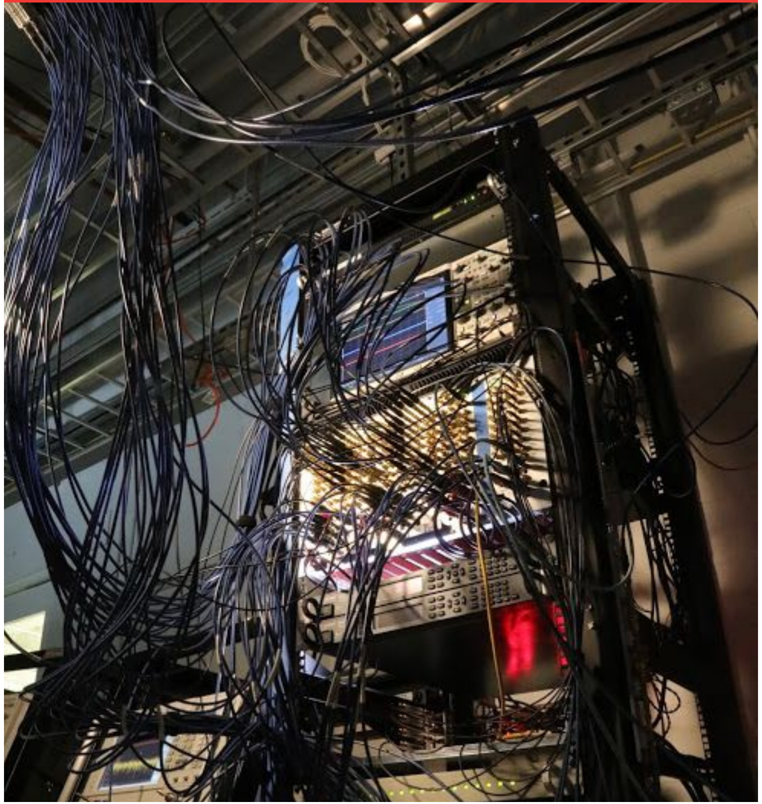


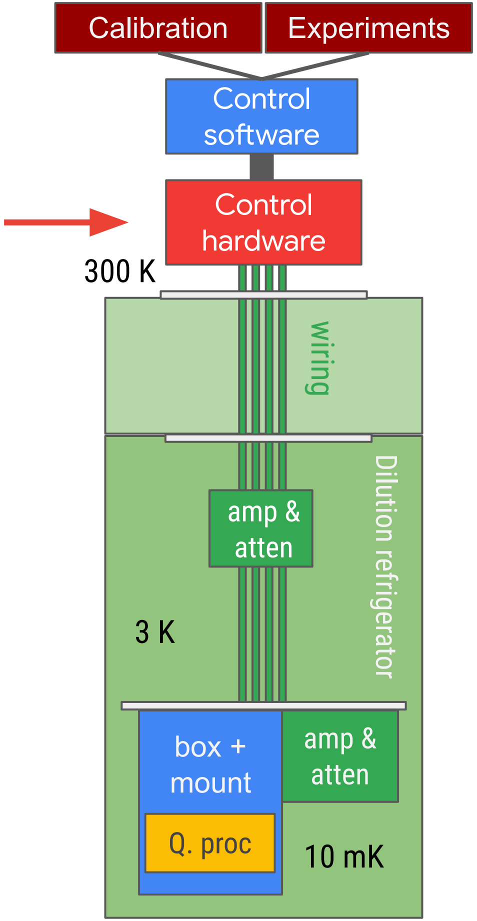
Qubit state measurement with readout resonator





