Google AI
Quantum

Is the hype real? An introduction to quantum computing

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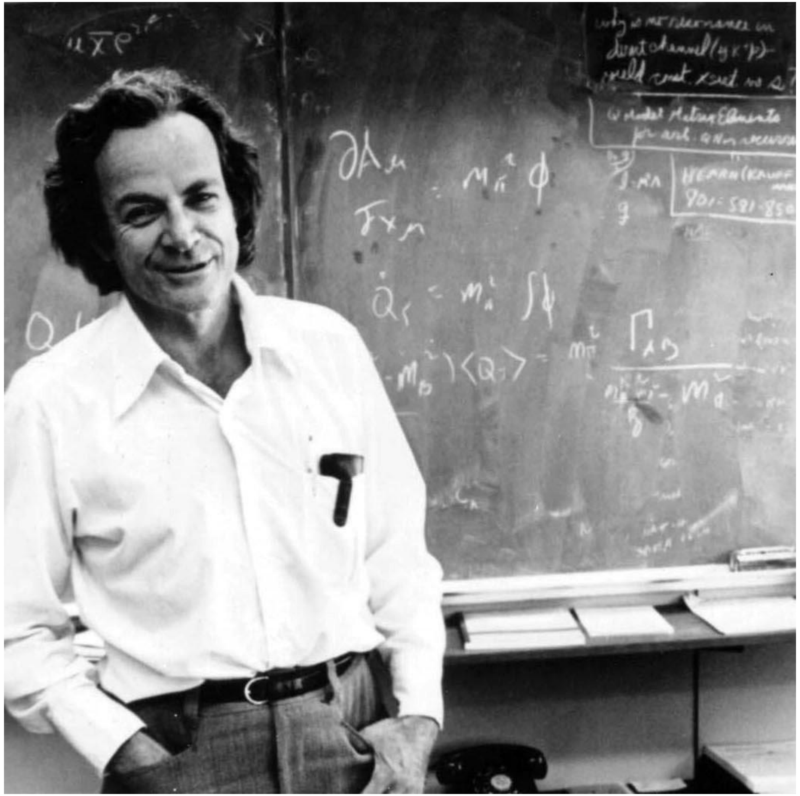
Google Santa Barbara
ISGC 2019, April 4, Taipei

By the end of this talk, hopefully you'll be able to tell hype from reality about quantum computing.

The mandatory quote: idea of quantum computing



"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

— Feynman, "Simulating Physics with Computers", Int. J. of Theo. Phys., **21**, 6/7, p. 467 (1982)

Wonderful

&

Not so easy

My kind of problem! 😄

Recent news

.... just Google "quantum computing"

Public funding around the world

Quantum computing research funding data in 2015 (Source: Tech Crunch https://tcrn.ch/2BfZS9i)

- European Union: $643 million
- U.S.: $421 million
- China: $257 million
- Germany: $140 million
- Britain: $123 million
- Canada: $117 million
- Twenty countries have invested at least $10 million

EU: Quantum Flagship started in 2018-10, 10+ years, €1B.

National Quantum Initiative of U.S.

https://www.congress.gov/bill/115th-congress/house-bill/6227

10 year plan

$1.2B over 5 years, not affecting other research fields as written in bill. Funding Agencies: NIST (400M), DOE (625M), NSF (250M).

Heavy emphasis on workforce development

"Quantum information science is the use of the laws of quantum physics for the **storage**, **transmission**, **manipulation**, or **measurement** of information."

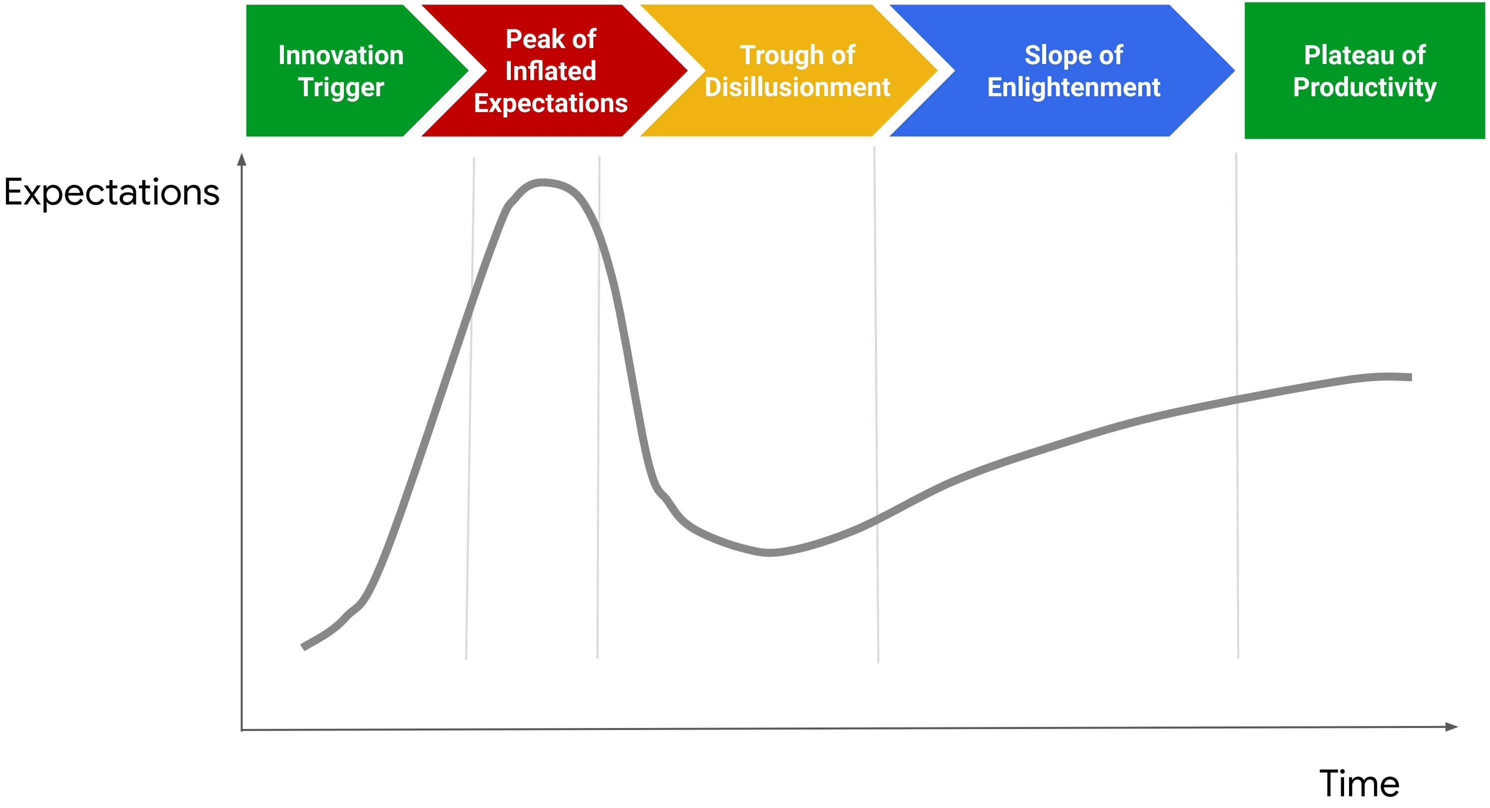
"Temperature" of researches

Talks and posters in the March Meeting of American Physical Society, 2019.

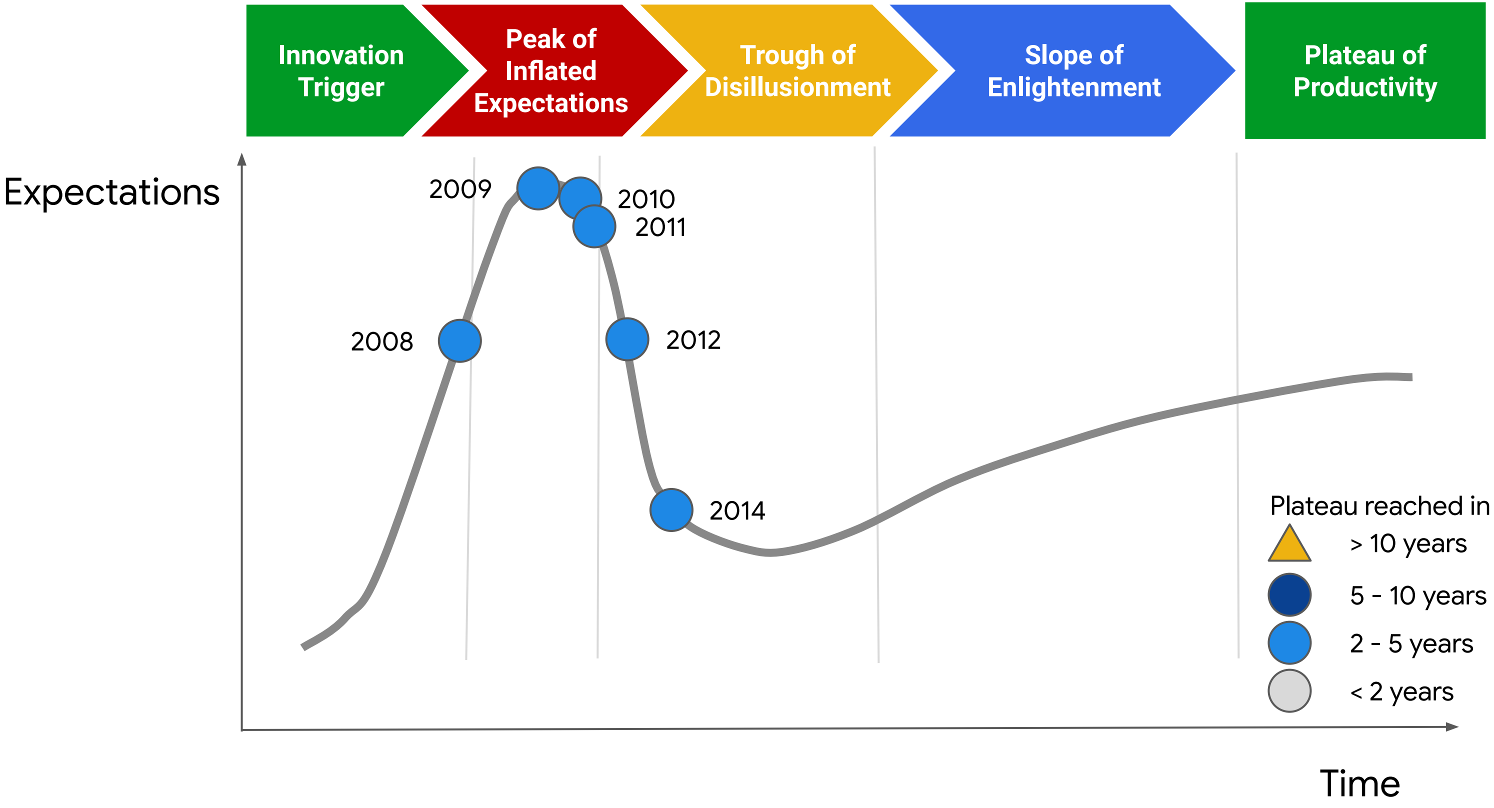
Search word in title or abstract	Talks	Posters	Total
qubit	631	23	654
quantum comput	333	24	357
quantum simulat	81	7	88
quantum algorithm	58	2	60
quantum anneal	47	0	47
NISQ	26	1	27
adiabatic quantum	14	1	15
QAOA	10	1	11
VQE	10	1	11
Union	861	41	902
Whole meeting	10160	1204	11364
Percentage	8.5%	3.4%	7.9%

p.s. Personal counts, your counts may vary

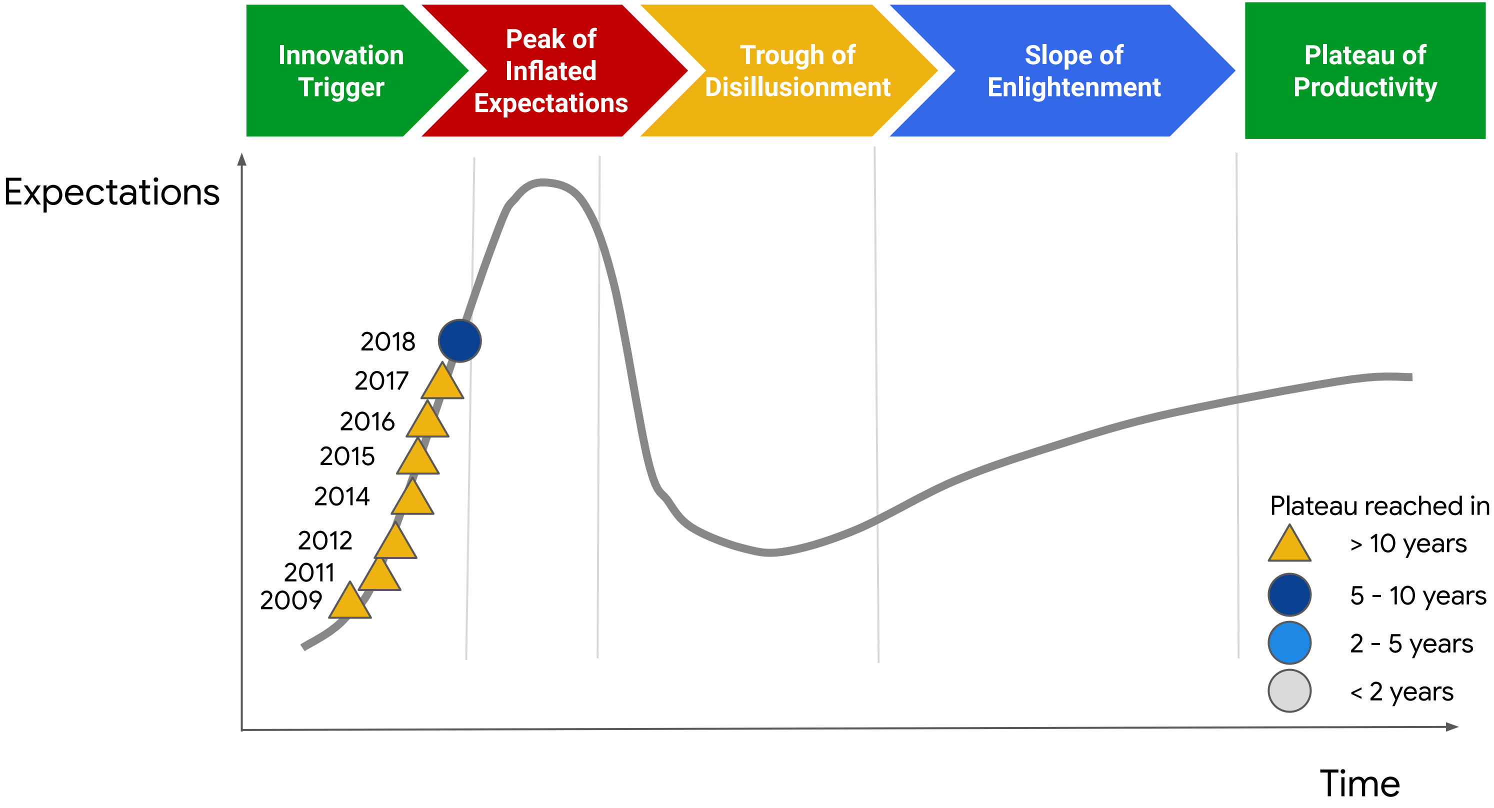
Gartner hype cycle of technologies



Past example: Cloud Computing



Quantum Computing on the hype curve



Quantum Computing Roadmap v2, 2004-04

> “ 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. ”

Not achieved yet!

> “ 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. ”

Skepticism

Dyakonov: "The perspectives of quantum computing appear to be extremely doubtful." Int. J. of Mod. Phys. Conf. Ser. **33**, 1460357 (2014)

- Precision of control and measurement at scale
  - Analog system
  - Instability of nonlinear system
  - Zhdanov: quantum control landscape is not "trap-free" [arXiv:1710.07753]
- Free evolution of quantum states
- How to debug an algorithm requiring 1000 qubits (2^{1000} amplitudes)?

The works

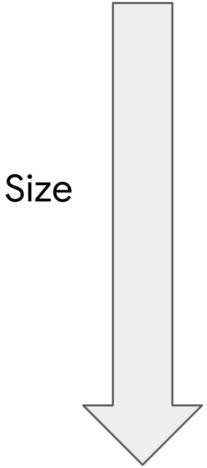
👷🔧🔩🔬

What is Quantum Computing?