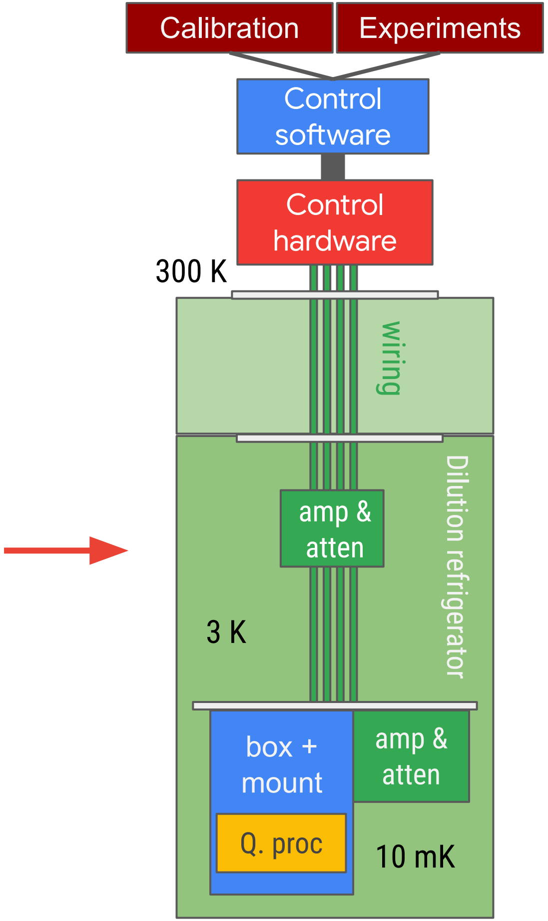
Custom Microwave Control Electronics

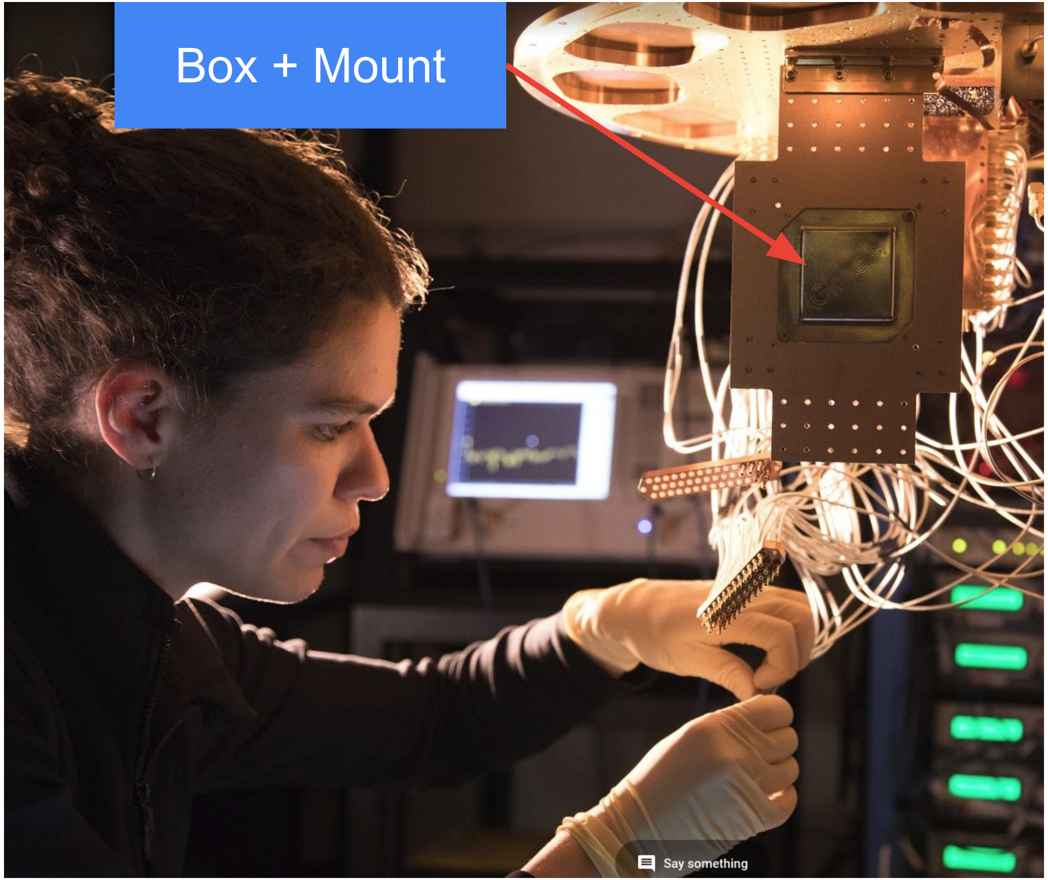


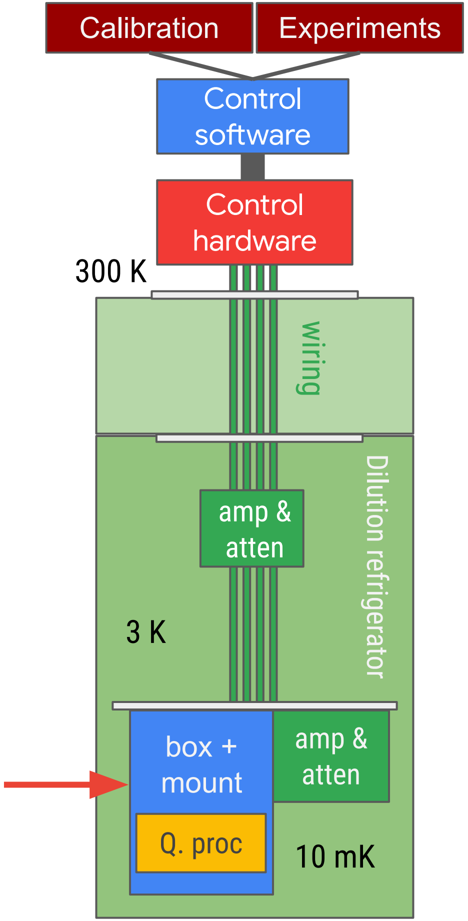


Wiring + amplifiers & filters

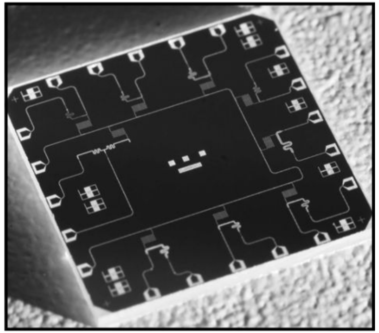
Dilution Refrigerator

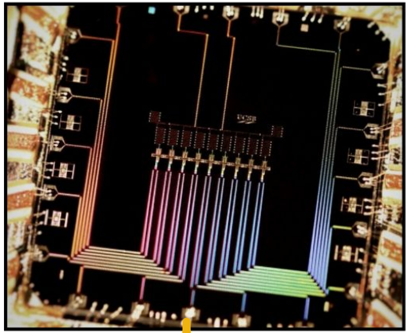


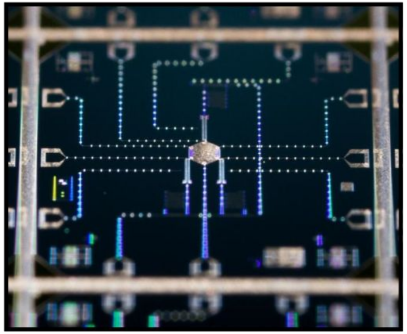

Box + Mount
Say something

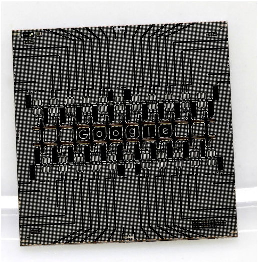

Calibration
Experiments
Control software
Control hardware
300 K
wiring
Dilution refrigerator
amp & atten
3 K
box + mount
amp & atten
Q. proc
10 mK

Fluxmon	**Xmon**	**Gmon**
- Flux qubit, tunable coupling - optimization problems	- X-shaped transmon qubit - gate-based QC	- Transmon qubit, tunable nearest-neighbor coupling



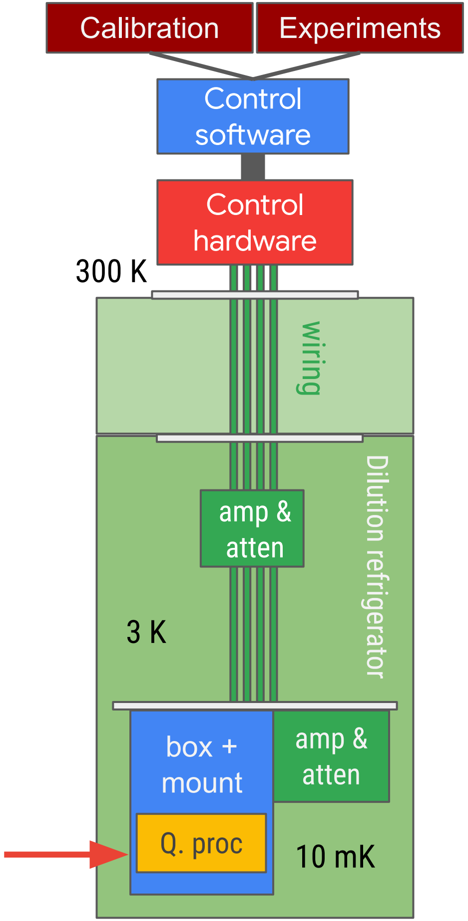




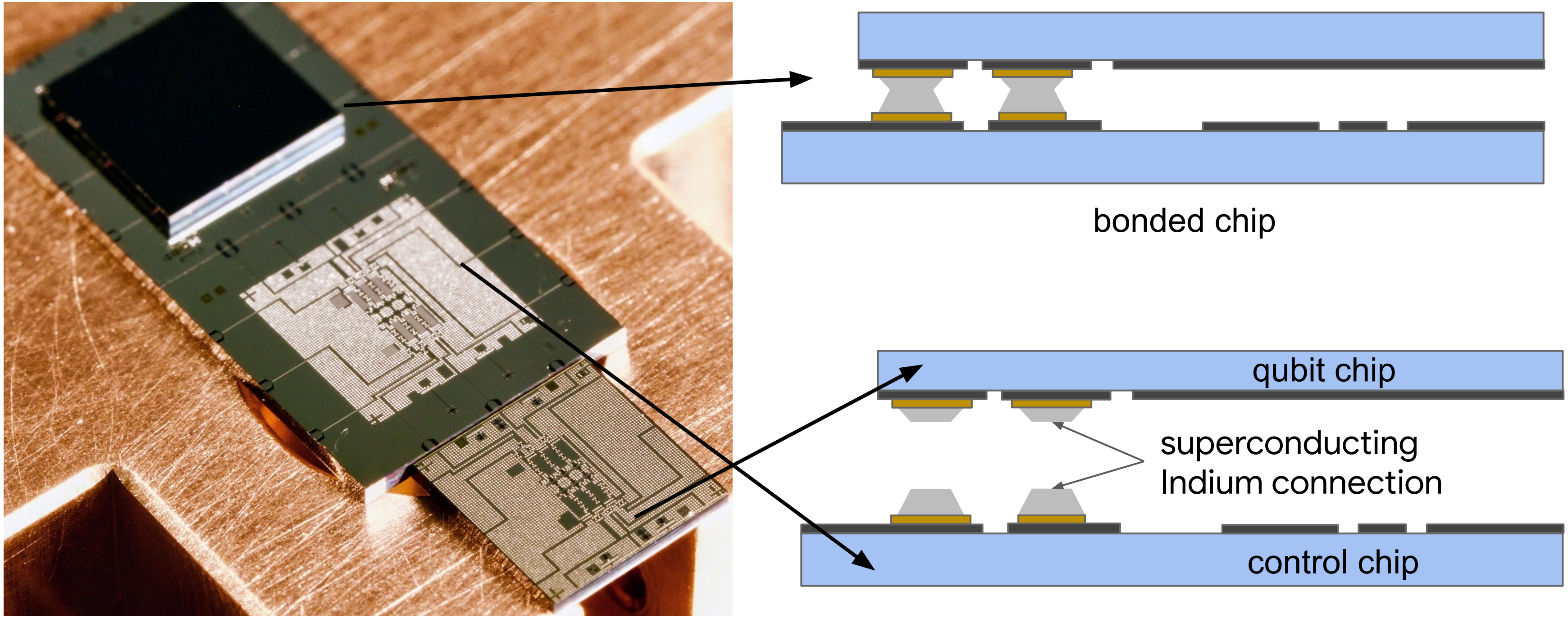


Foxtail: 22 qubits

Bristlecone: 72 qubits



Flip chip geometry with bump bonds



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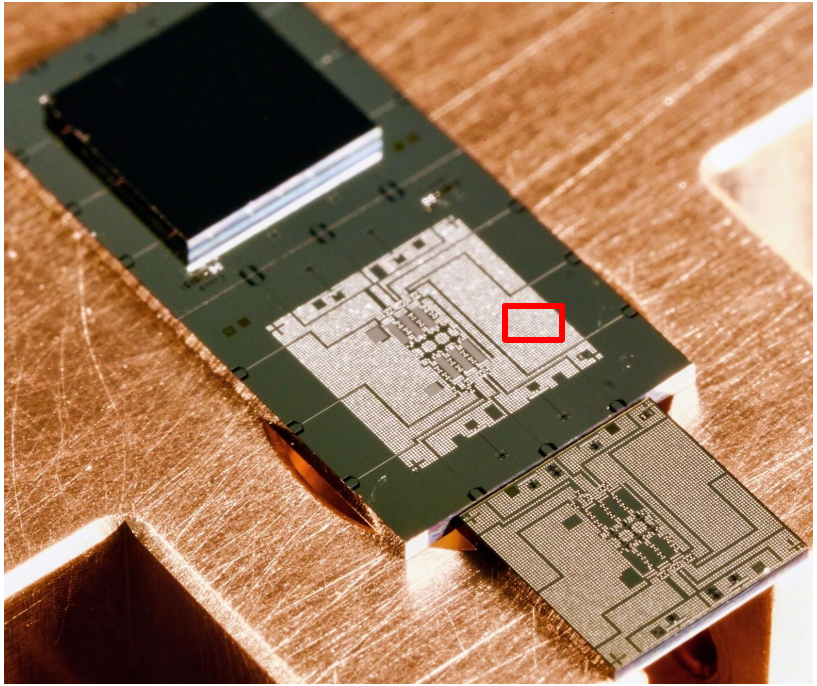
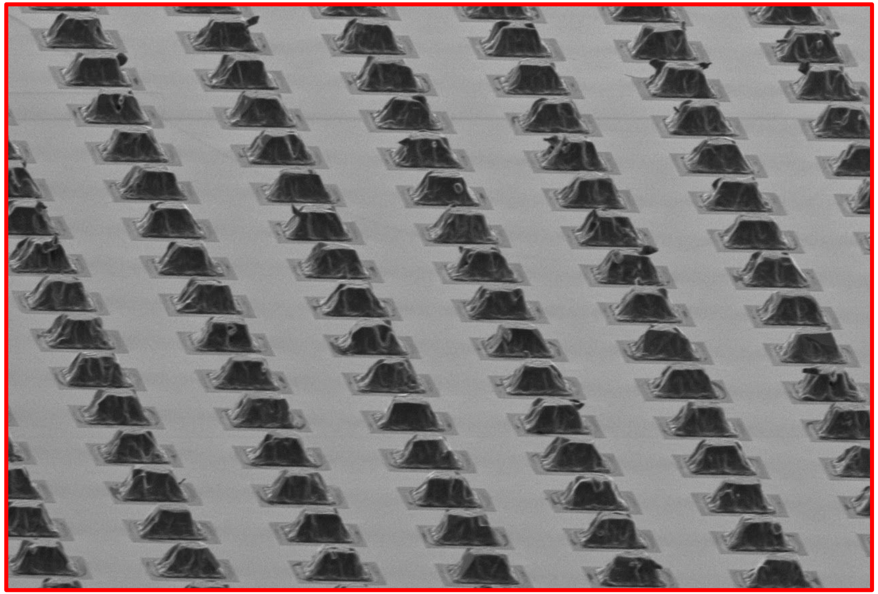
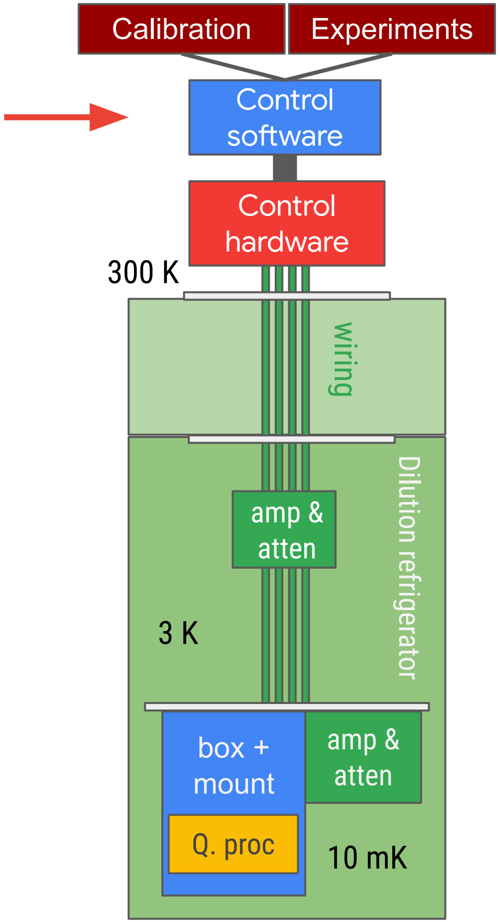