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

Some 2-state quantum systems:

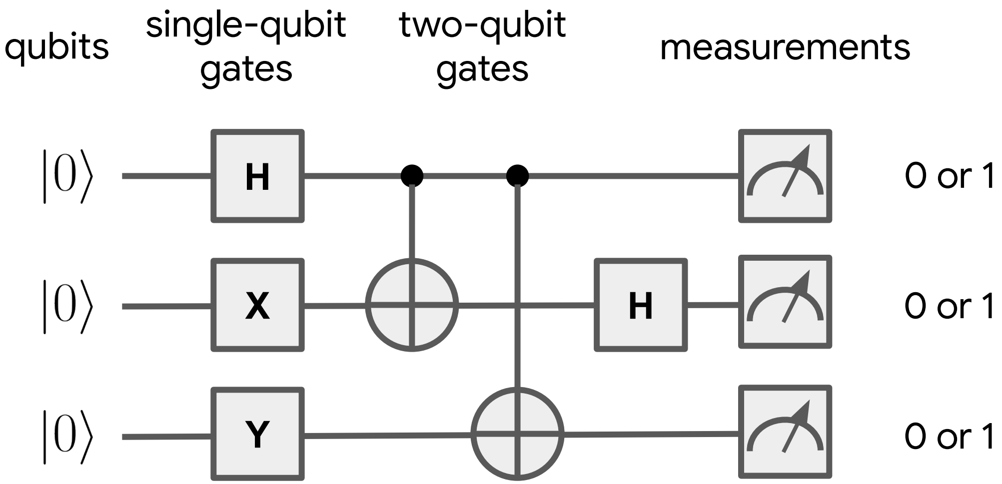
- Photons with 2 modes: polarizations, cavities, etc
- Nuclear spins: up & down
- Trapped Ions: ground state and excited state
- Neutral Atoms: motion state or internal state
- Molecular spins: up & down
- Quantum dots: spin up & down
- Superconducting circuits:



The computation model

Turing machine → Quantum Turing machine

Alternatively: Quantum circuit



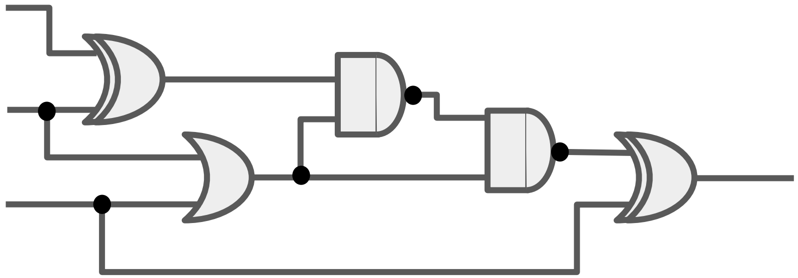
Other models: quantum annealing, adiabatic quantum computing.

Classical logic circuit

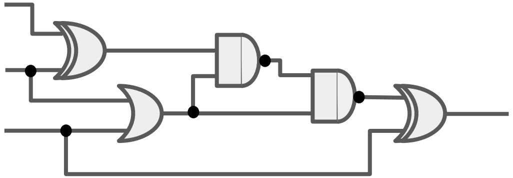
input bits

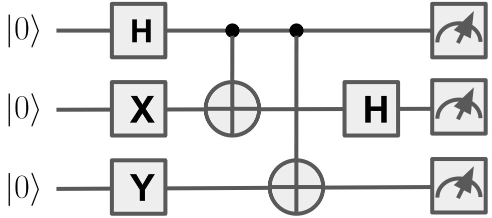
logic gates

output bits



Key differences





One bit = {0, 1} = 0 or 1

One qubit = c_0 |0> + c_1 |1>, $|c_0|^2 + |c_1|^2 = 1$

Superposition

n bits = $\{0, 1\}^n$

Stores 1 in 2^n

n qubits = c_0 |00..0> + c_1 |00..1> + c_{D-1} |11...1>, D = 2^n

Stores 2^n at the same time

Physical system: gates

Physical system: qubits

Voltage level: bits

Microwave pulses / photons / etc: gates

Trivial to copy bits

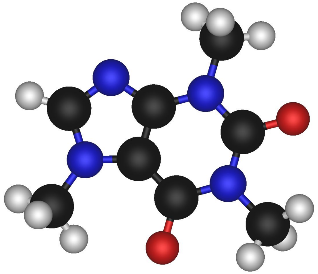
No-cloning theorem

Deterministic*

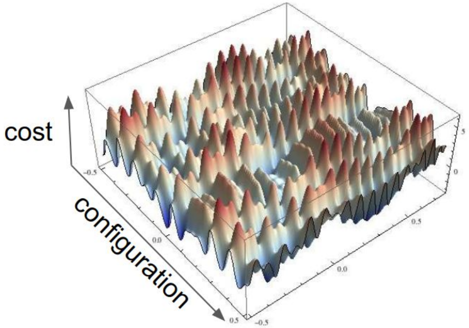
Probabilistic, P(measures x) = $|c_x|^2$

Projected applications of quantum computing

Quantum Simulation



Optimization



Factoring

$$15 = 5 \times 3$$

Exponential speedup for factorization

Classical factorization: $O\left(e^{1.9(\log N)^{1/3}(\log\log N)^{2/3}}\right)$

Shor's algorithm (1994) $O\left((\log N)^2(\log\log N)(\log\log\log N)\right)$

For RSA-2048, N ~ 2^{2048}, it can be age of universe vs. < 1 day.

Implications for RSA encryption, public key infrastructure.

NIST's call-for-proposal on Post-Quantum (Quantum-safe) Cryptography.

- Round-2 candidates announced on January 30, 2019
- Details at https://csrc.nist.gov/Projects/Post-Quantum-Cryptography/

2519590847565789349402718324004
8398571429282126204032027777137
8360436620207075955562640185258
8078440691829064124951508218929
8559149176184502808489120072844
9926873928072877767359714183472
7026189637501497182469116507761
3379859095700097330459748808428
4017974291006424586918171951187
4612151517265463228221686998754
9182422433637259085141865462043
5767984233871847744479207399342
3658482382428119816381501067481
0451660377306056201619676256133
8441436038339044149526344321901
1465754445417842402092461651572
3350778707749817125772467962926
3863563732899121548314381678998
8504044536402352738195137863656
4391212010397122822120720357
(617 digits, $200,000 award)

Why quantum computing is hard: Errors

Bloch sphere representation of a qubit:

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

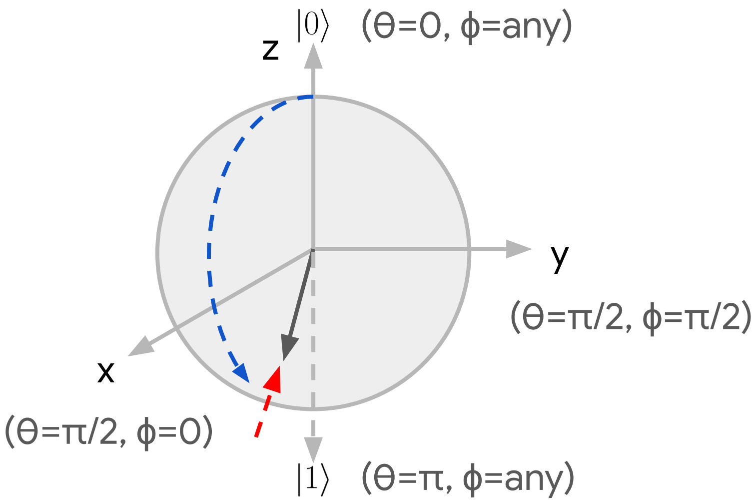
A gate operation: from (θ, ϕ) to (θ', ϕ')

- can be realized as a rotation
- NOT gate = rotate along x-axis by π
- What about π/2 rotation?

Qubit control is fundamentally challenging

- Analog control errors: over/under rotation, deviation of the rotation axis
- Decoherence (environmental) errors: random bit flips / phase changes

Polar coordinates (θ, ϕ)



Qubit error mechanisms inform nearly all design decisions

End Goal: Universal Fault-Tolerant QC

Qubit error rates ~10^{-2}-10^{-3} per operation

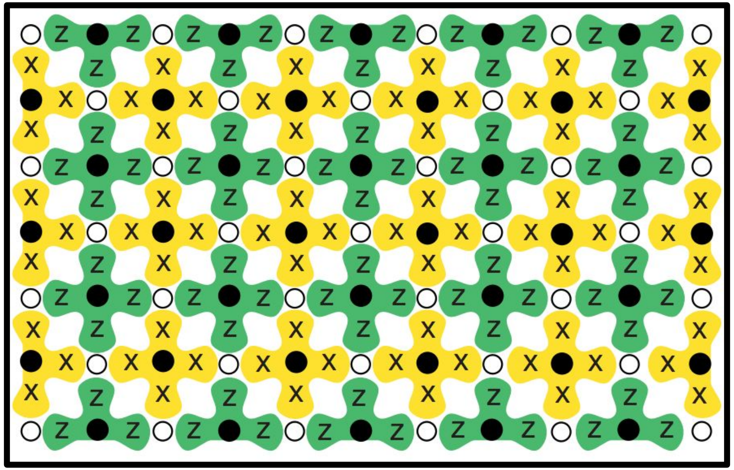
Universal QC requires ~10^{-10}

Error correction:

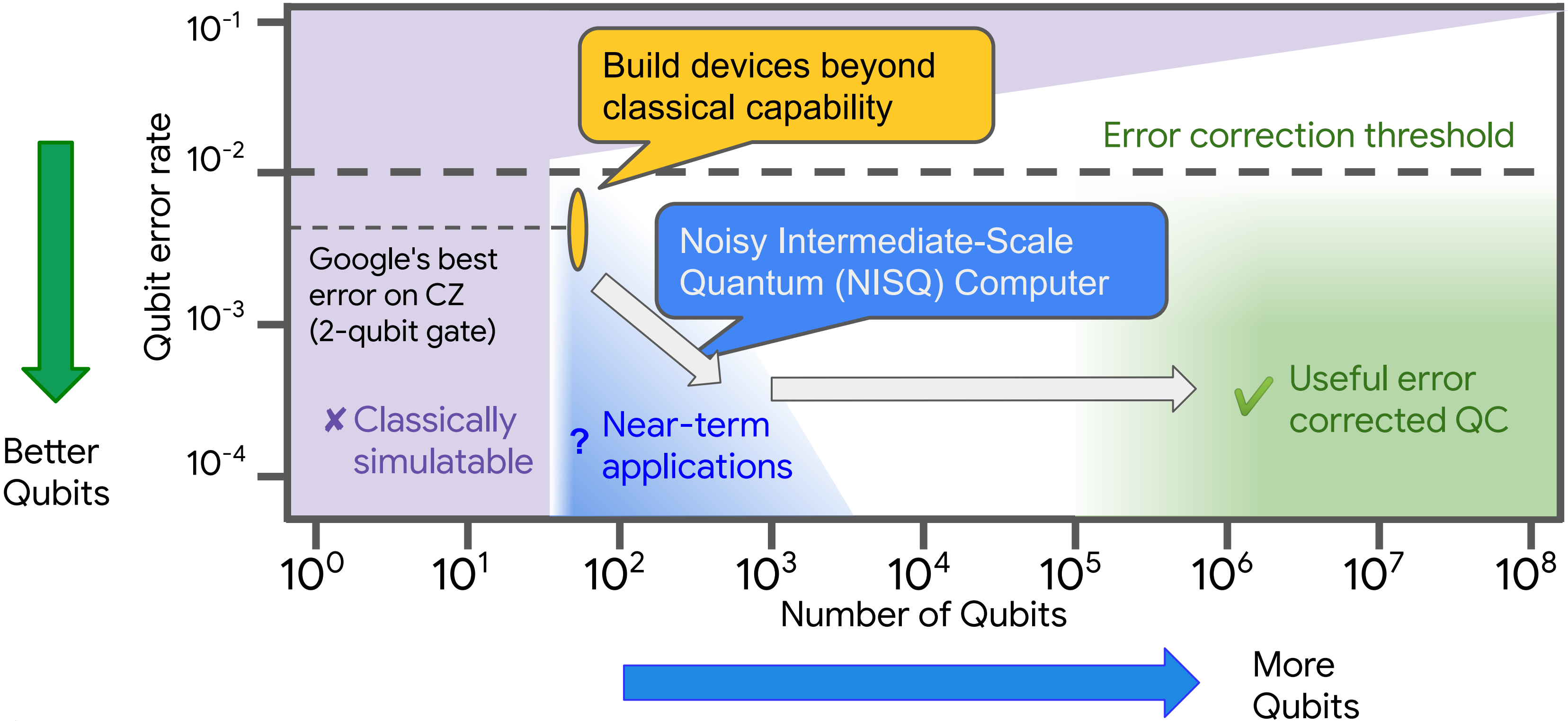
- Low error logical qubit made with many physical qubits

Surface code error correction:

- 2D array of qubits (nearest-neighbor coupling)
- Modest error rates (10^{-2} threshold, 10^{-3} target)
- Useful at 10^5-10^6 physical qubits



When is a Quantum Computer Useful?



Many Faces of Quantum Computers

DiVincenzo Criteria for Quantum Computers

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

Published in 1996

D. P. DiVincenzo, Topics in Quantum Computers. In: Mesoscopic Electron Transport, L. Kowenhoven, G. Schoen and L. Sohn (eds.), NATO ASI Series E, Kluwer Ac. Publ., Dordrecht, 1996; arXiv:cond-mat/9612126v2.

Two more criteria were added for quantum communications later.

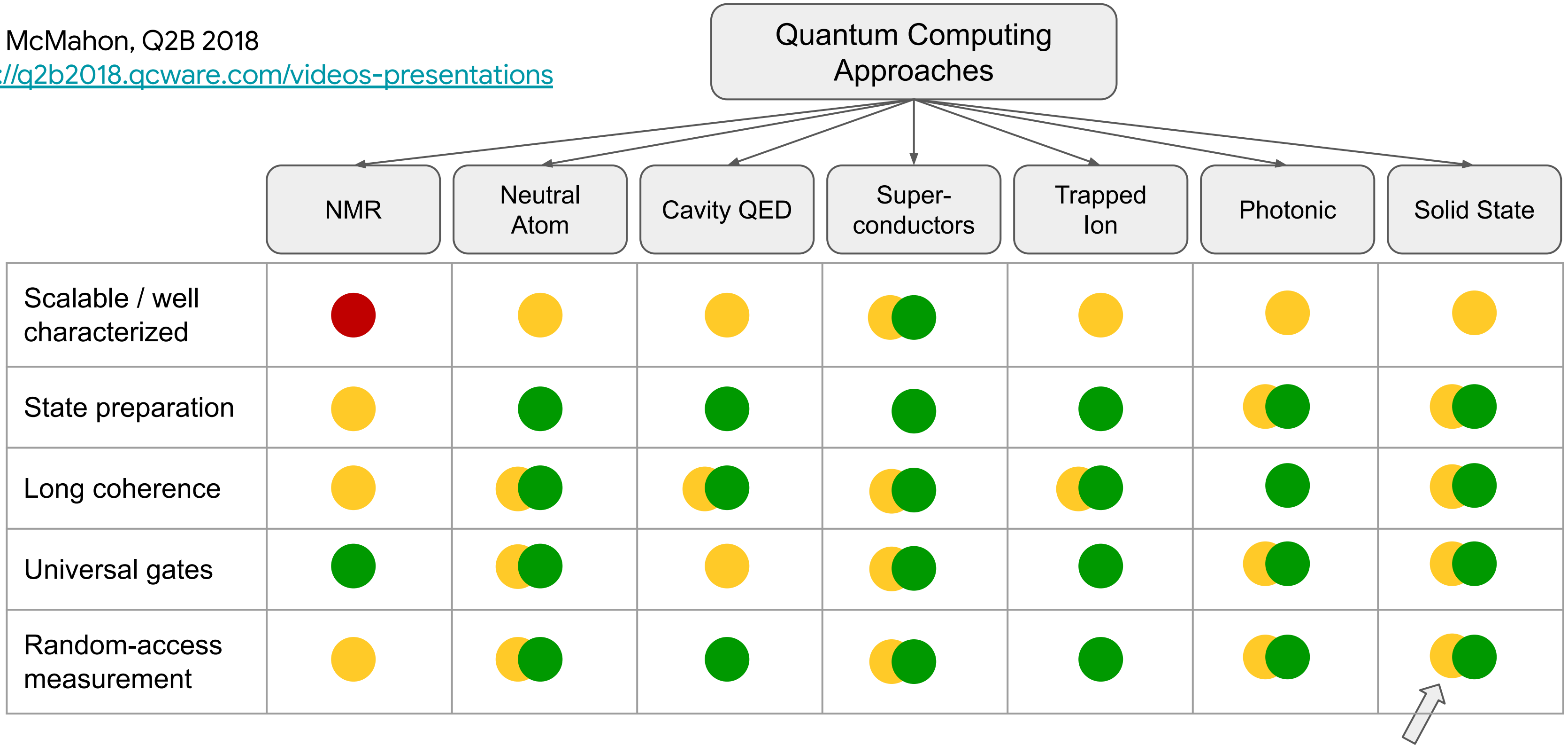
QC Roadmap 2.0 (2004)
https://qist.lanl.gov/pdfs/qc_roadmap.pdf

Quantum Computing Approaches

	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

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



	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
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QC Roadmap 2.0 (2004)

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

Google AI
Quantum

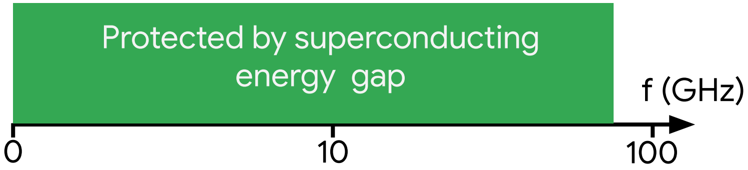
Principle of Superconducting Qubits (1/4)

Superconductor

- No resistance, no energy loss / information loss via Joule heating.
- Collective motion in a macroscopic quantum state: same wave function for every electron.

$$\psi(\vec{r}) = a(\vec{r})\ e^{i\phi(\vec{r})}$$

- Energy gap Δ: electrons in superconducting state can absorb photons with E > Δ to jump to normal state. $\Delta_{\text{Aluminum}} = 3.4 \times 10^{-4}$ eV ≈ 82 GHz.

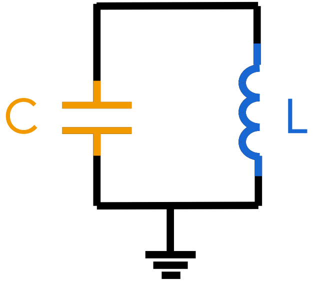


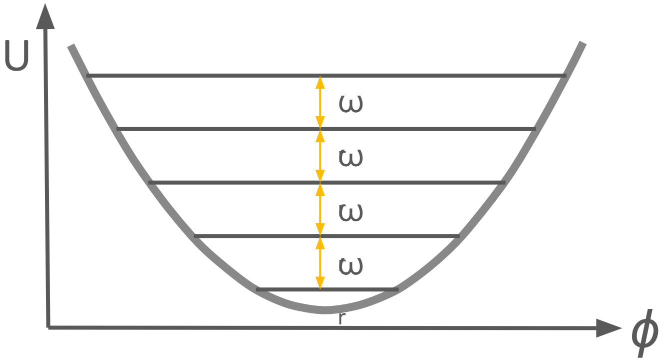
Principle of Superconducting Qubits (2/4)

Inductor-Capacitor (LC) circuit: harmonic oscillator.

$$V_L = L\frac{dI}{dt} \qquad V_c = \frac{Q}{C}$$

Hamiltonian $H = Q^2/2C + \phi^2/2L$





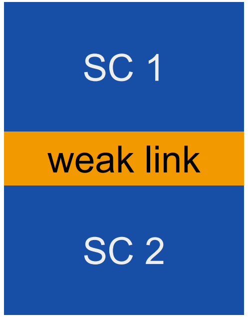
Problem: same frequency between all adjacent levels, no way to guarantee a 2-state system.

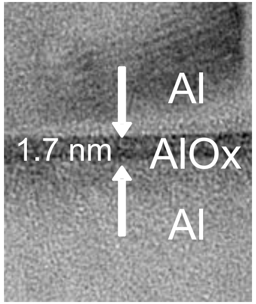
Principle of Superconducting Qubits (3/4)

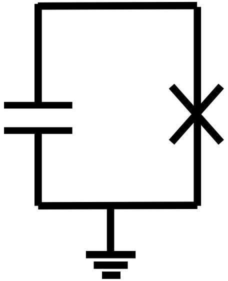
Josephson Junction as a non-linear inductor.

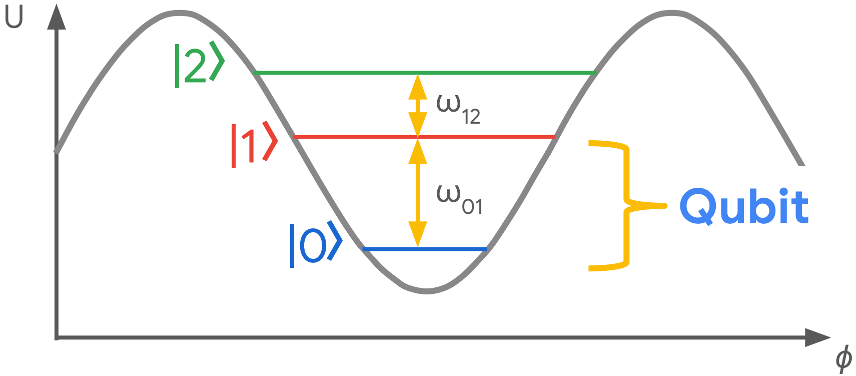
Thickness of weak link need to be < ~10 nm.

$$\begin{aligned}\phi &= \phi_1 - \phi_2\\ I &= I_c \sin\phi\\ V_{JJ} &= \frac{\hbar}{2e}\frac{\partial\phi}{\partial t}\\ &= \underbrace{\frac{\hbar}{2eI_c\cos\phi}}_{\text{equivalent inductance}}\frac{dI}{dt}\end{aligned}$$



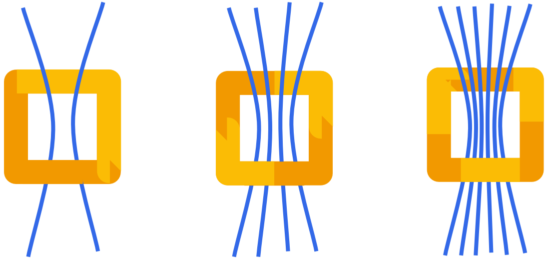






Principle of Superconducting Qubits (4/4)

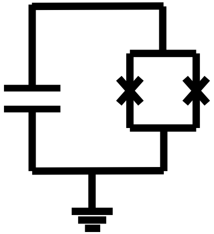
SQUID (2 JJs in a loop) as a variable non-linear inductor.



Magnetic flux through the loop is quantized

External flux bias voltage ⟶ current ⟶ B field ⟶ flux
⟶ JJ current ⟶ JJ phase diff ⟶ JJ inductance

A 2-level system with controllable resonance frequency.



Region of Operation

Take advantage of well-engineered hardware developed for consumer applications (WiFi, LTE, etc.)

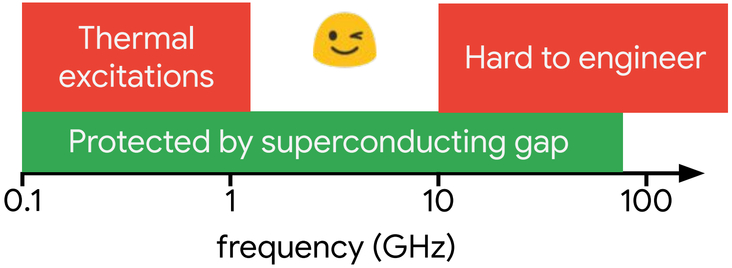
- > 10 GHz hard to engineer

Dilution refrigerator cools to <50 mK

- We operate at T ~ 10 mK (~ 0.2 GHz) to minimize thermal noises

Typical values (transmon):

- $\omega = (LC)^{-1/2}$, $L \approx 8$ nH, $C \approx 80$ fF yields $0 \leftrightarrow 1$ transition frequency ≈ 6 GHz

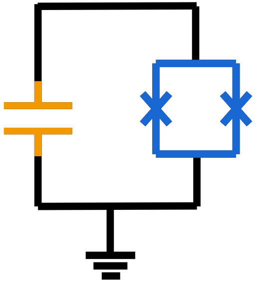


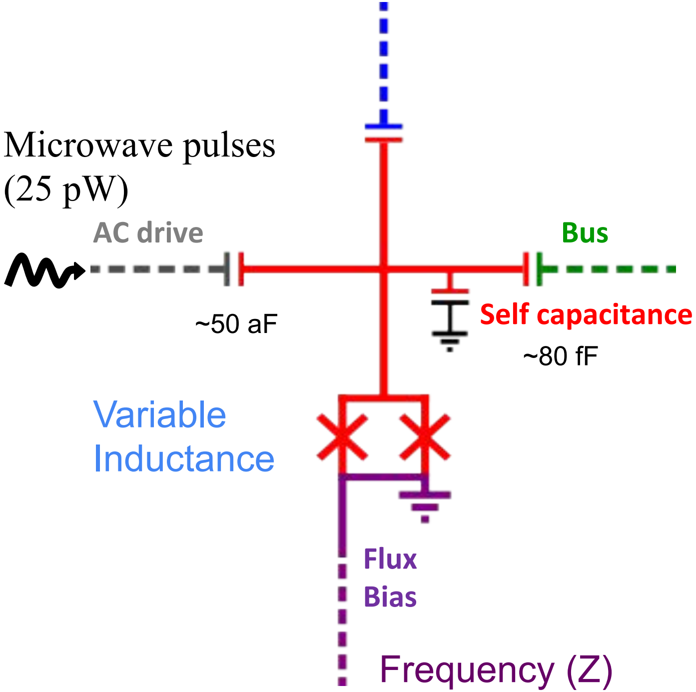
Thermal excitations

Hard to engineer

Protected by superconducting gap

Qubit Circuit





Readout
resonator

Microwave pulses
(25 pW)

AC drive

~50 aF

Bus

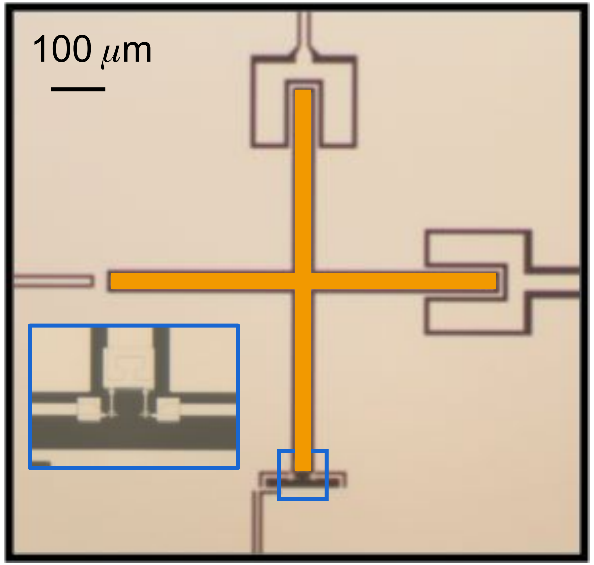
Self capacitance

~80 fF

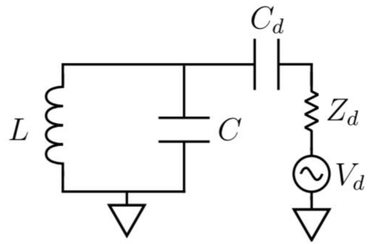
Variable
Inductance

Flux
Bias

Frequency (Z)



Qubit control example: Rabi Oscillation



Driving a qubit on-resonance with a wave

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

causes the qubit to oscillate btw |0> and |1>.

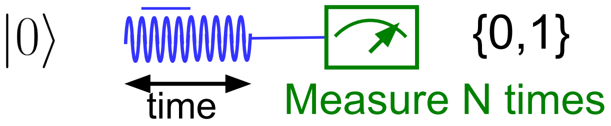
$$|\psi(t)\rangle = \cos(\tfrac{\Omega}{2}t)|0\rangle + ie^{i\phi}\sin(\tfrac{\Omega}{2}t)|1\rangle$$

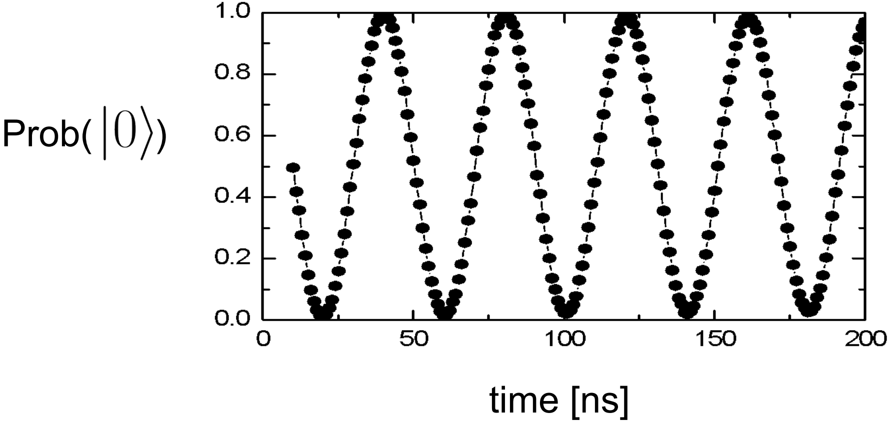
$$\Omega = \frac{C_d}{C+C_d}\frac{V_0 Q_{zpf}}{\hbar}$$ (Rabi frequency)

where

$$Q_{zpf} = \langle 0|Q^2|0\rangle^{\frac{1}{2}}$$

is the zero-point fluctuation of charge.

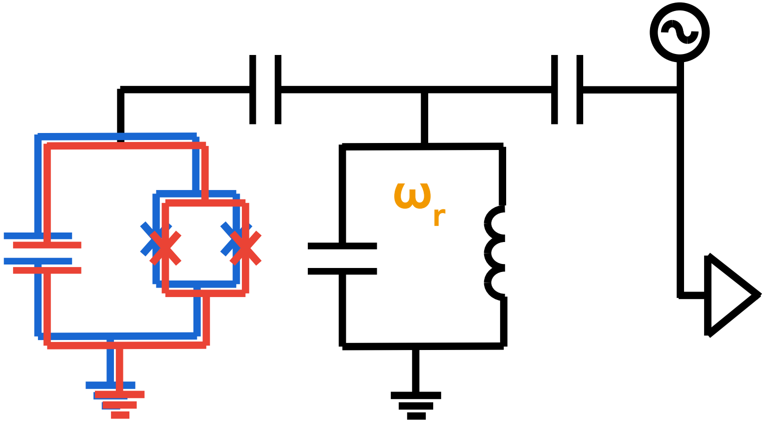


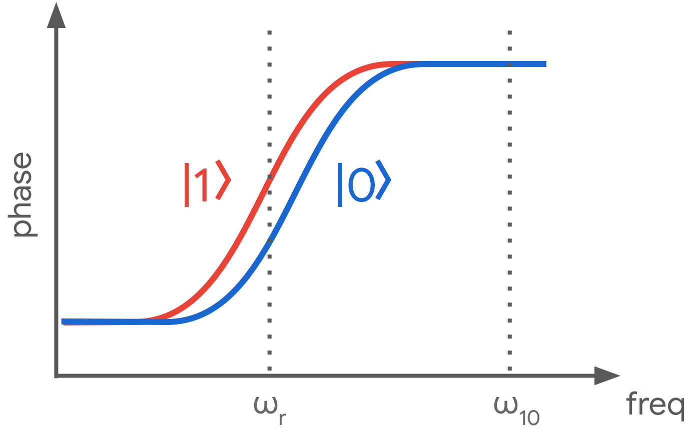


Readout

Dispersive Readout

- Frequency of an off-resonant resonator coupled to qubit depends on state of the qubit
- Probe the off-resonant resonator



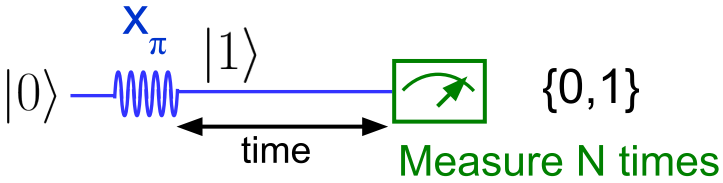


Decoherence

Two commonly used time scales:

1. T_1 = relaxation time from |1> to |0>.
2. T_2 = characteristic time for a coherent ensemble of qubits to become non-coherent (e.g. due to interaction with environment).

X_π = a waveform that rotates a qubit along x-axis by π on the Block sphere.