B. Foxen et al. Quantum Science and Technology, Volume 3, Number 1 (2017)

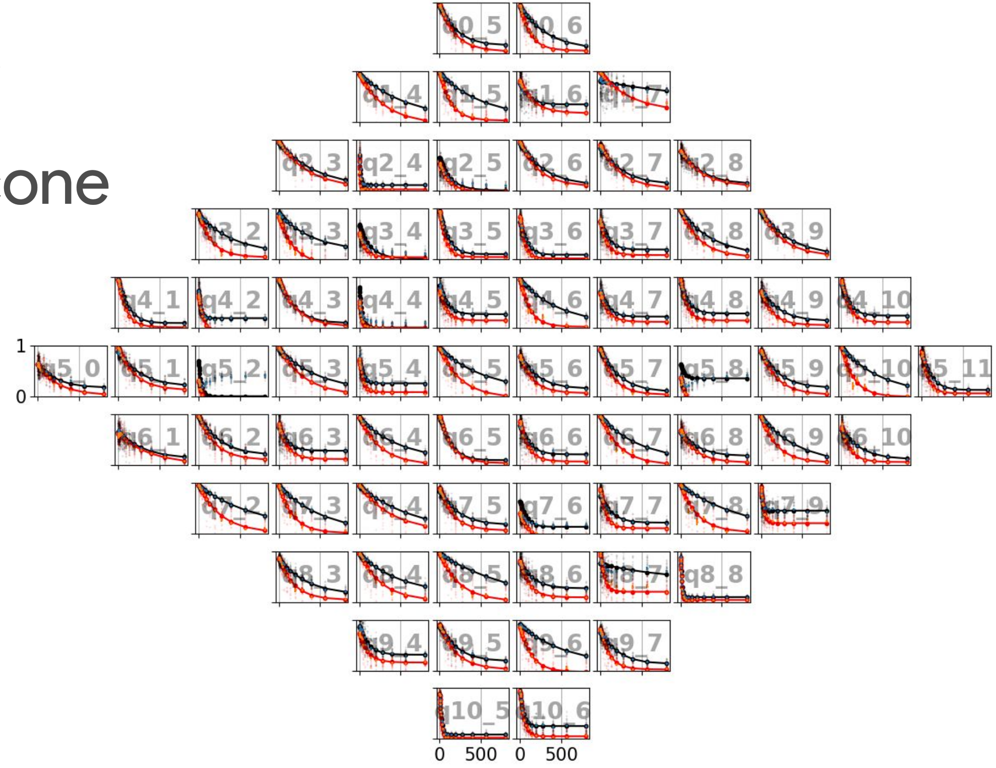
Quantum OS

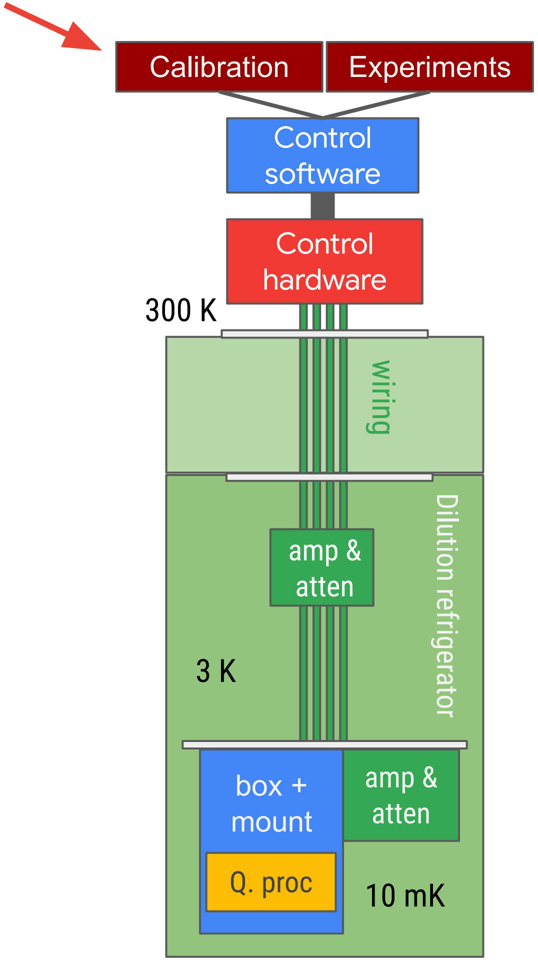
- Micro-services
  - LabRAD: service architecture / RPC
  - scheduling, gate compiler, FPGA, GPIB, etc. are servers
  - Experiments are initiated from clients
- Private github repo
  - Python + scala + rust
  - Coding styles / formatter / linter / type check
  - Code reviews / continuous integration
- Automate calibrations, experiments
  - Make hard things easy to move forward



Calibration: Key to Quality

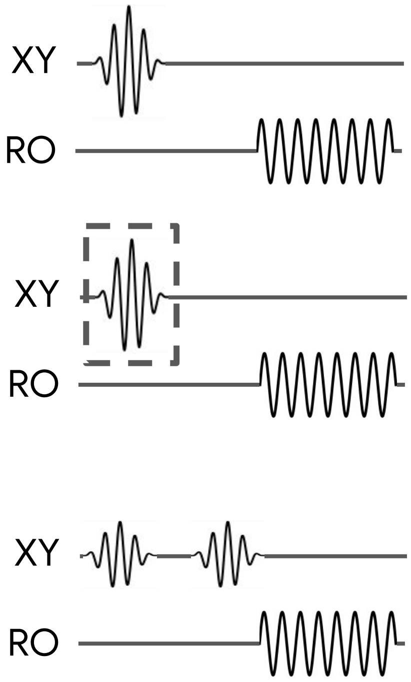
Bristlecone

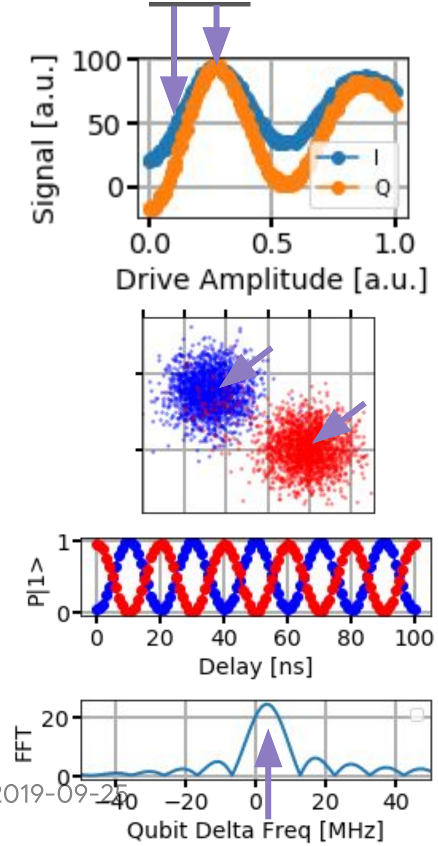




Bootstrapping

Experiment	Control Sequence	Data	Cal Value
Rabi			π amp. = 0.3 π/2 amp. = 0.15
Readout			0-state = (25, -20) 1-state = (100, 100)
Ramsey			f_{10} = 6.0 GHz +3 MHz





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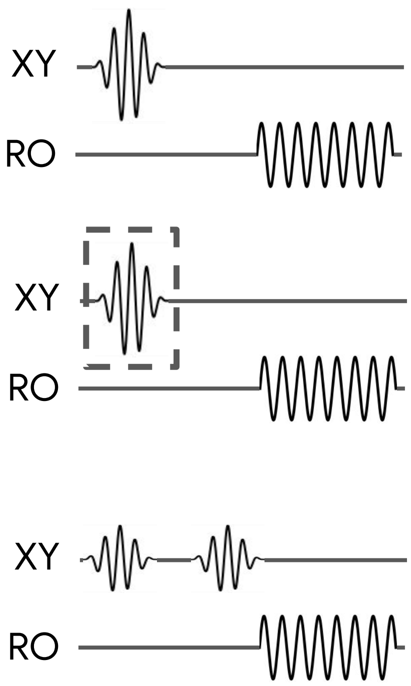
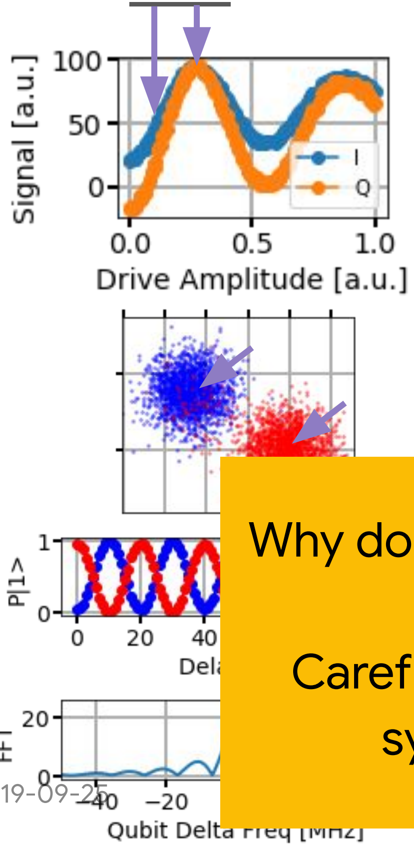
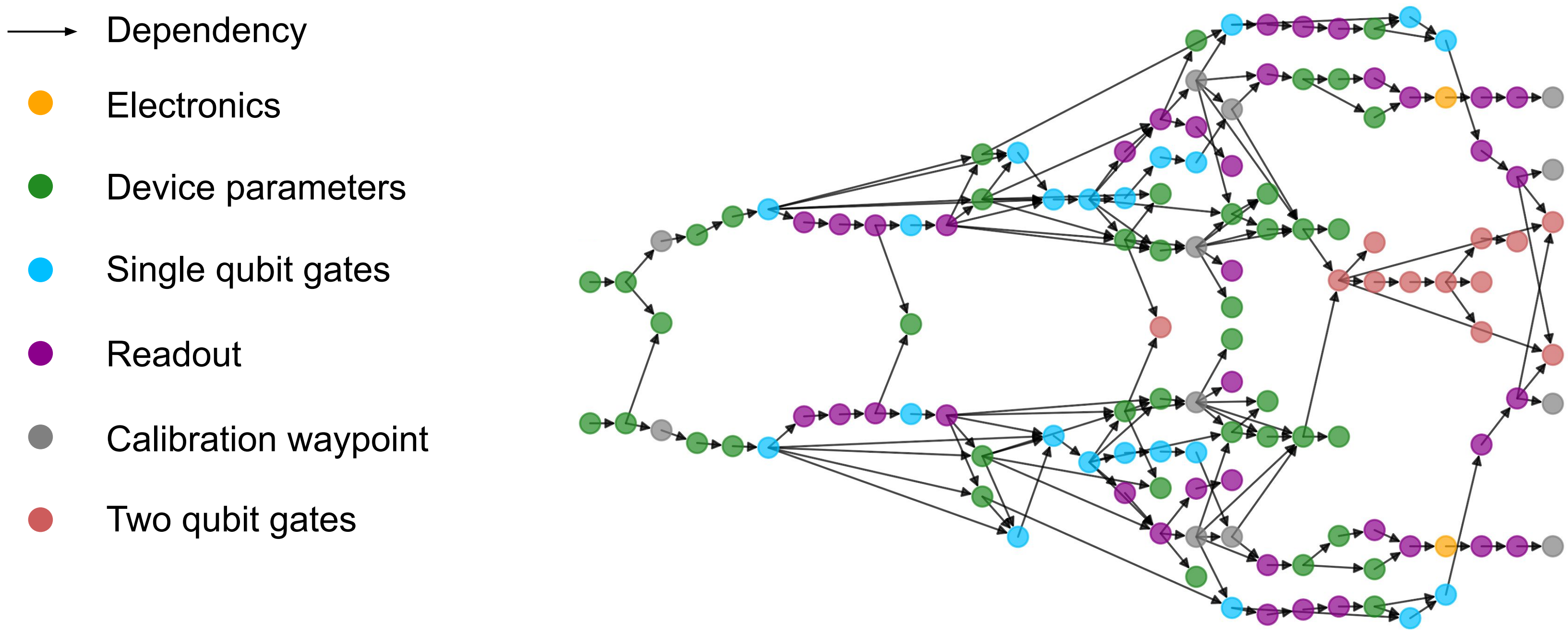




Why does this sequence work?

Careful order to **bootstrap** system knowledge

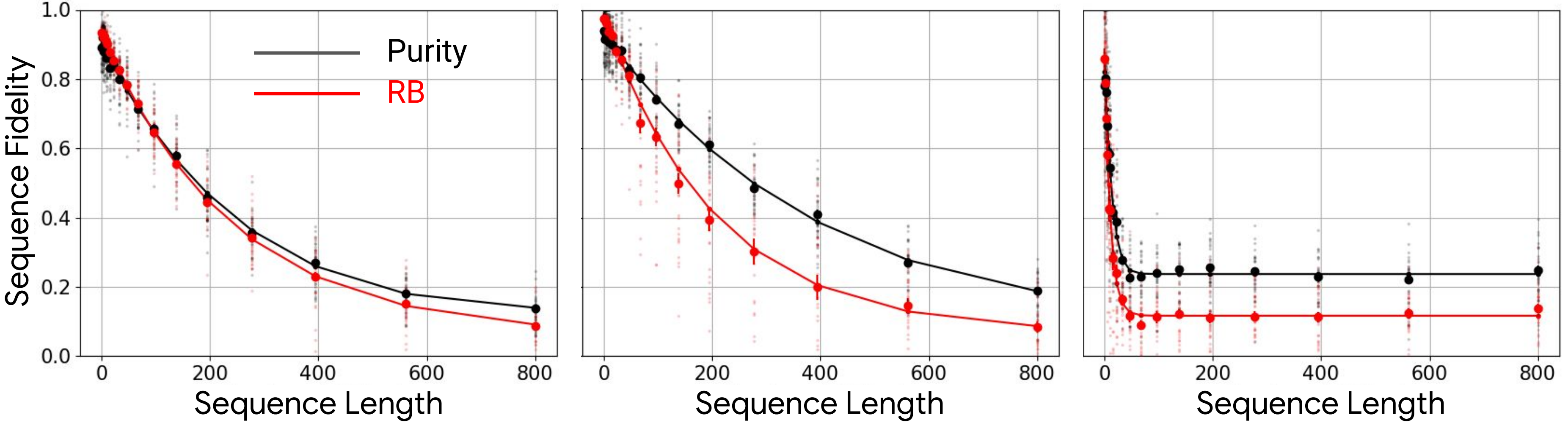
Calibration Dependency Graph



White paper on automation: [arxiv: 1803.03226](https://arxiv.org/abs/1803.03226)

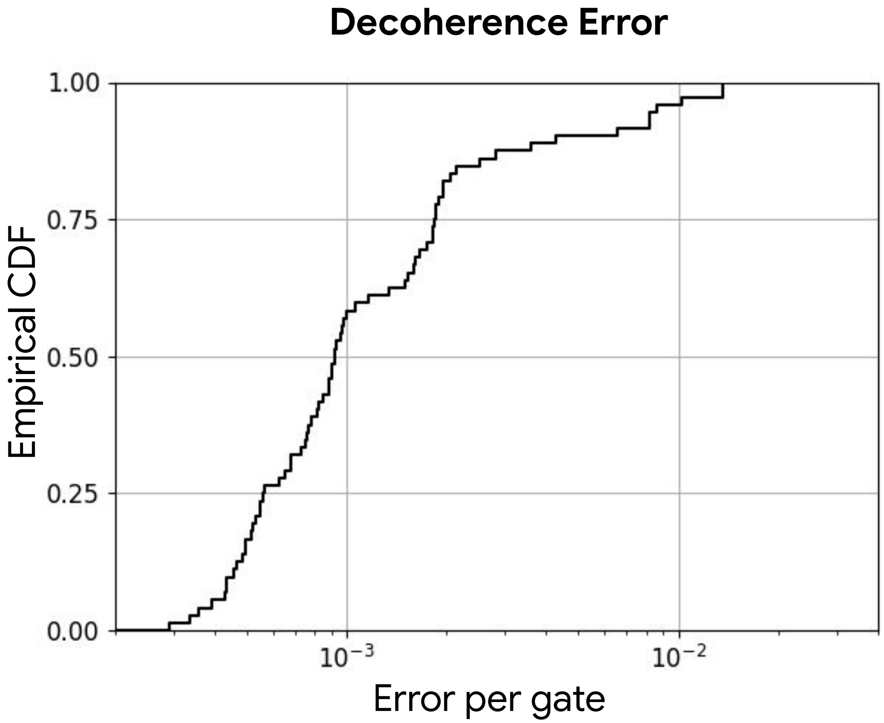
Data: Randomized Benchmarking vs. Purity

Error = 1 - fidelity. Purity ⟶ decoherence error, RB ⟶ total error.