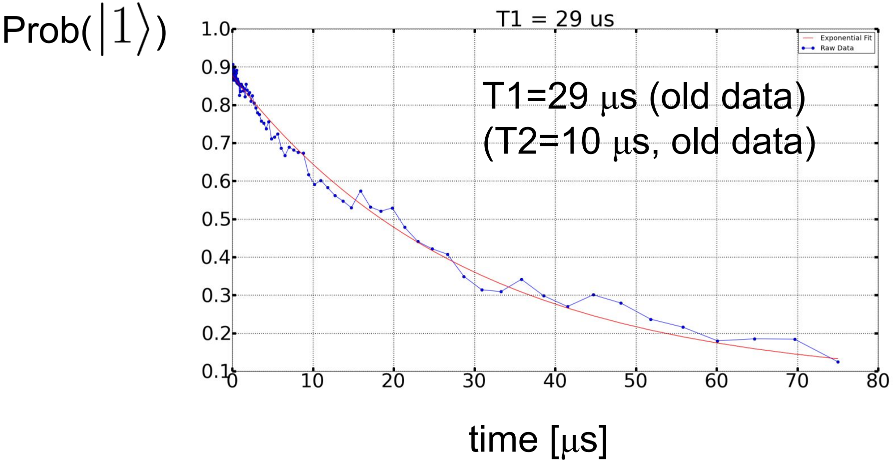


$|0\rangle$ X_π $|1\rangle$

time

{0,1}

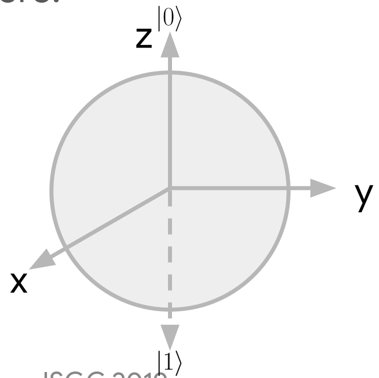
Measure N times



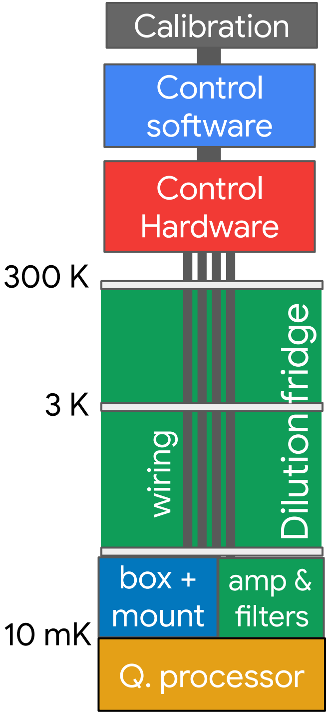
Prob($|1\rangle$)

T1=29 μs (old data)
(T2=10 μs, old data)

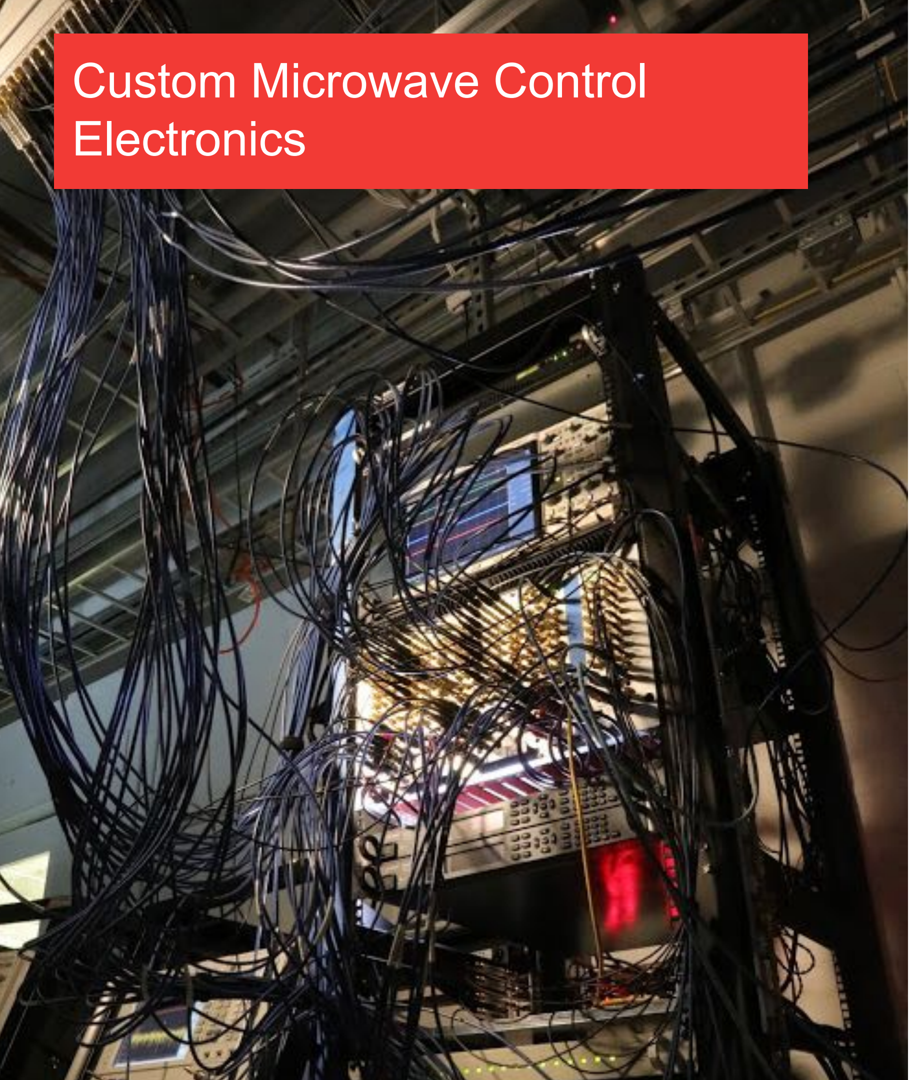
time [μs]

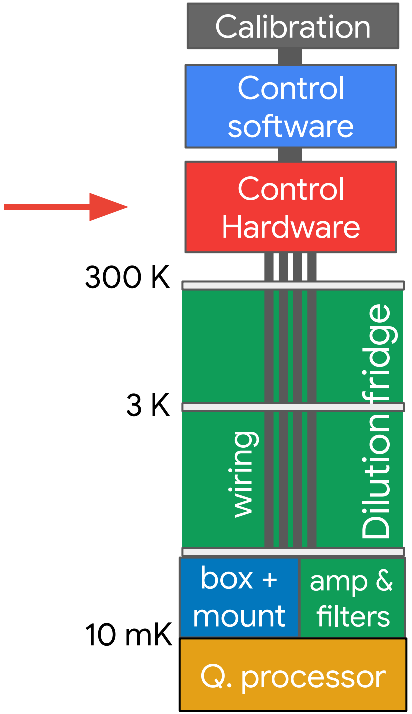


Superconducting qubit system stack



Custom Microwave Control Electronics





Calibration

Control software

Control Hardware

300 K

3 K

10 mK

wiring

Dilution fridge

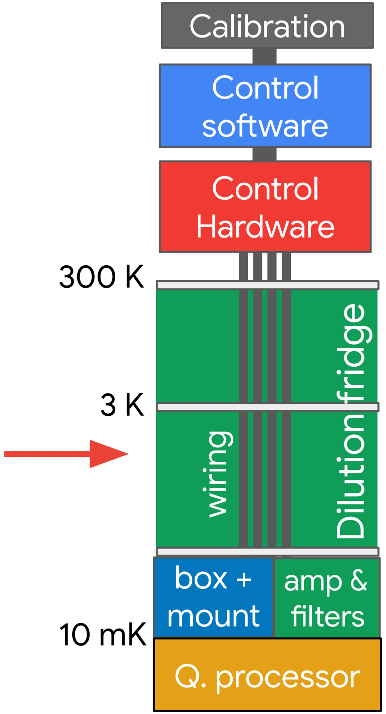
box + mount

amp & filters

Q. processor


Wiring + amplifiers & filters


Dilution Refrigerator


Calibration

Control software

Control Hardware

300 K

3 K

10 mK

wiring

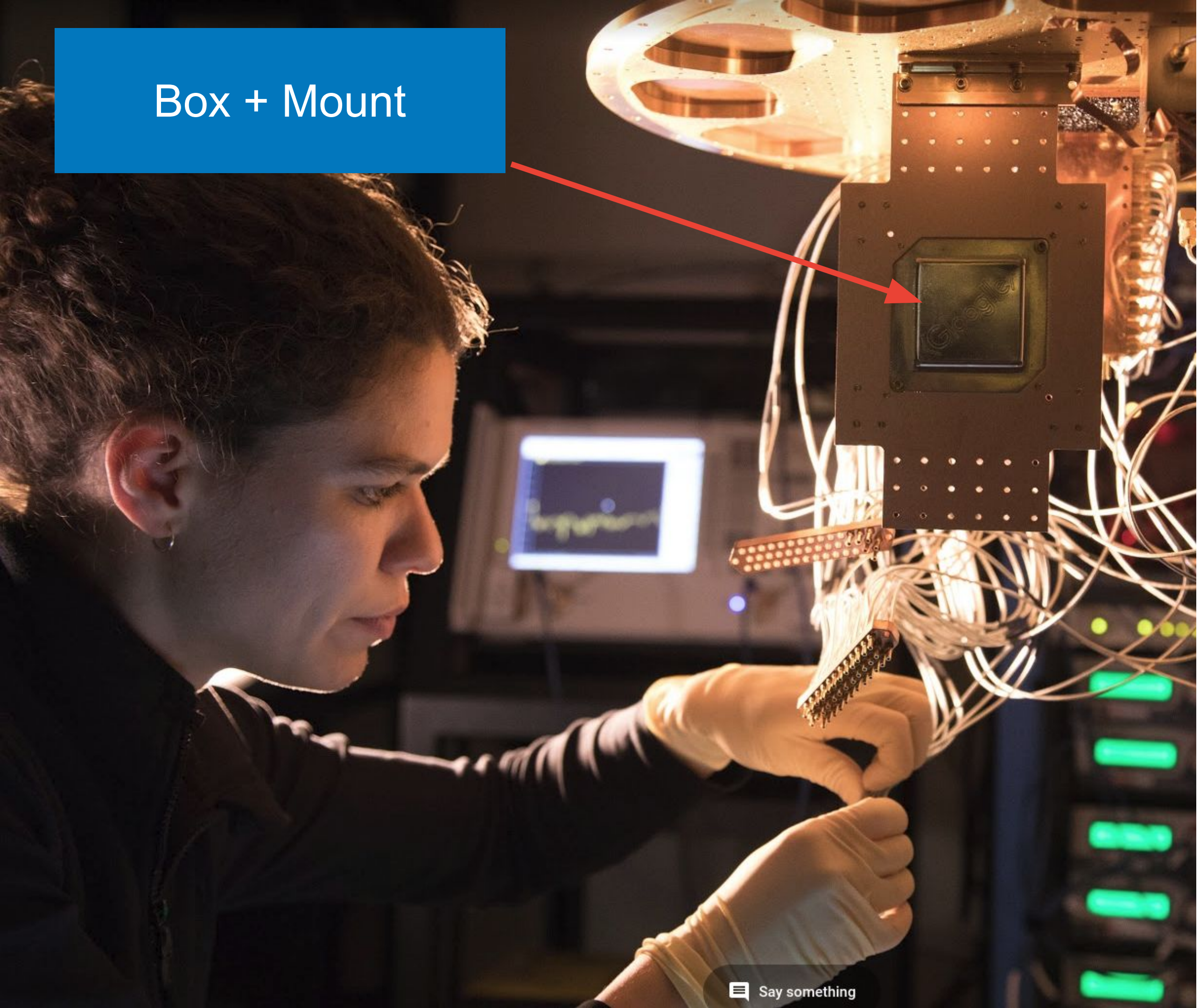
Dilution fridge

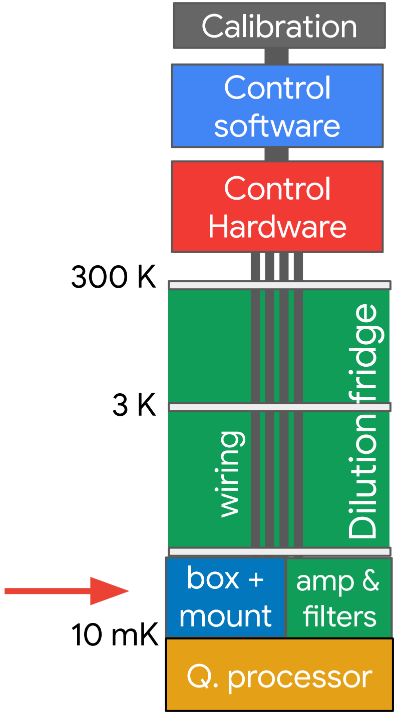
box + mount

amp & filters

Q. processor

Box + Mount




Calibration

Control software

Control Hardware

300 K

3 K

10 mK

wiring

Dilution fridge

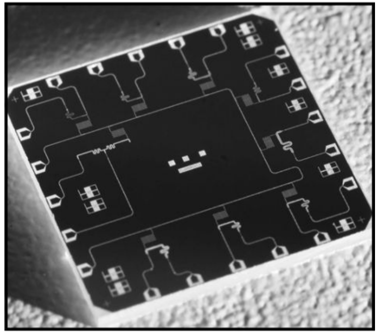
box + mount

amp & filters

Q. processor

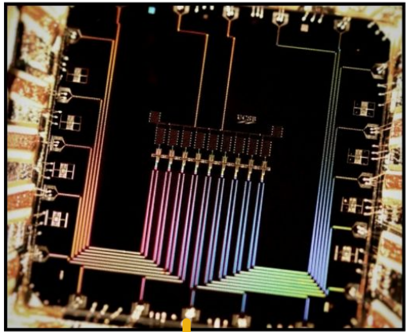
Fluxmon

- Flux qubit, tunable coupling
- optimization problems



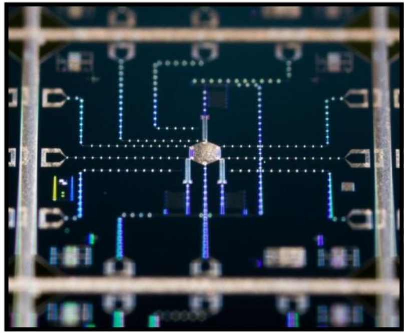
Xmon

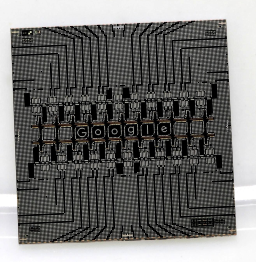
- X-shaped transmon qubit
- gate-based QC (requires error correction)



Gmon

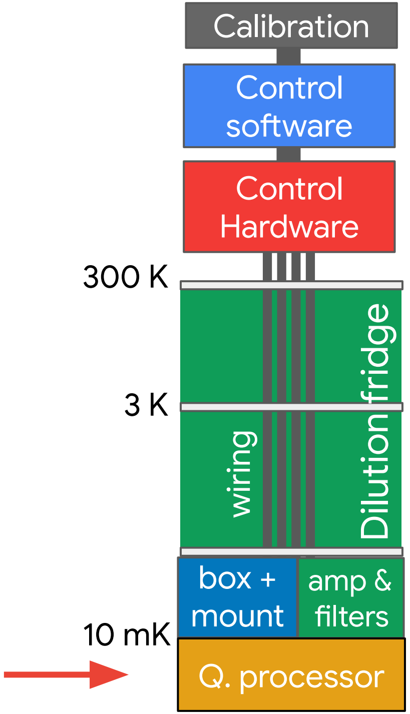
- Transmon qubit, tunable nearest-neighbor coupling
- simulation problems





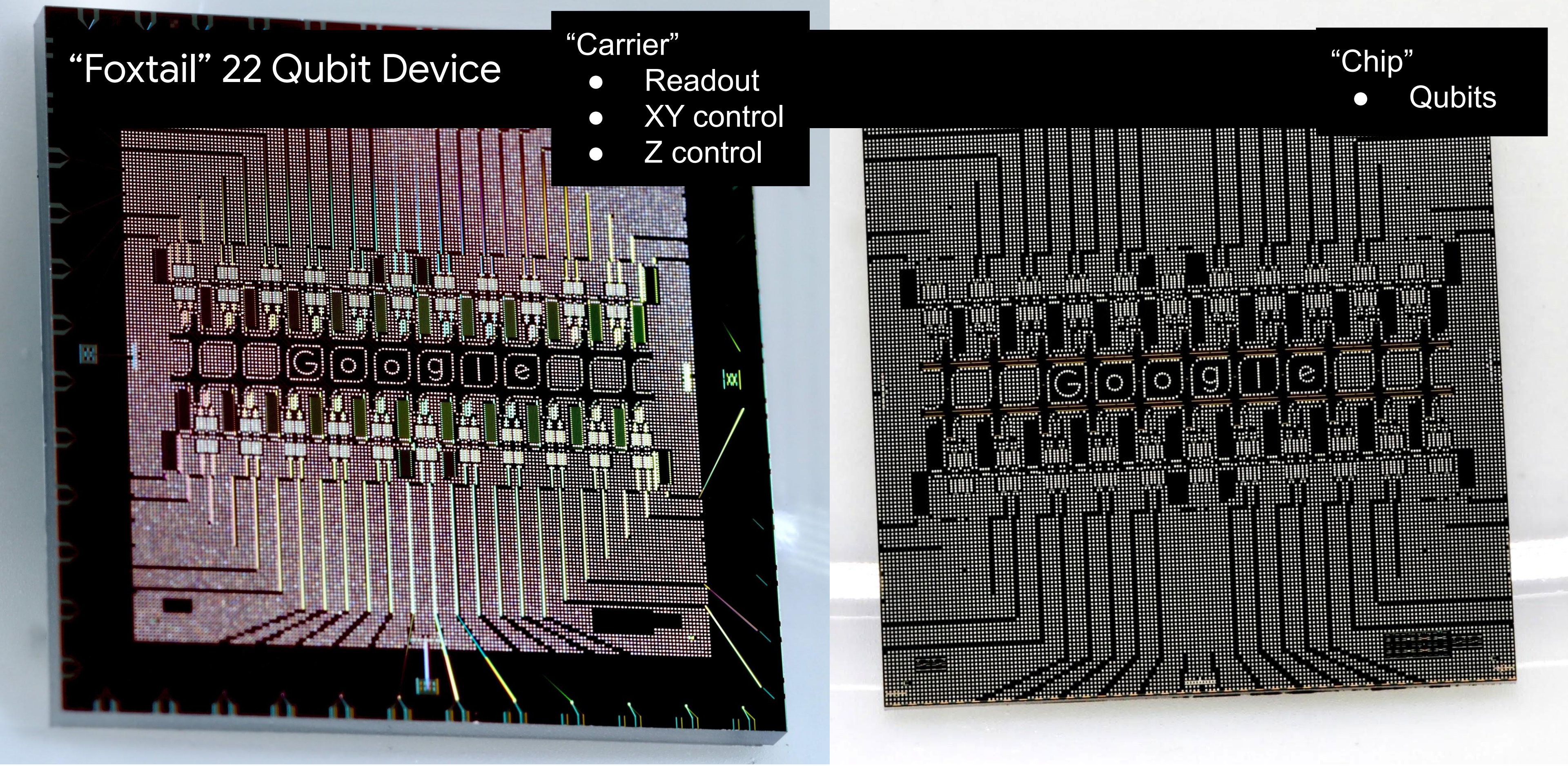
Foxtail: 22 qubits

Bristlecone: 72 qubits



Calibration
Control software
Control Hardware
300 K
3 K
10 mK
wiring
Dilution fridge
box + mount
amp & filters
Q. processor