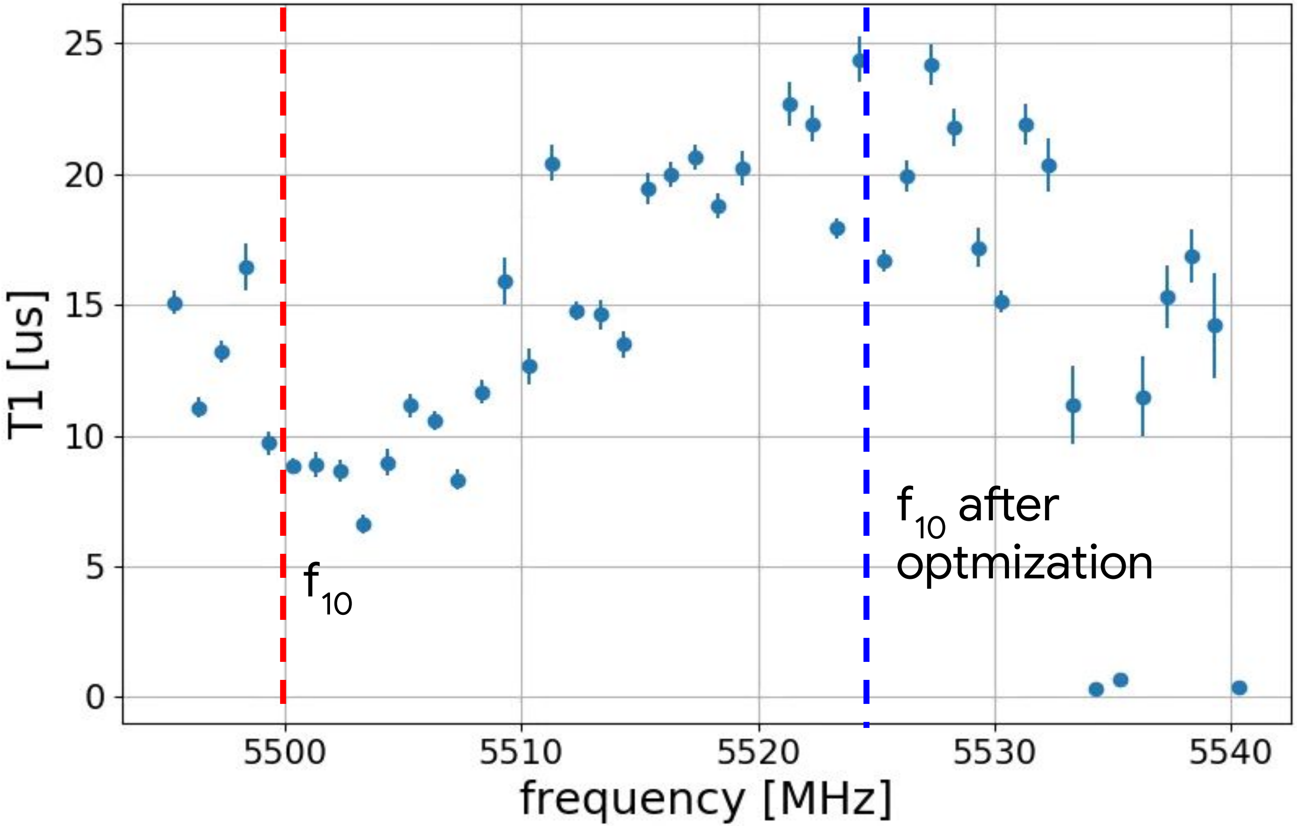
Low decoherence error	**Low decoherence error**	**High decoherence error**
Low total error	**Medium total error**	**High total error**
qubit #1	qubit #2	qubit #3

Empirical CDF: for measuring improvements

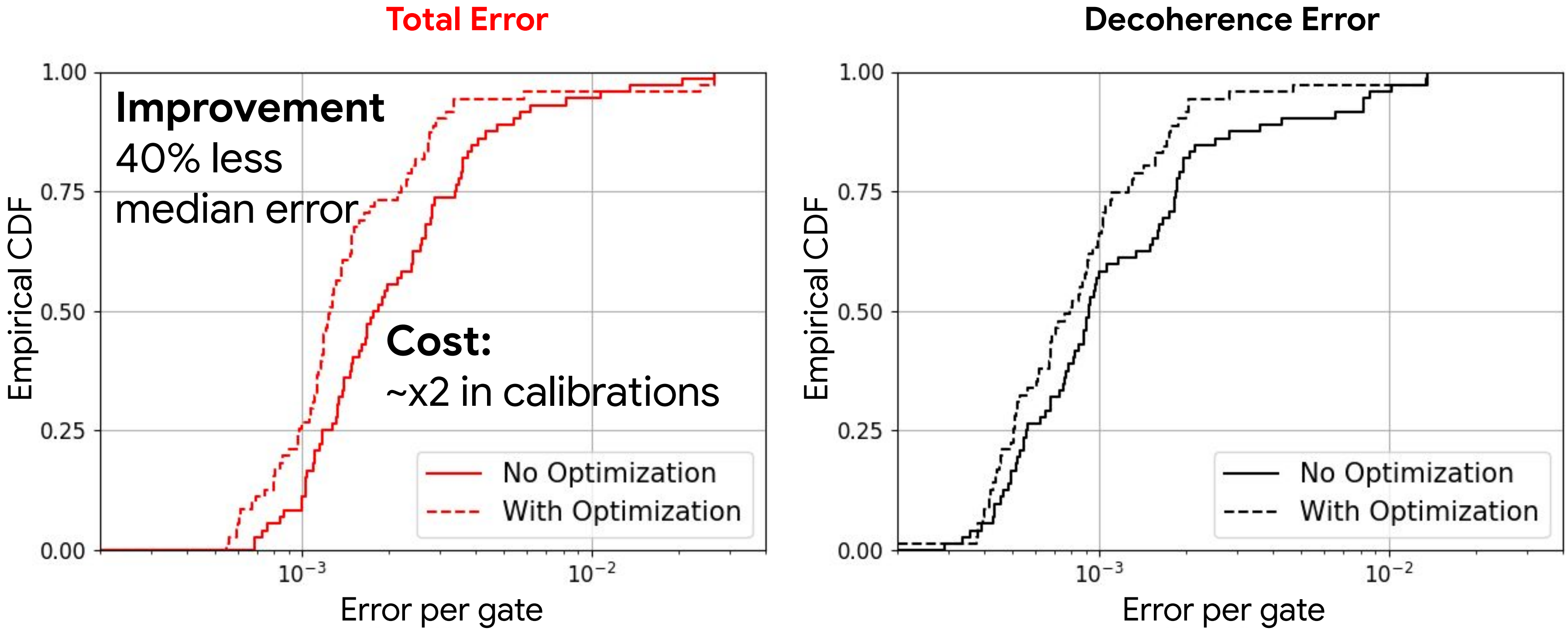


Calibration Study: Frequency Optimization

Larger
is
better



Fidelity improvements from frequency optimization



Experiments

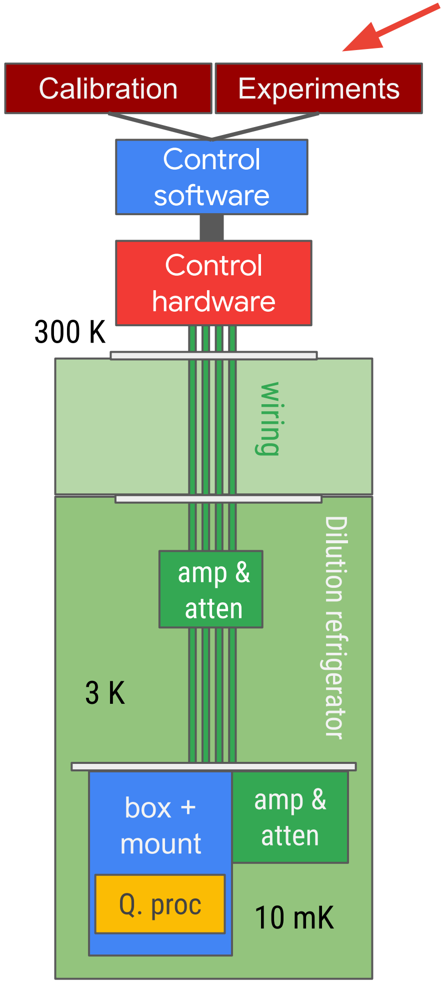
Noise study

Error/control study

Algorithm study

Sampling from random quantum circuit

etc.