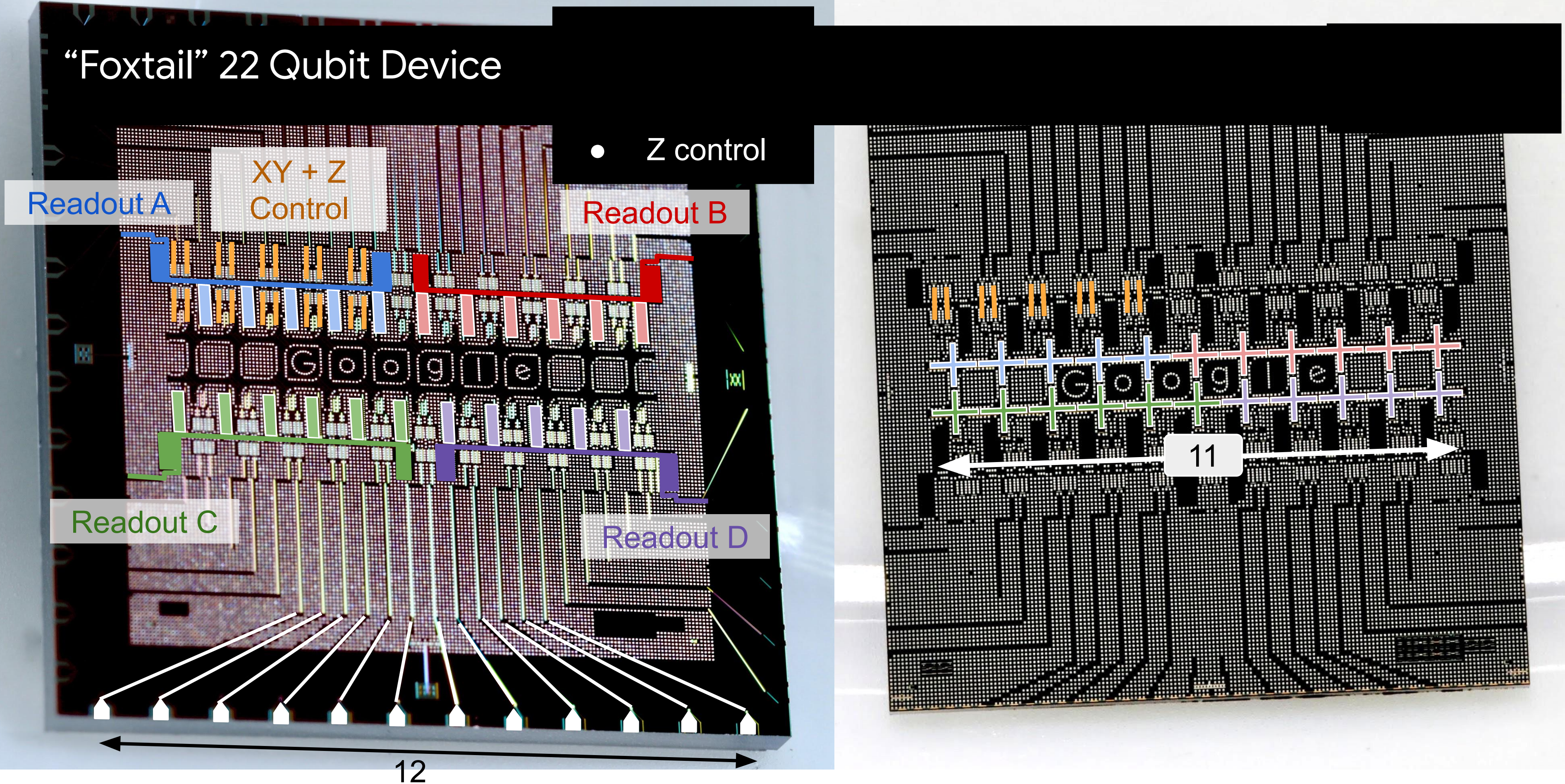
“Foxtail” 22 Qubit Device



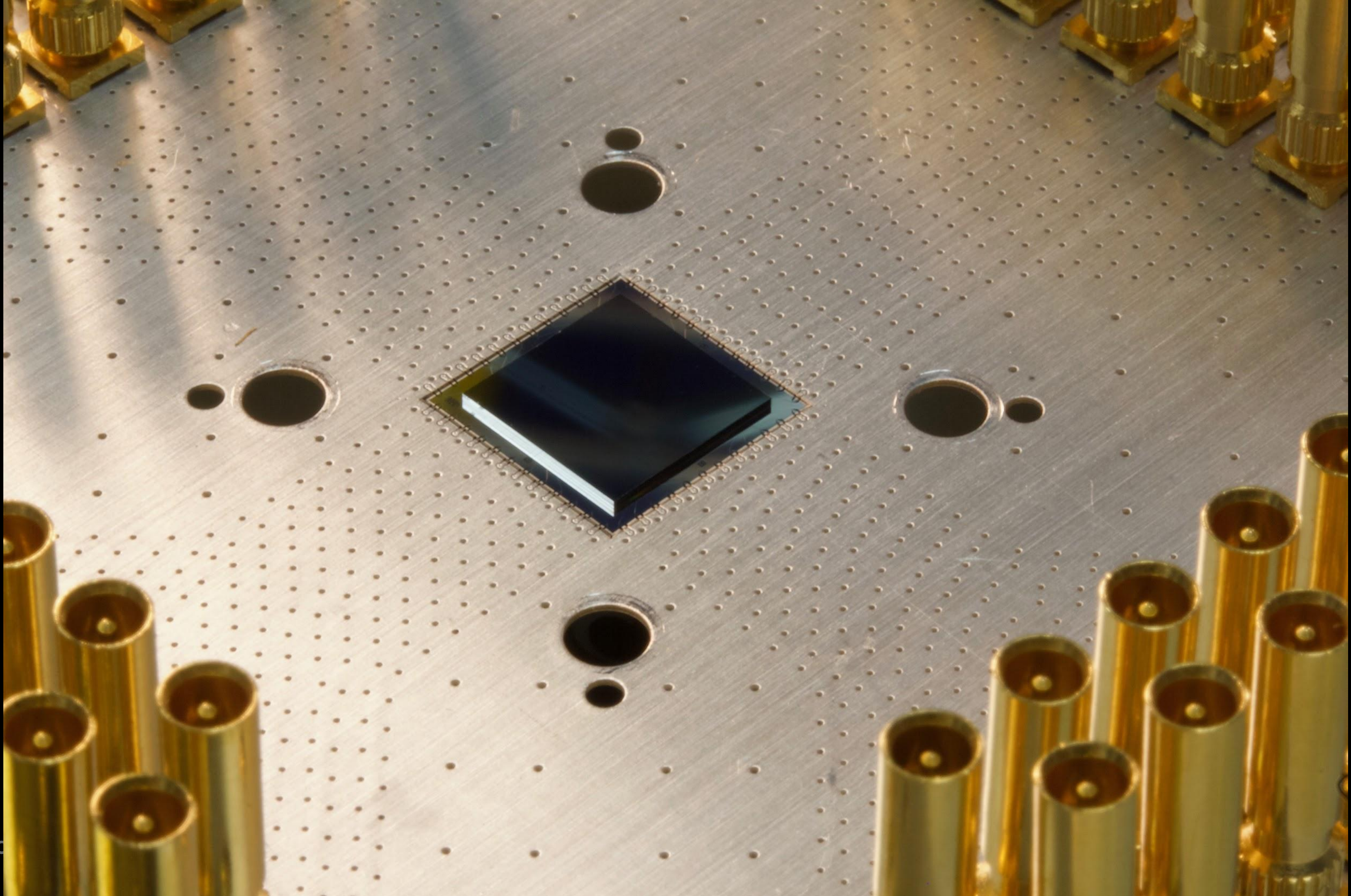
“Carrier”
- Readout
- XY control
- Z control

“Chip”
- Qubits

“Foxtail” 22 Qubit Device

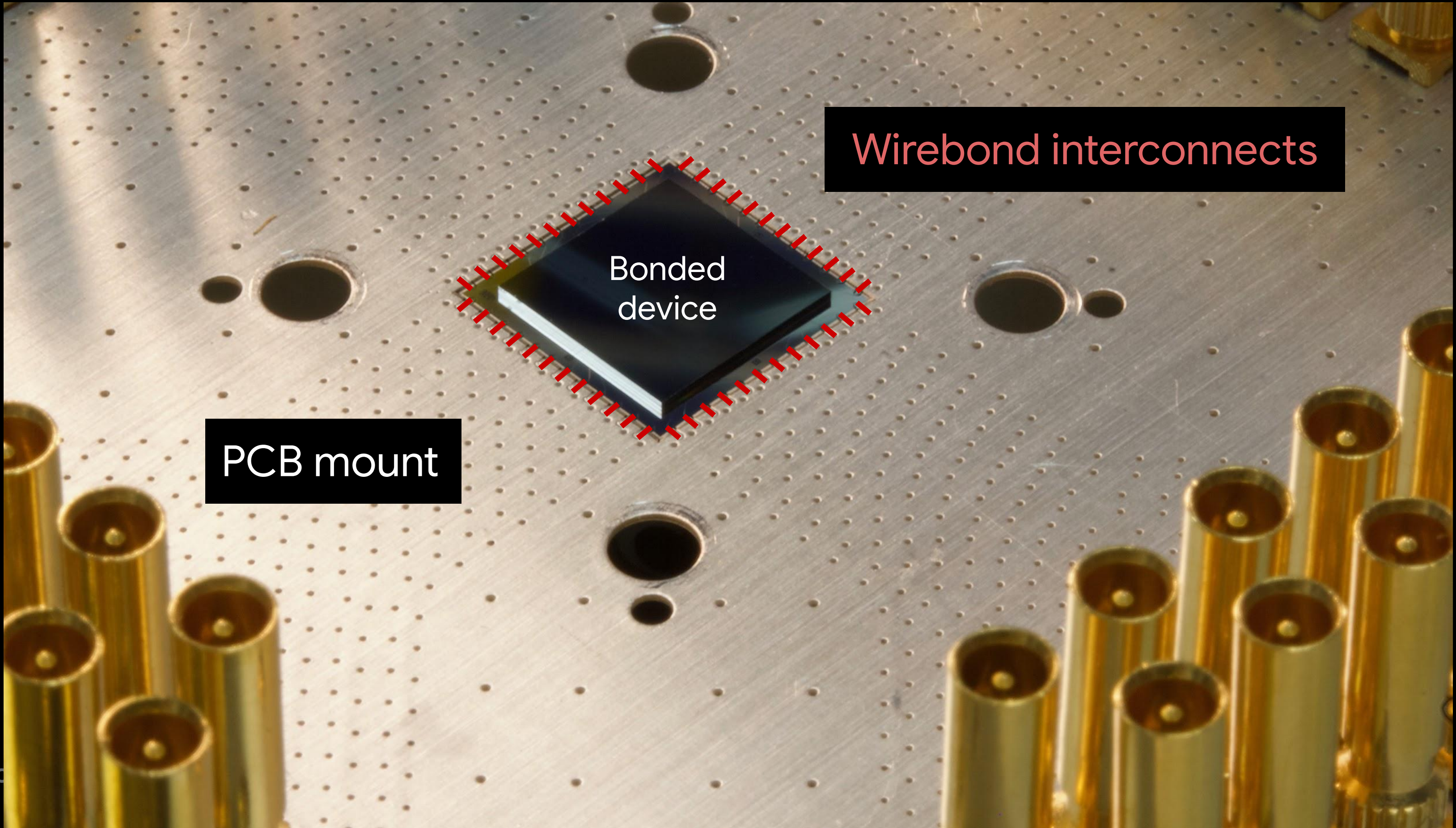


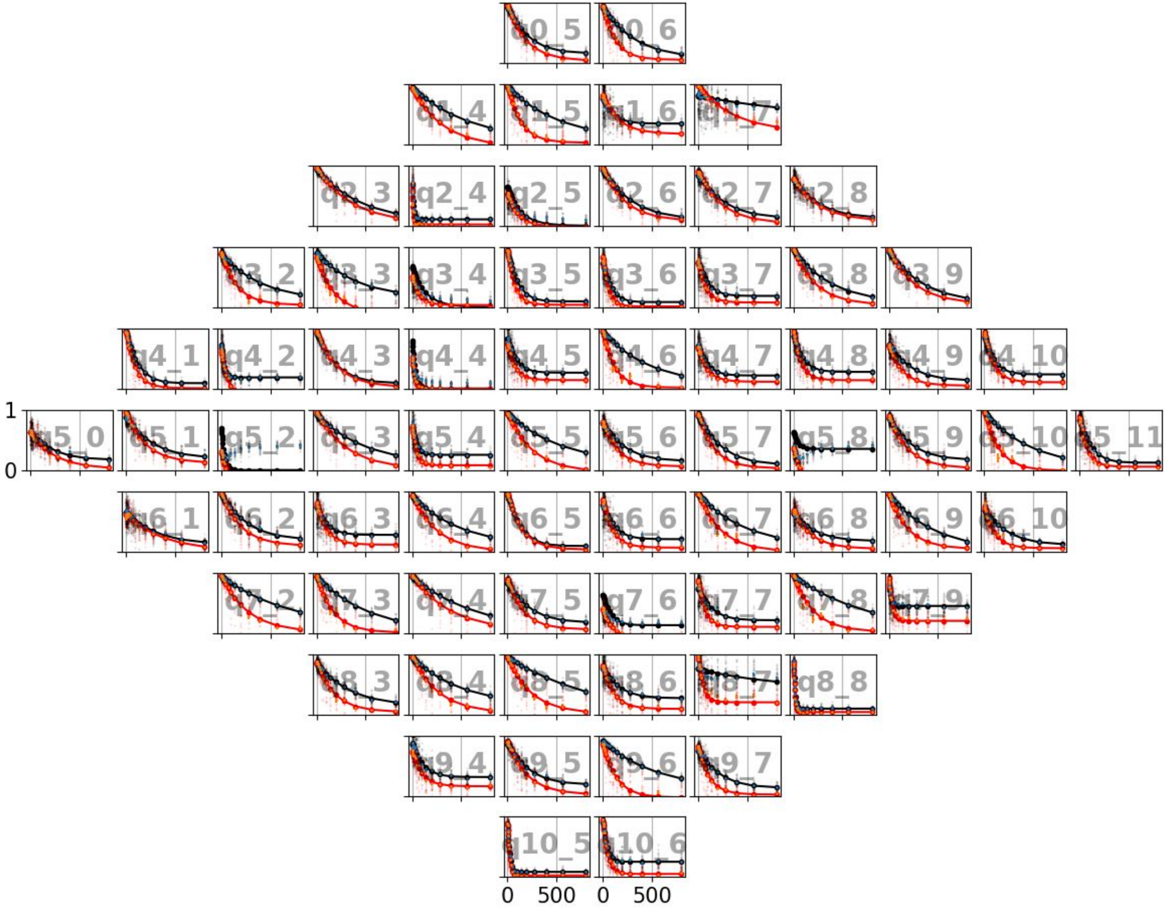
- 2x11 grid
- 48 waveguides
- 4 readout lines
- 5-6 qubits per cell

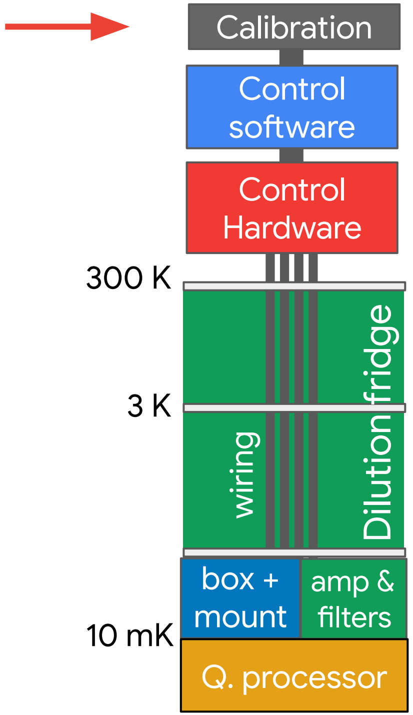


Go

High-density coax







Calibration

Control software

Control Hardware

300 K

3 K

10 mK

wiring

Dilution fridge

box + mount

amp & filters

Q. processor

Calibration: Key to Quality

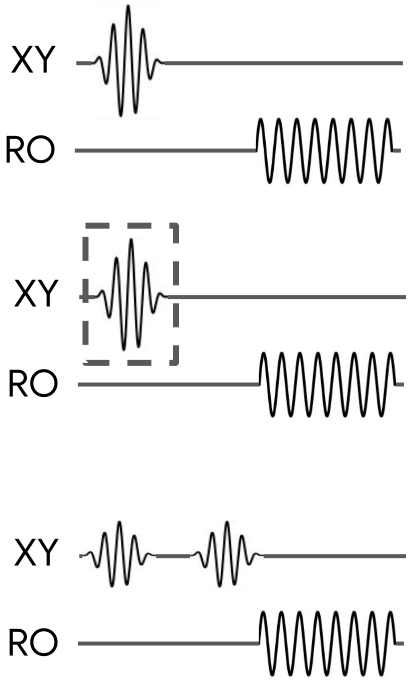
Experiment

Rabi

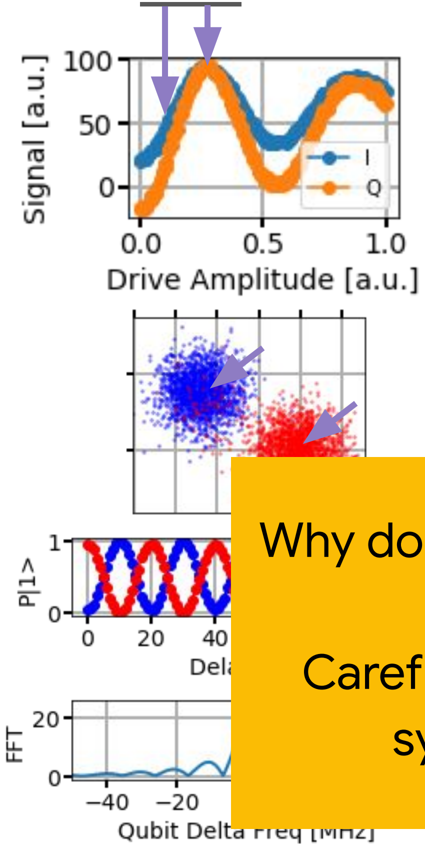
Readout

Ramsey

Control Sequence



Data



Cal Value

π amp. = 0.3
π/2 amp. = 0.15

0-state = (25, -20)
1-state = (100, 100)

Why does this sequence work?

Careful order to **bootstrap** system knowledge

Calibration Dependency Graph

→ Dependency

● Electronics

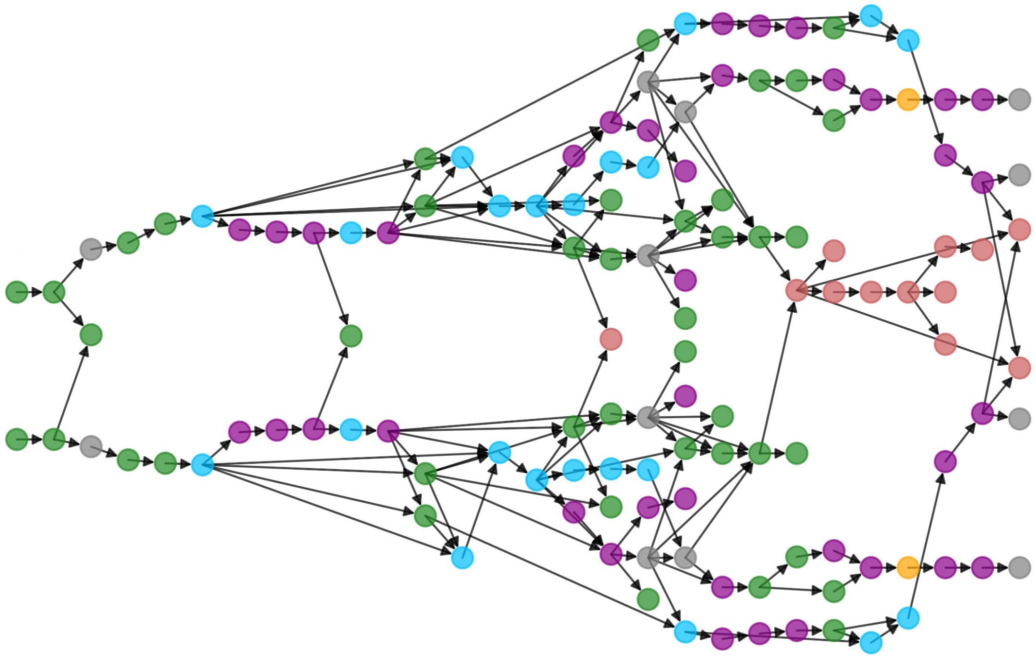
● Device parameters

● Single qubit gates

● Readout

● Calibration waypoint

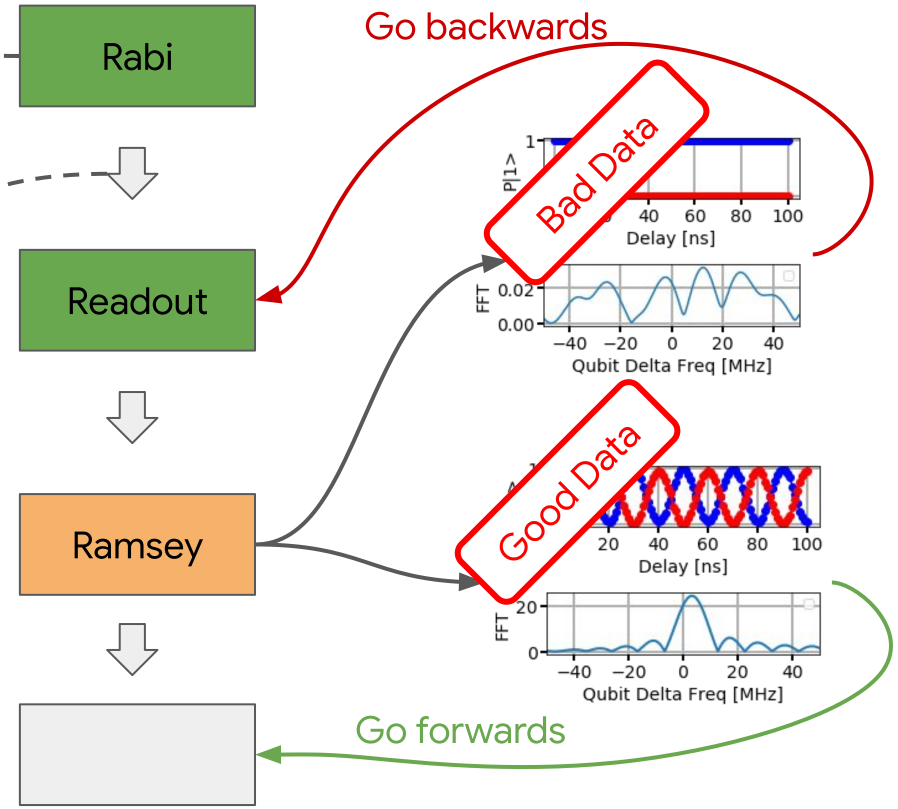
● Two qubit gates



Optimus: Automatic Calibration Graph Traversal

Each cal = node in graph

Dependence = directed edge



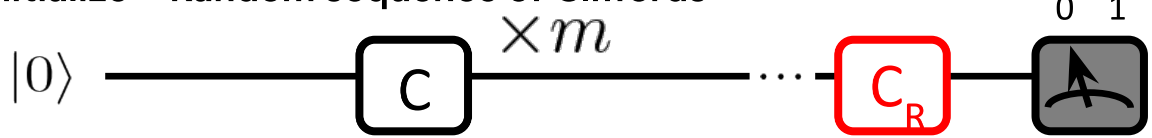
- Calibration dependences = Directed Acyclic Graph
- Each calibration makes **decisions:**
  a. Is data good?
  b. Parameter updates
- System calibration = graph traversal

Optimus white paper: arxiv: 1803.03226

Optimization Example - Randomized Benchmarking

Standard benchmarking

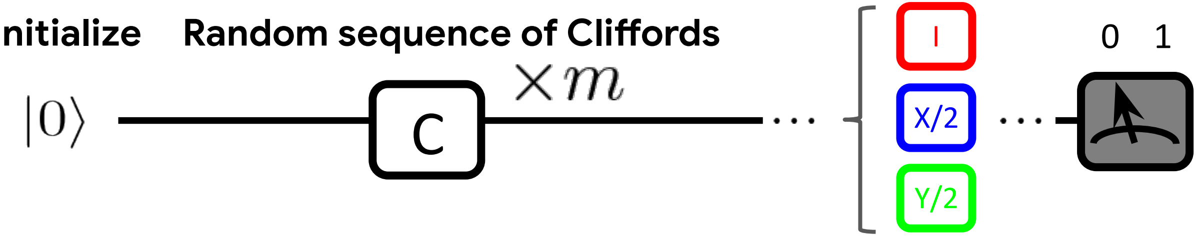
Initialize **Random sequence of Cliffords** **Recover and measure**



Measures ***total error***

Purity Benchmarking

Initialize **Random sequence of Cliffords** **Tomography**

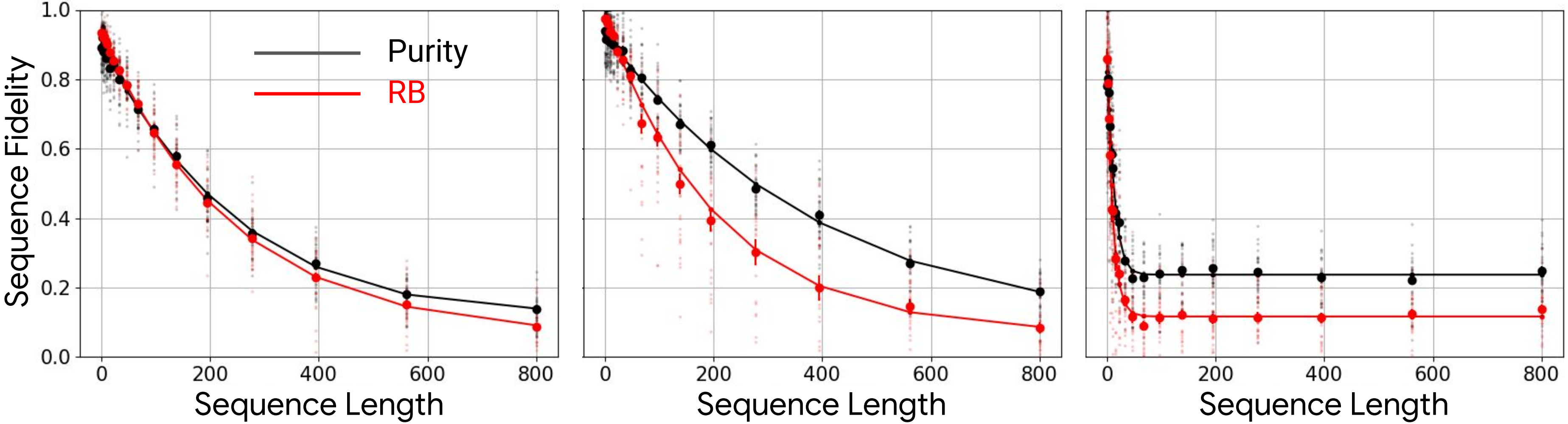


Measures ***decoherence error***

J. Wallman et al, NJP 17, 2015
G. Feng et al, PRL 117, 2016

Data: Randomized Benchmarking vs. Purity

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



Low decoherence error
Low total error

qubit #1

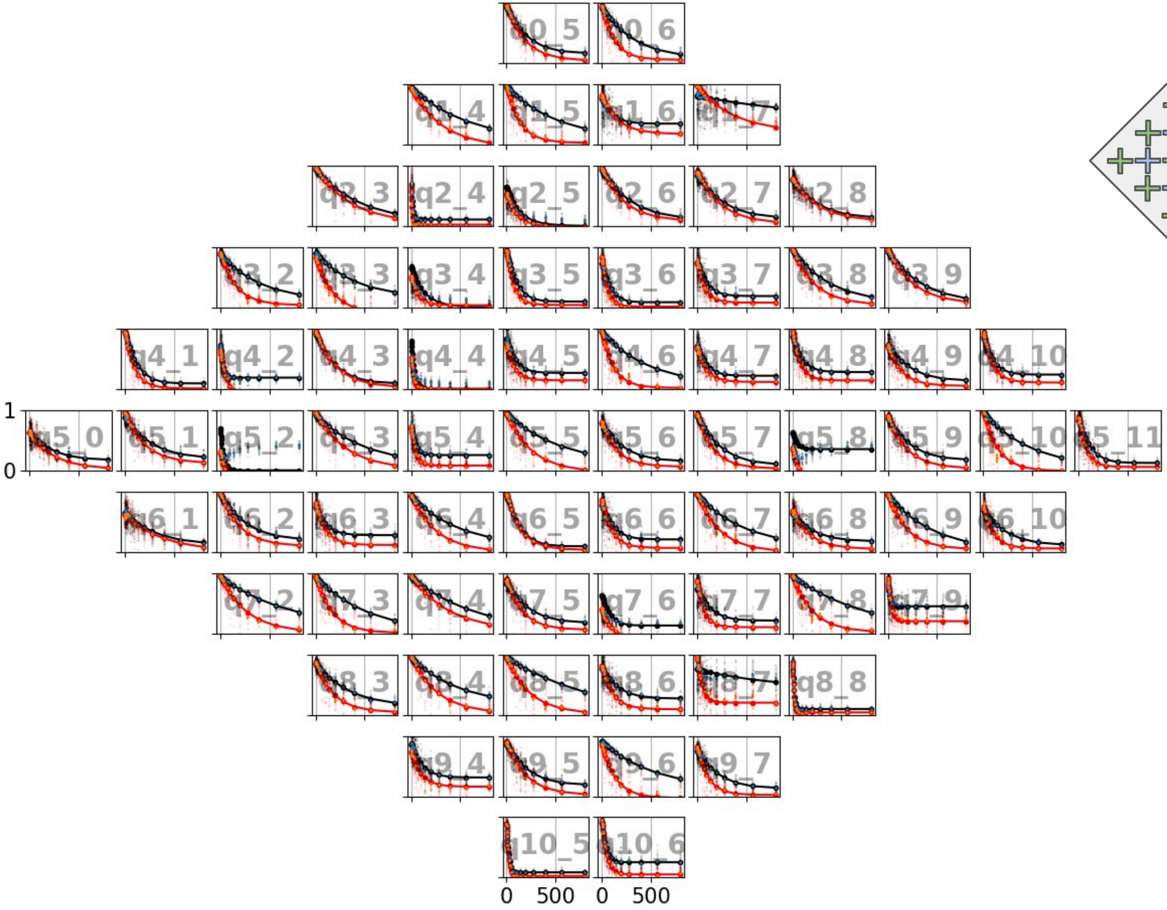
Low decoherence error
Medium total error