Pursuit of quantum supremacy

Quantum supremacy

arXiv:1203.5813

QUANTUM COMPUTING AND THE ENTANGLEMENT FRONTIER

JOHN PRESKILL

Institute for Quantum Information and Matter
California Institute of Technology
Pasadena, CA 91125, USA

We therefore hope to hasten the onset of the era of *quantum supremacy*, when we will be able to perform tasks with controlled quantum systems going beyond what can be achieved with ordinary digital computers. To realize that dream, we must overcome the formidable enemy of *decoherence*, which makes typical large quantum systems behave classically. So another question looms over the subject:

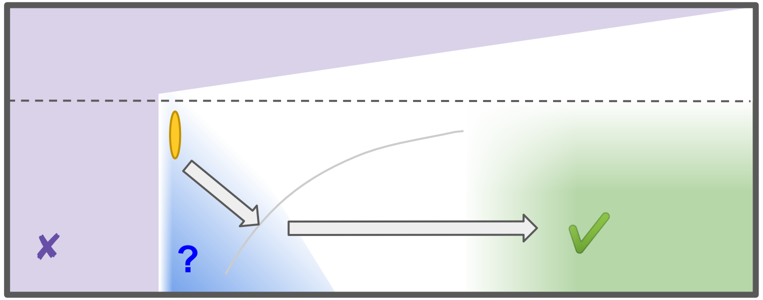
Is controlling large-scale quantum systems merely ***really, really hard****, or is it* ***ridiculously hard****?*

Quantum supremacy

Find **one** problem and demonstrate supremacy with real quantum hardware.

- A test of both quantity (number of qubits) and quality (fidelity).
- The problem itself does not need to have real world applications.

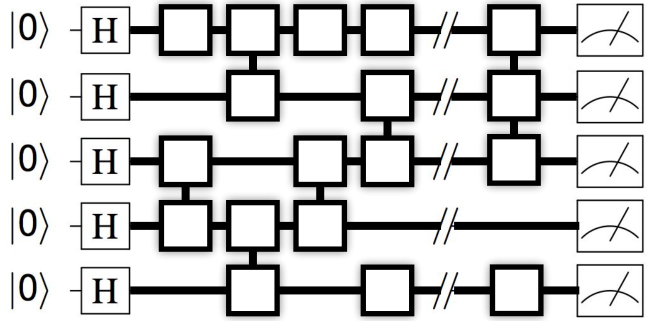
It's like a **beam test** on detectors.



My personal take: "Before claiming that you can fly, can you show that you can run instead of just walking?"

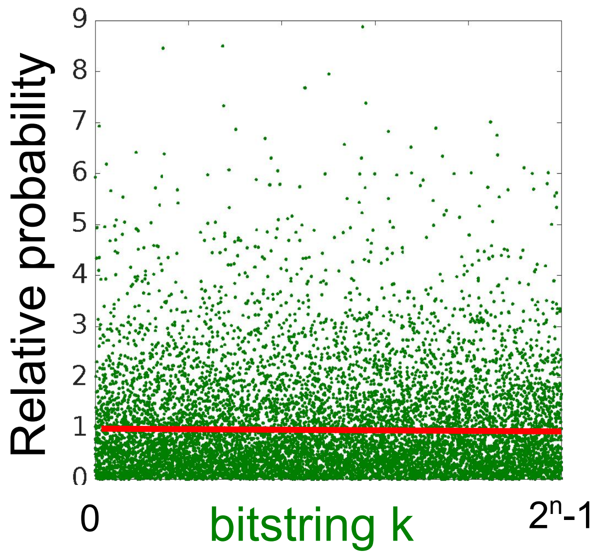
The problem Google picked: quantum sampling

Problem: Given a random quantum circuit of **n** qubits and depth **m**, sample **M** bitstrings according to the probability distribution of the final state.



$$|0\rangle^{\otimes n} \mapsto H^{\otimes n}|0\rangle^{\otimes n} = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes n} \mapsto U\left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes n} = \sum_{i=1}^{2^n} c_i |x_i\rangle$$

$$p_U(x_i) = |c_i|^2$$



Quantum sampling: theory

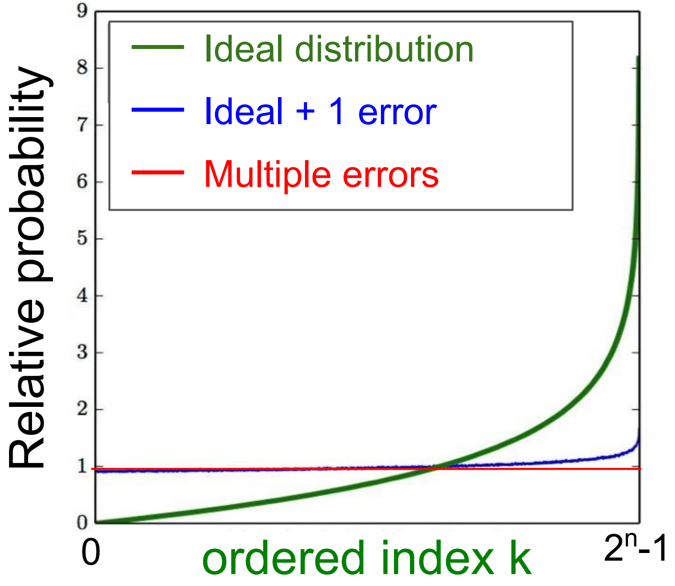
Prob(k) ~ Porter-Thomas distribution when error = 0 (ideal).

$$P(p) \propto e^{-Dp}$$

D = dimension of Hilbert space = 2^n

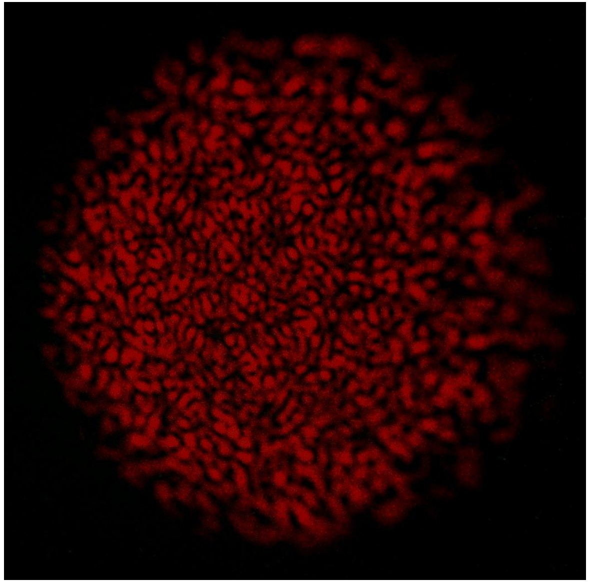
Decoherence error destroys it

~ uniform distribution



S. Boixo et al. Nature Physics **14**, 595–600 (2018), arXiv:1608.00263

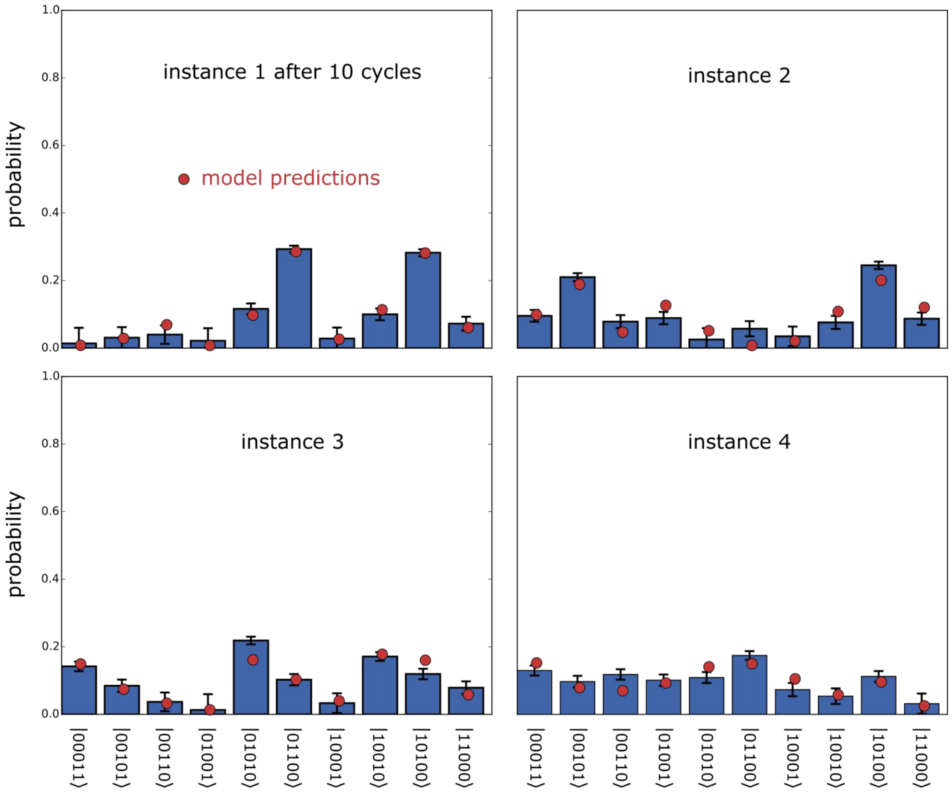
Intuition: coherence test



Coherent quantum interference: speckles

Incoherent classical light

Experimental Results with 5 qubits



Looks good qualitatively!

Quantitatively?