qubit #2

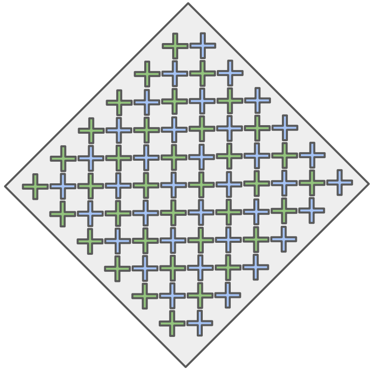
High decoherence error
High total error

qubit #3

Analysis - Raw Data



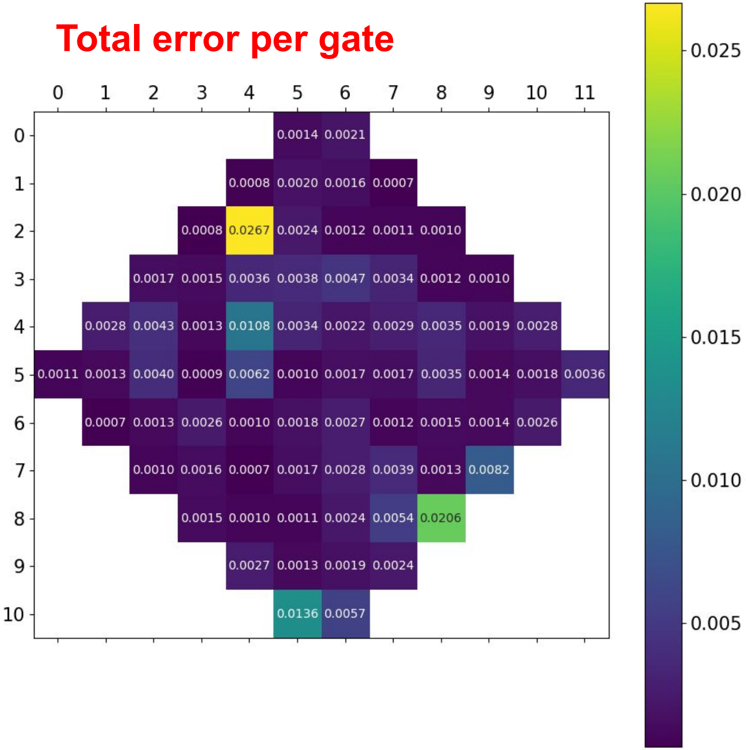
Bristlecone grid



Google AI Quantum

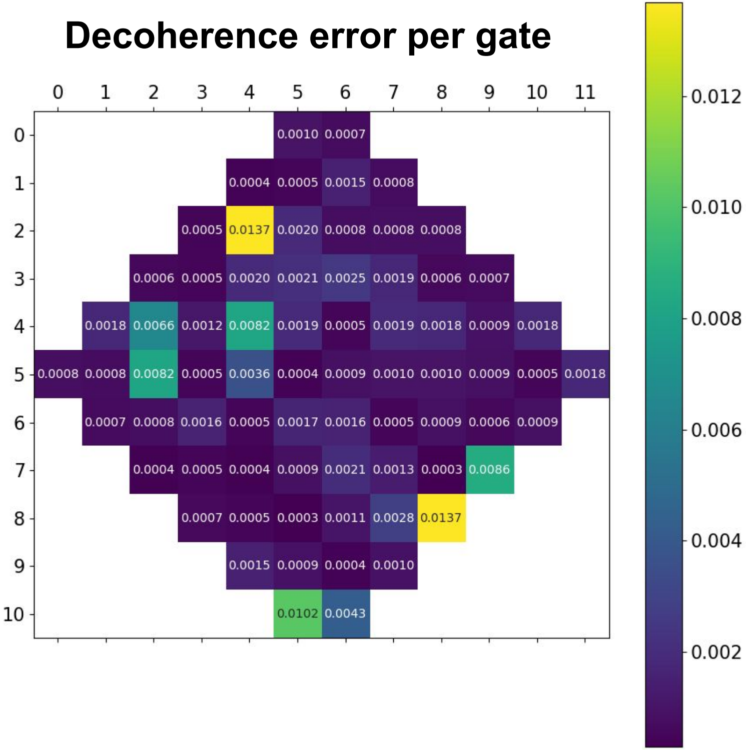
Analysis - Heatmap

Total error per gate



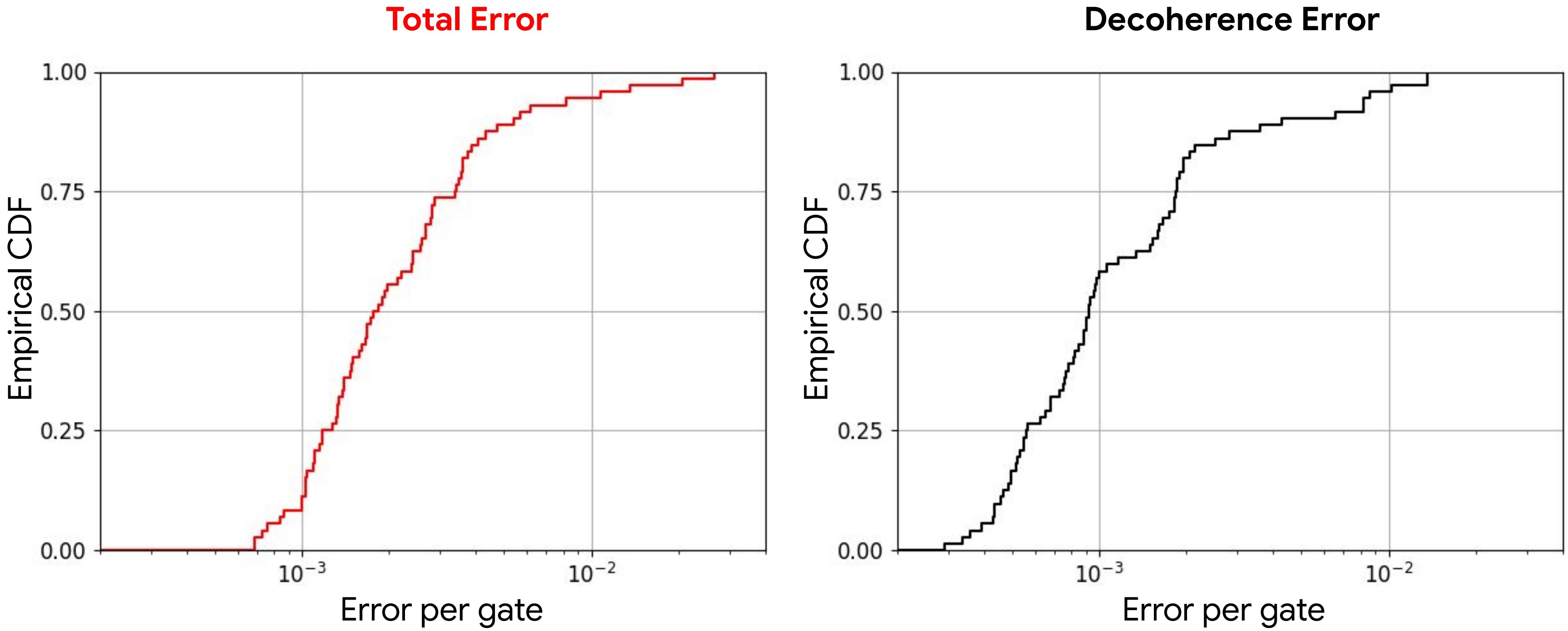
	0	1	2	3	4	5	6	7	8	9	10	11
0						0.0014	0.0021					
1					0.0008	0.0020	0.0016	0.0007				
2				0.0008	0.0267	0.0024	0.0012	0.0011	0.0010			
3			0.0017	0.0015	0.0036	0.0038	0.0047	0.0034	0.0012	0.0010		
4		0.0028	0.0043	0.0013	0.0108	0.0034	0.0022	0.0029	0.0035	0.0019	0.0028	
5	0.0011	0.0013	0.0040	0.0009	0.0062	0.0010	0.0017	0.0017	0.0035	0.0014	0.0018	0.0036
6		0.0007	0.0013	0.0026	0.0010	0.0018	0.0027	0.0012	0.0015	0.0014	0.0026	
7			0.0010	0.0016	0.0007	0.0017	0.0028	0.0039	0.0013	0.0082		
8				0.0015	0.0010	0.0011	0.0024	0.0054	0.0206			
9					0.0027	0.0013	0.0019	0.0024				
10						0.0136	0.0057					

Decoherence error per gate



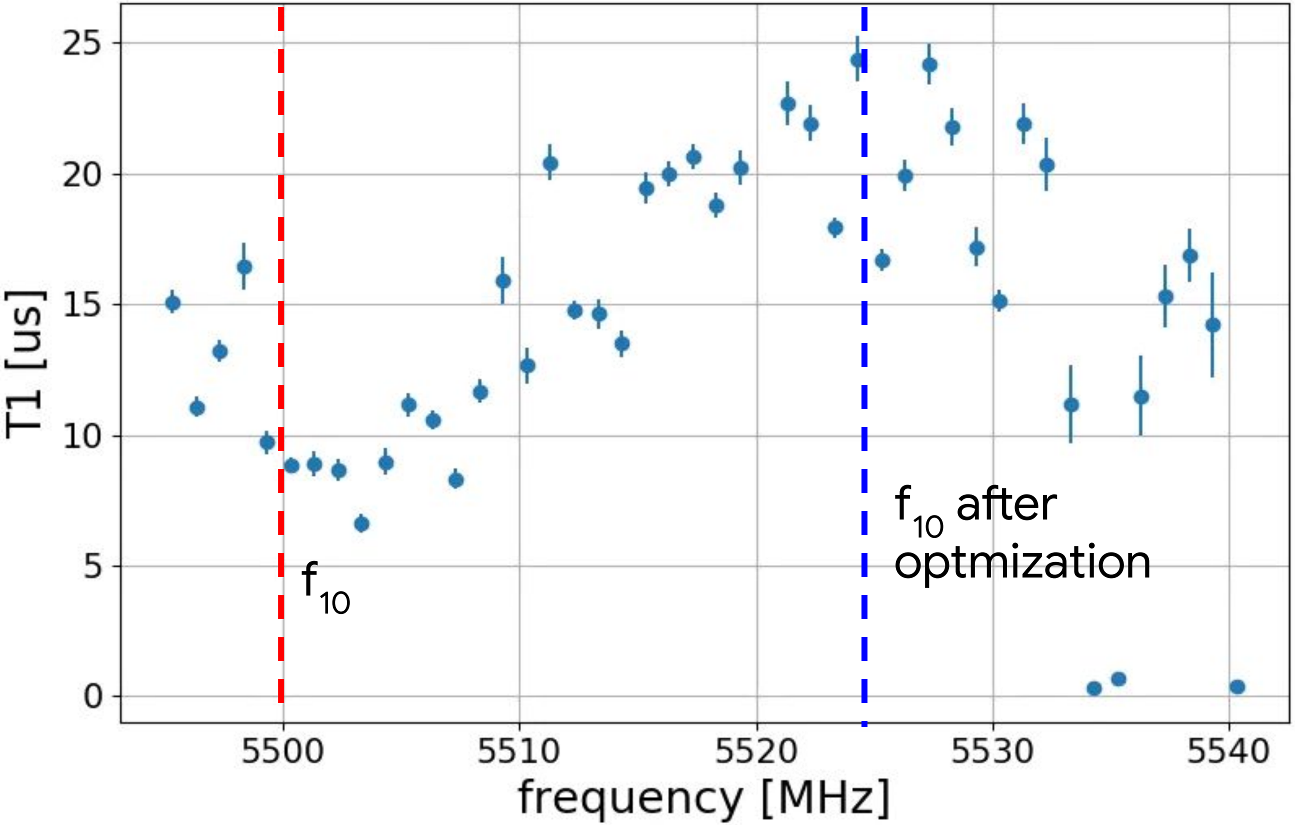
	0	1	2	3	4	5	6	7	8	9	10	11
0						0.0010	0.0007					
1					0.0004	0.0005	0.0015	0.0008				
2				0.0005	0.0137	0.0020	0.0008	0.0008	0.0008			
3			0.0006	0.0005	0.0020	0.0021	0.0025	0.0019	0.0006	0.0007		
4		0.0018	0.0066	0.0012	0.0082	0.0019	0.0005	0.0019	0.0018	0.0009	0.0018	
5	0.0008	0.0008	0.0082	0.0005	0.0036	0.0004	0.0009	0.0010	0.0010	0.0009	0.0005	0.0018
6		0.0007	0.0008	0.0016	0.0005	0.0017	0.0016	0.0005	0.0009	0.0006	0.0009	
7			0.0004	0.0005	0.0004	0.0009	0.0021	0.0013	0.0003	0.0086		
8				0.0007	0.0005	0.0003	0.0011	0.0028	0.0137			
9					0.0015	0.0009	0.0004	0.0010				
10						0.0102	0.0043					

Calibration Study: Frequency Optimization

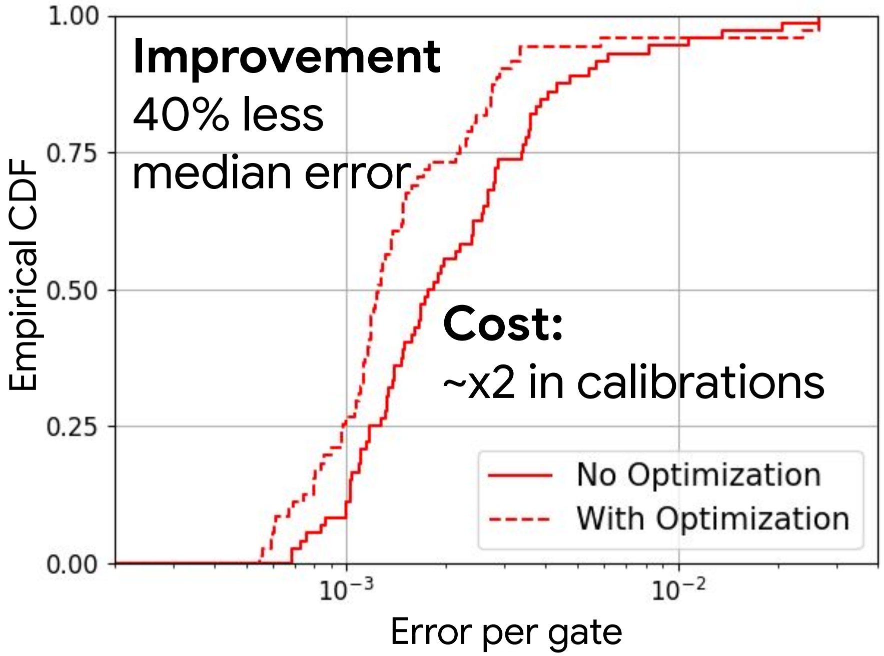


Calibration Study: Frequency Optimization

Larger
is
better



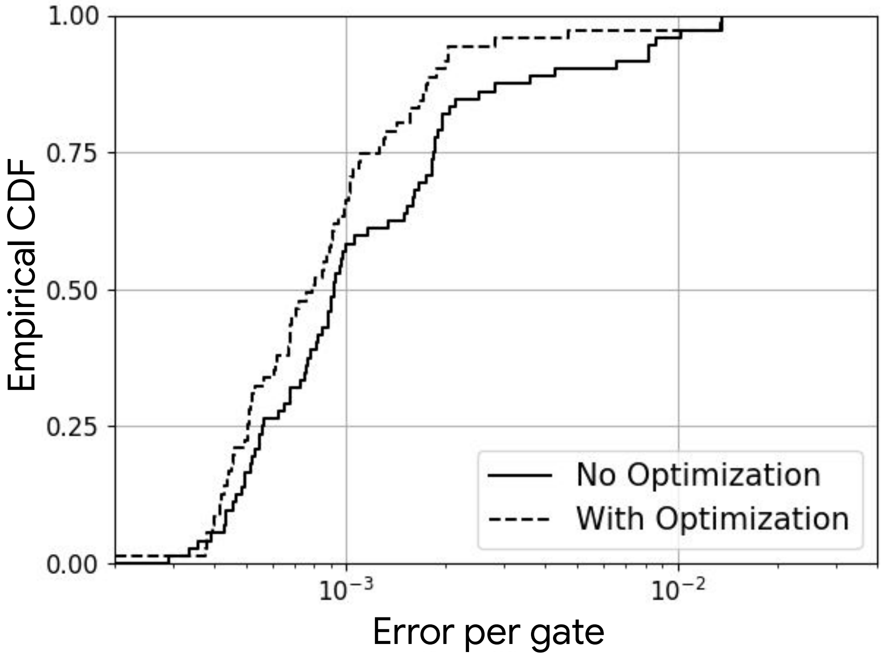
Fidelity improvements from frequency optimization



Total Error

Improvement
40% less
median error

Cost:
~x2 in calibrations



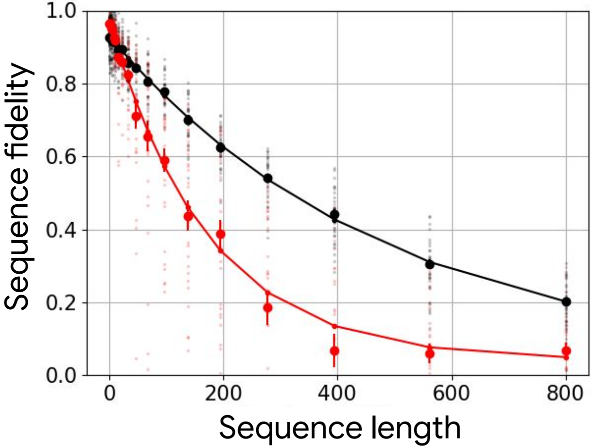
Decoherence Error

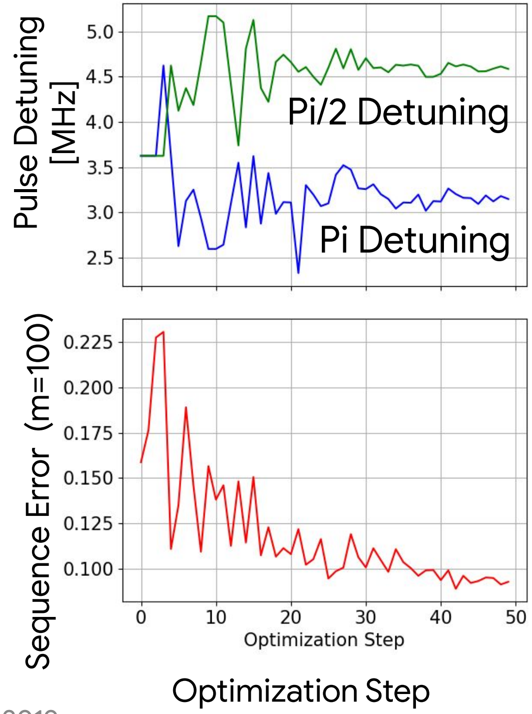
Calibration Study: ORBIT

Kelly et al, Phys. Rev. Lett. **112**, 240504 (2014)