Cross-entropy benchmark (XEB)

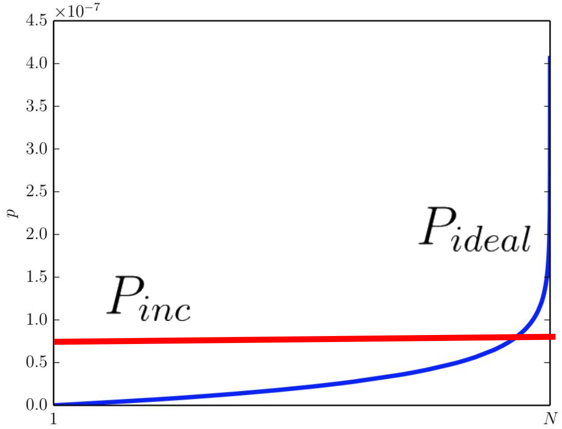
Cross entropy between 2 distributions *p* and *q*:

$$S(p(k), q(k)) \equiv -\sum_i p(k_i) \log q(k_i)$$

Fidelity $F = \dfrac{S(P_{inc}, P_{ideal}) - S(P_{expt}, P_{ideal})}{S(P_{inc}, P_{ideal}) - S(P_{ideal}, P_{ideal})}$

$$F = \begin{cases} 0, & \text{if } P_{expt} = P_{inc} \\ 1, & \text{if } P_{expt} = P_{ideal} \end{cases}$$

from classical simulation of ideal circuit

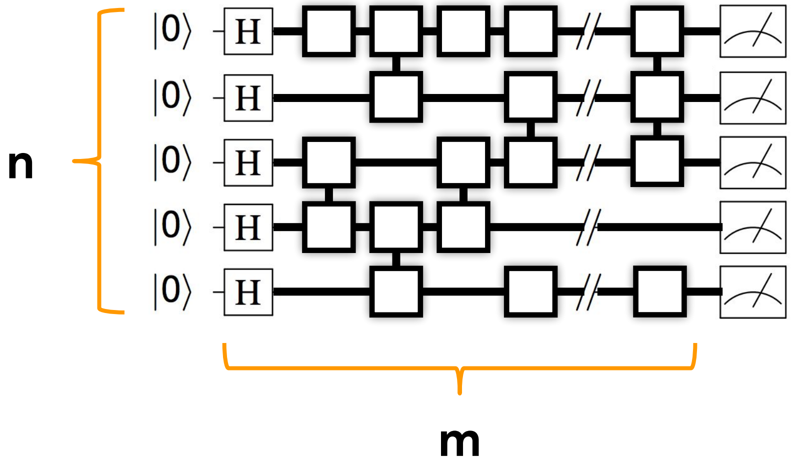


ordered index k_i

Likelihood ratio yields similar results

The quantum supremacy question

Given a random quantum circuit with **n** qubits and depth **m**, what's the amount of computation (core * hours) needed for a classical computer to sample **M** bitstrings from a quantum computer with fidelity **F**?



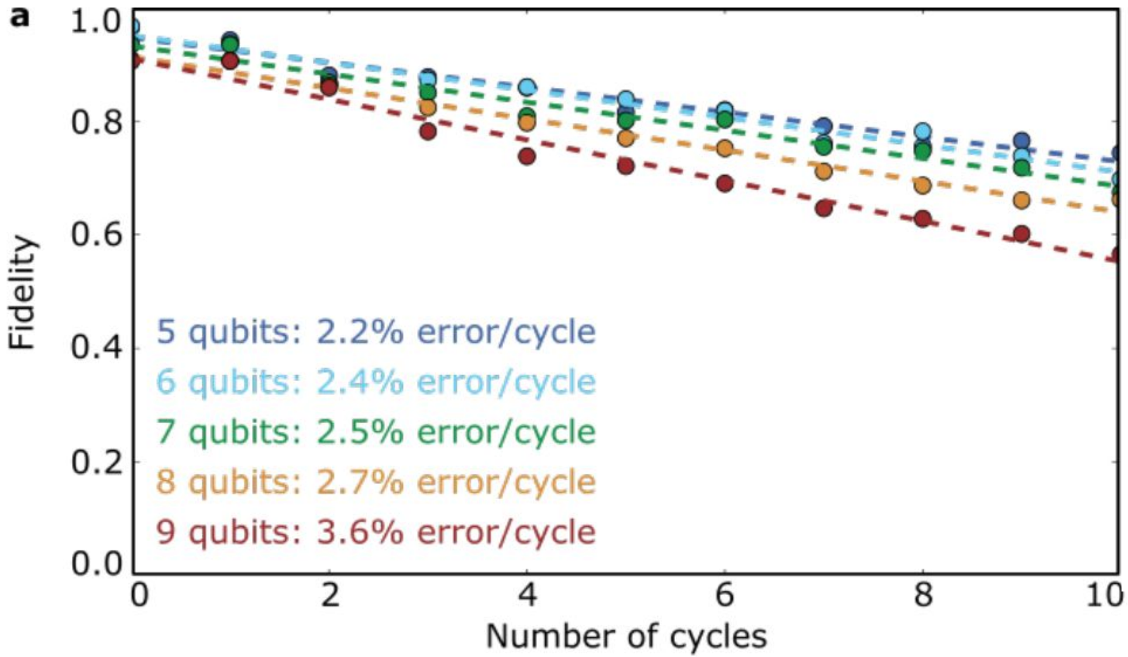
Expect:

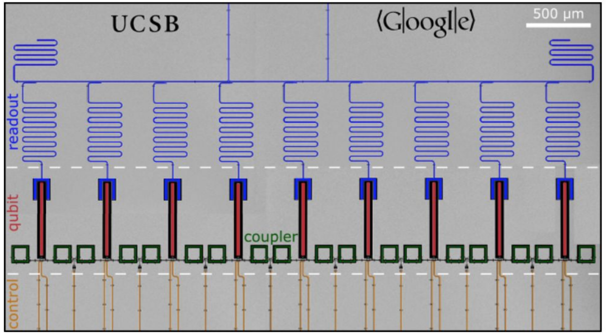
For large enough **n** and **m** with a decent **F**, this is out of reach for classical computers.

How good is your quantum computer hardware?

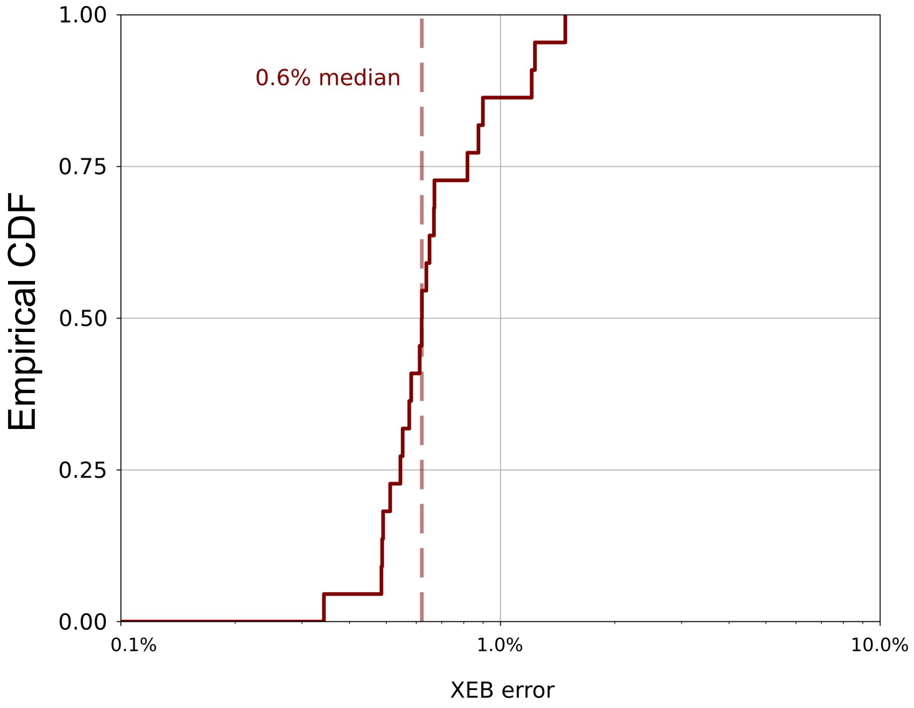
Data from 9-qubit experiments

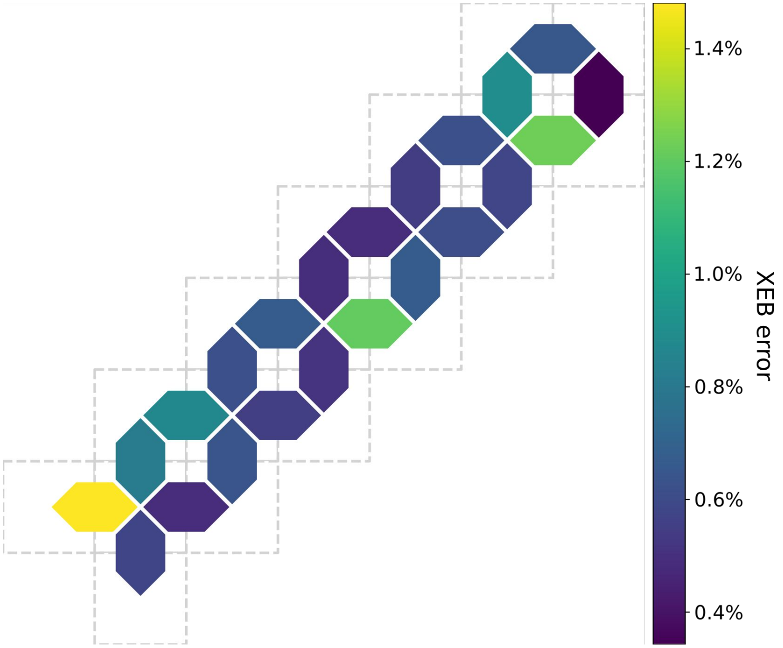
"A blueprint for demonstrating quantum supremacy with superconducting qubits", Science **13** Apr 2018 | arXiv:1709.06678



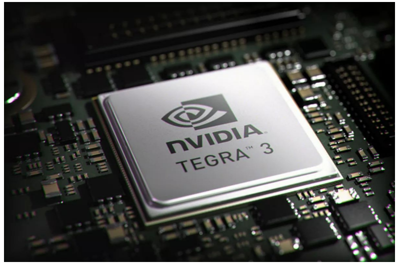


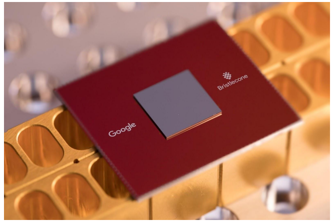
Two-qubit gate errors from an 18-qubit chip





Classical computing power vs. quantum





Simulation on Summit

Establishing the Quantum Supremacy Frontier with a 281 Pflop/s Simulation

Benjamin Villalonga[1,2,3,*], Dmitry Lyakh[4,5†], Sergio Boixo[6,‡], Hartmut Neven[6,+], Travis S. Humble[4,§], Rupak Biswas[1,×], Eleanor G. Rieffel[1,¶], Alan Ho[6,‖], and Salvatore Mandrà[1,7,⊢]

[1] Quantum Artificial Intelligence Lab. (QuAIL), NASA Ames Research Center, Moffett Field, CA 94035, USA
[2] USRA Research Institute for Advanced Computer Science (RIACS), 615 National, Mountain View, California 94043, USA
[3] Institute for Condensed Matter Theory and Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[4] Quantum Computing Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[5] Scientific Computing, Oak Ridge Leadership Computing, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[6] Google Inc., Venice, CA 90291, USA
[7] Stinger Ghaffarian Technologies Inc., 7701 Greenbelt Rd., Suite 400, Greenbelt, MD 20770

https://arxiv.org/abs/1905.00444

Estimation for a hypothetical 49 qubit QC

		Runtime (hours)			Energy cost (MWh)		
Circuit size	Target fidelity (%)	Electra	Summit	QPU	Electra	Summit	QPU
$7 \times 7 \times (1 + 40 + 1)$	0.5	59.0	2.44	0.028	96.8	21.1	4.2×10^{-4}

49 qubits @ depth 40

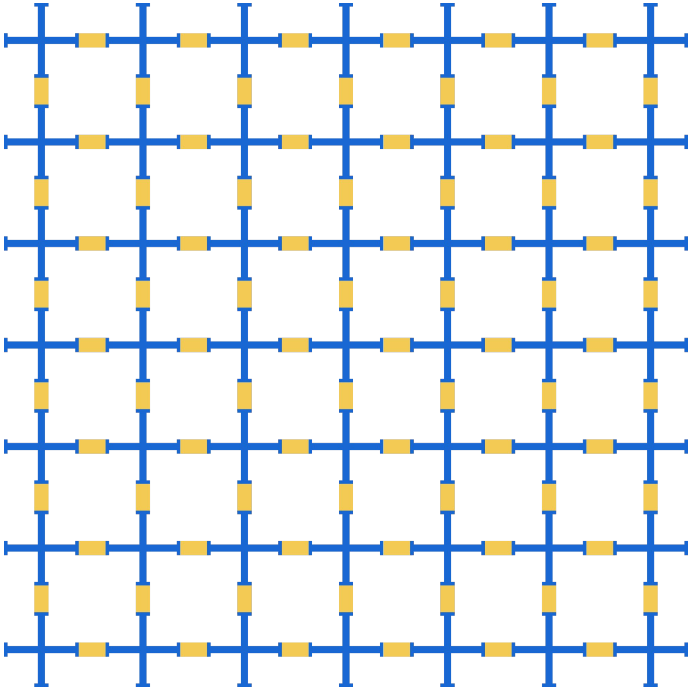
$O(10^2)$ advantage

$O(10^5)$ advantage

https://arxiv.org/abs/1905.00444

Projection for quantum supremacy

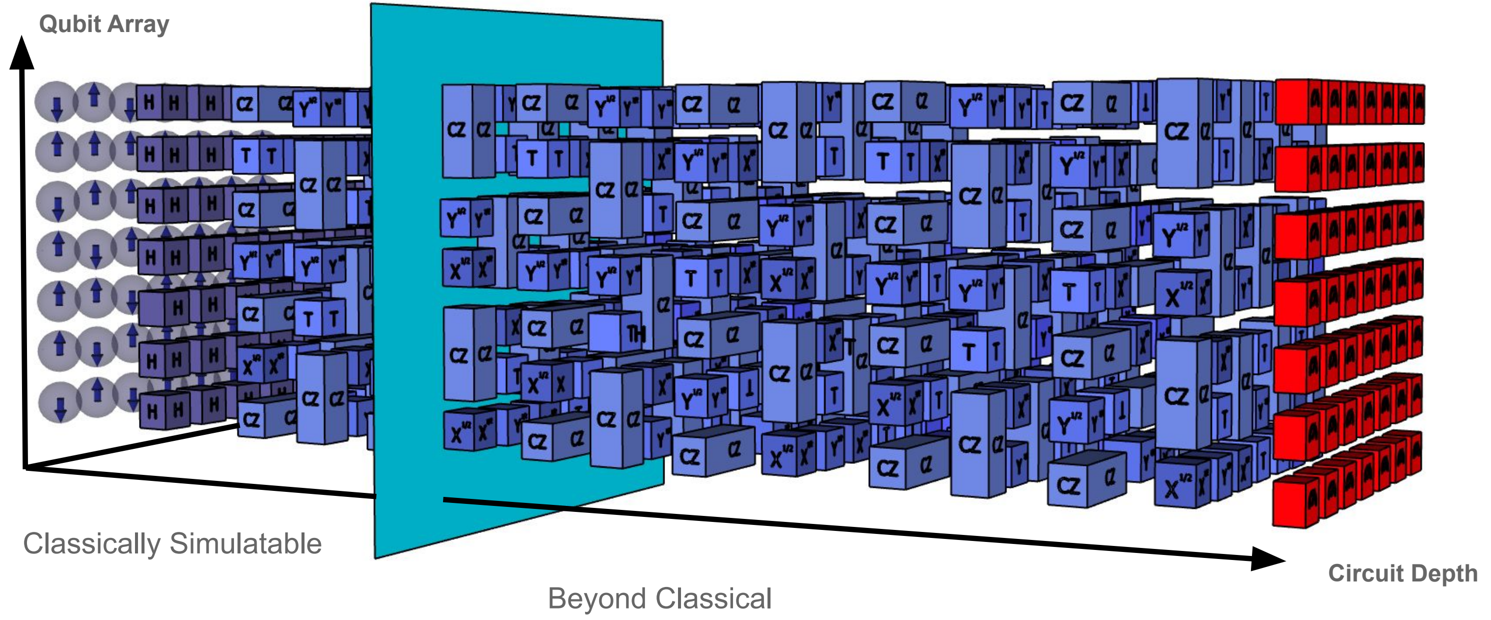
Supremacy ~49 qubits & depth ~12



		Error
1-Qubit gate fidelity	99.9%	0.1%
2-Qubit gate fidelity	99.2%	0.8%
Readout fidelity	97.0%	3%
Projected supremacy fidelity	$\boxed{1.6\%}$	

Measurements needed for 5-sigma supremacy: **M** ~ 10^5

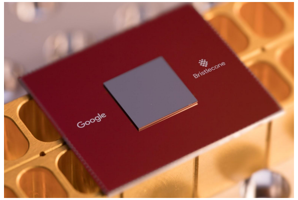
Established Frontier of Quantum Computation



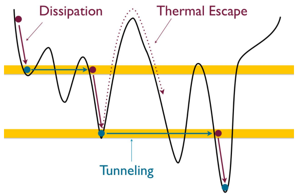
Collaboration opportunities

Google Academic Funding

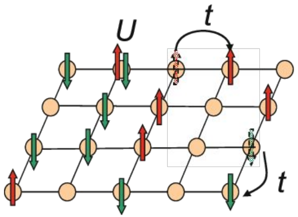
Faculty Research Awards	Focus Awards
1 year funding	2 - 3 years
1 graduate student	1+ graduate student
Collaborate with Google researchers	
Potential access to hardware	
8 awarded in 2018	
Application deadline: 10/1 5am JST	



Better hardware



Better algorithm



First applications

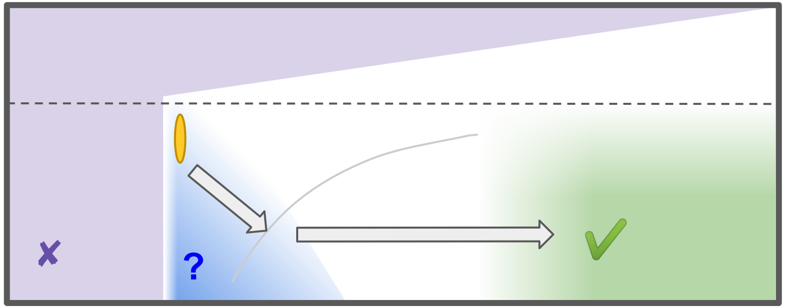
Conclusions

Quantum computing will grow as hardware becomes more capable

Google is attempting to reach quantum supremacy

Primary challenge: good coherence at larger scale / implement error correction

Collaboration opportunities




Google AI
Quantum