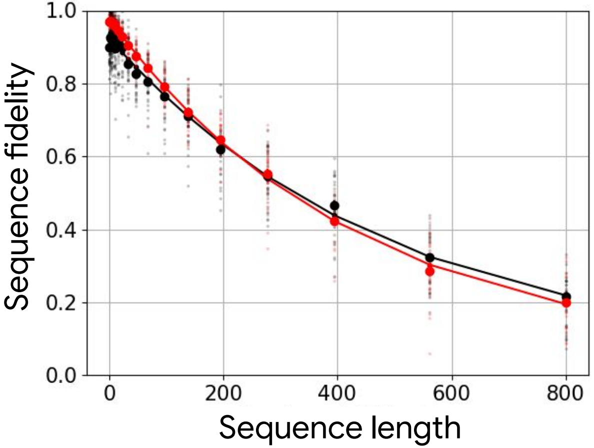
Optimize pulse parameters using RB as the objective function

Total error/gate: 2.9e-3

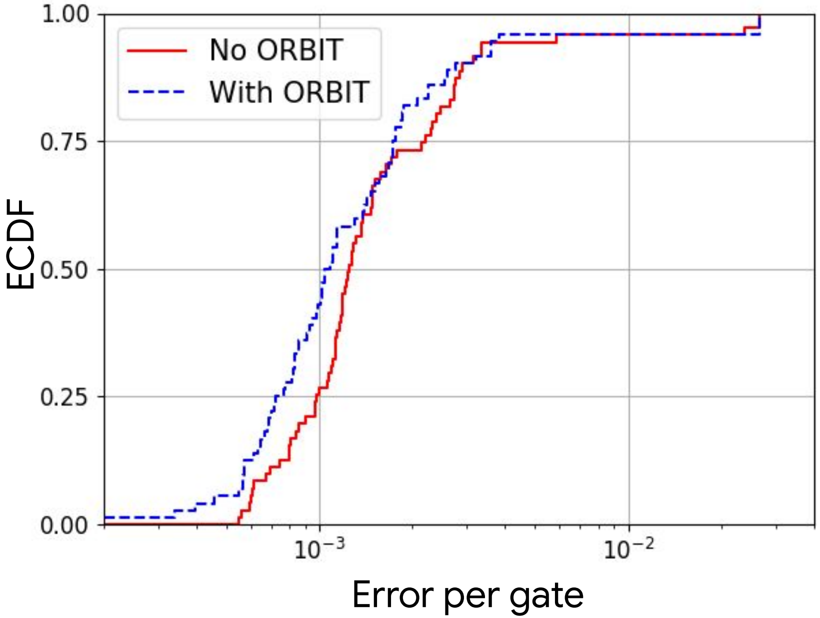




Total error/gate: 1.1e-3



Calibration Science: ORBIT



Improvement:
10% less median error

Cost:
Randomized benchmarking x 50 *per qubit*


DON'T CARE HOW
GOOD
BAD
I WANT IT NOW
imgflip.com

Before Quantum Computers are available...

What you can do:

- Get to know quantum gates and program them.
- Research how to solve the problem you care about with quantum algorithms.
    - Construct your own quantum circuit or use software packages.
    - If it's an optimization problem, maybe quantum annealing can help you.
- Simulate a small version of your quantum program on classical computers to study their properties, and maybe improve them.

Cirq

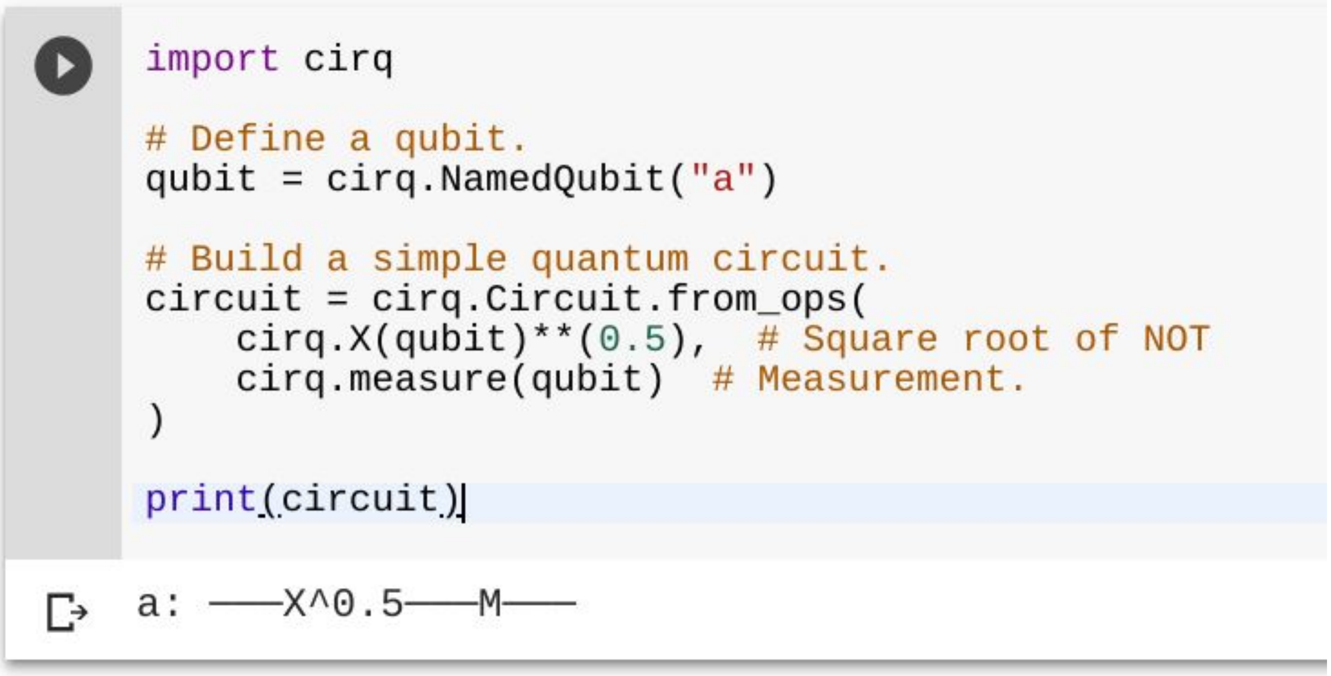
An open source Python framework for
Noisy Intermediate Scale Quantum (NISQ) algorithms

https://github.com/quantumlib/Cirq

Cirq

Google AI Quantum

- An open source Python framework for writing, optimizing, and running quantum programs on near term hardware.



```python
import cirq

# Define a qubit.
qubit = cirq.NamedQubit("a")

# Build a simple quantum circuit.
circuit = cirq.Circuit.from_ops(
    cirq.X(qubit)**(0.5),  # Square root of NOT
    cirq.measure(qubit)  # Measurement.
)

print(circuit)
```

```
a: ───X^0.5───M───
```

Other frameworks

IBM QISKit

Rigetti Forest

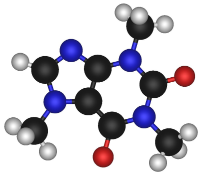
Connected to their quantum hardware

Xanadu Strawberry

Microsoft LIQUID

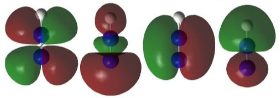
...

How to study chemistry on a quantum computer



molecule specification

compute basis



express operators in basis

$$H = \sum_{p,q} h_{pq}\, a_p^\dagger a_q + \frac{1}{2} \sum_{p,q,r,s} h_{pqrs}\, a_p^\dagger a_q^\dagger a_r a_s$$

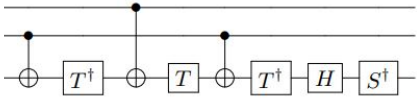
$$h_{pq} = \int dr\, \phi_p^*(r) \left(-\frac{\nabla^2}{2} + U(r) \right) \phi_q(r)$$

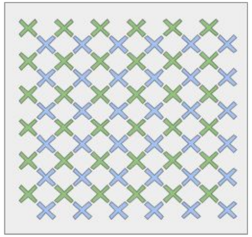
map electrons to qubits

$$a_p^\dagger = (X_p - iY_p)\, Z_{p-1} Z_{p-2} \cdots Z_0$$

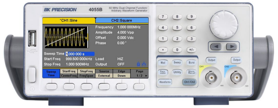
$$a_p = (X_p + iY_p)\, Z_{p-1} Z_{p-2} \cdots Z_0$$

compose quantum algorithm

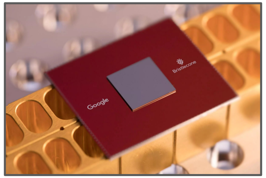




compile to restricted connectivity hardware



convert gates to microwave pulses (quantum control)



compute/prepare wavefunction

measure observables

Google AI Quantum

OpenFermion

OpenFermion is an Apache 2 open source project for quantum simulation

- Generate Hamiltonians for arbitrary molecules and materials in arbitrary basis sets
- Automatically compiles quantum algorithms to circuits

Quantum programming framework agnostic

- Google Cirq, Microsoft LIQUID, IBM QISKit, Xanadu Strawberry, Rigetti Forest, etc.
- We also develop open source project connecting OpenFermion to Cirq

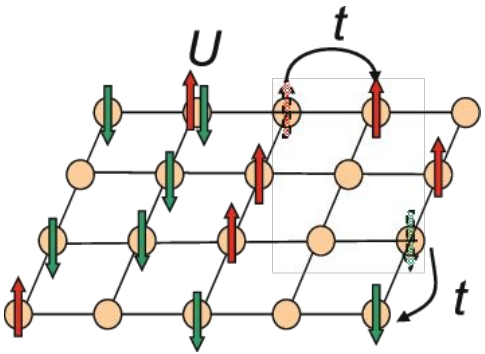
OpenFermion-Cirq

Contributions from two dozen academic labs as well as government and startups

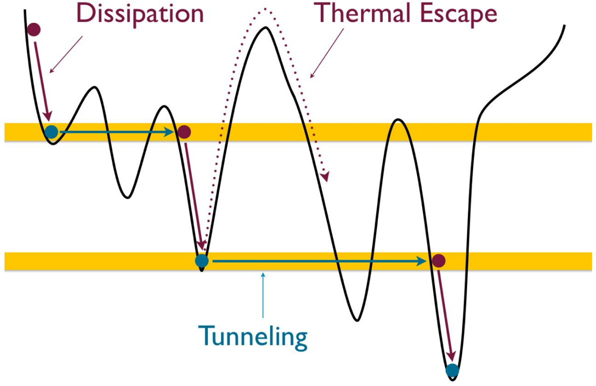
Google rigetti quantum computing ZAPATA QUSIM D-Wave The Quantum Computing Company™ BERKELEY LAB XANADU NASA QUTech

~150 active (visible) forks and use in nearly all new papers

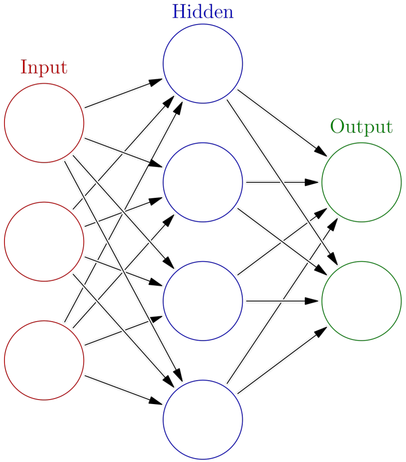
Next Experiments



Fermi-Hubbard Model
(Simulation)



Population Transfer + QAOA
(Optimization)



Quantum Neural Networks
(Machine Learning)

Collaboration Opportunities

Google Academic Funding

Focus Awards

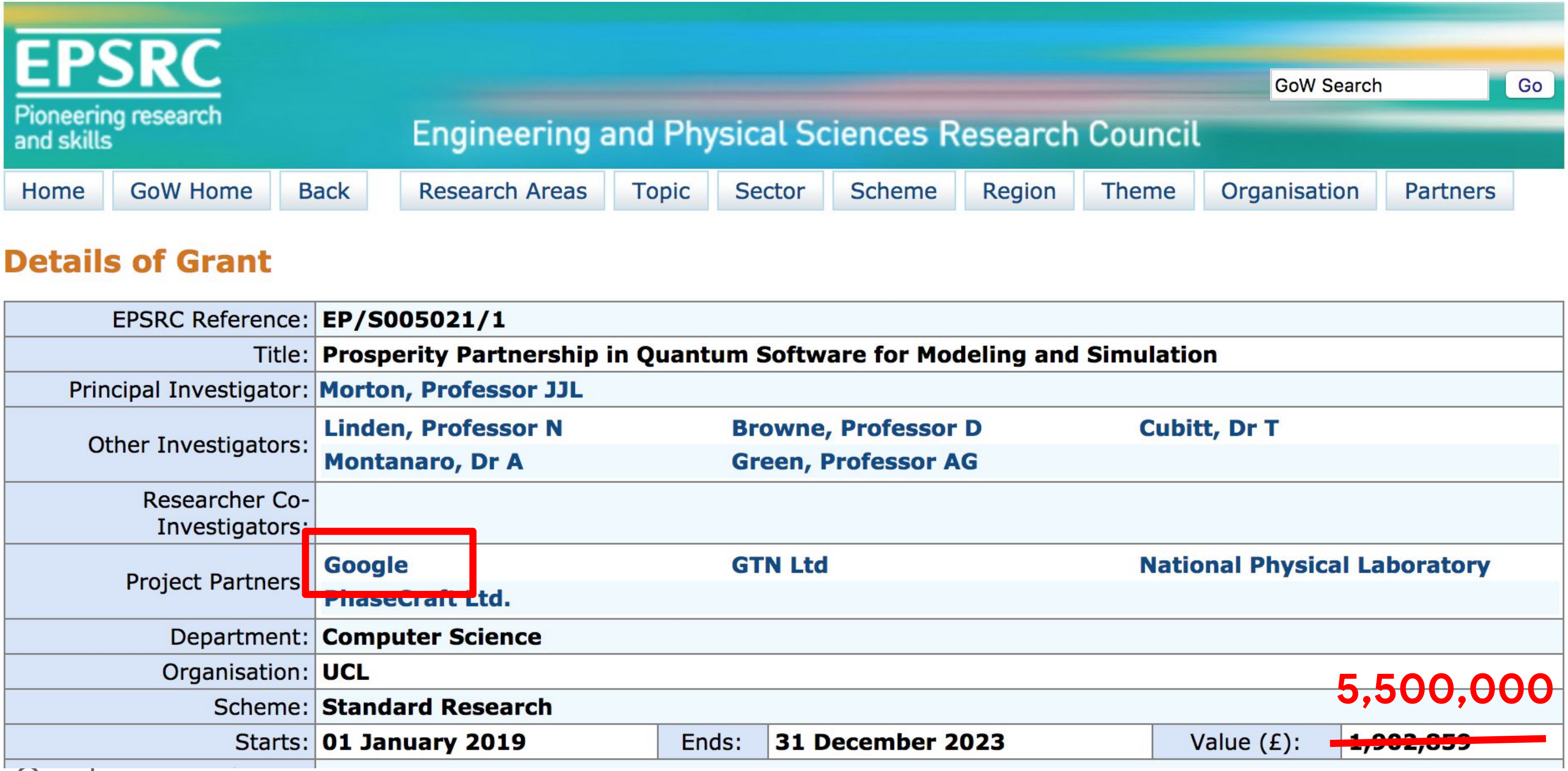
- 2~3 years
- 1+ graduate students
- Access to researchers
- Potential access to hardware
- 8 awarded in 2018

Faculty Research Awards

- 1 year funding
- 1 graduate student
- Access to researchers
- Potential access to hardware
- 8 awarded in 2018

Submit proposals to : quantumsymposium-2019@google.com

Joint Awards - £5.5m UK Prosperity Partnership



EPSRC
Pioneering research and skills

Engineering and Physical Sciences Research Council

Details of Grant

EPSRC Reference:	**EP/S005021/1**
Title:	**Prosperity Partnership in Quantum Software for Modeling and Simulation**
Principal Investigator:	**Morton, Professor JJL**
Other Investigators:	**Linden, Professor N** **Browne, Professor D** **Cubitt, Dr T** **Montanaro, Dr A** **Green, Professor AG**
Researcher Co-Investigators:	
Project Partners	**Google** **GTN Ltd** **National Physical Laboratory** **PhaseCraft Ltd.**
Department:	**Computer Science**
Organisation:	**UCL**
Scheme:	**Standard Research**
Starts:	**01 January 2019**
Ends:	**31 December 2023**
Value (£):	~~**1,902,859**~~ 5,500,000

Looking into the future

> “It was the best of times, it was the worst of times,
> it was the age of wisdom, it was the age of foolishness,
> it was the epoch of belief, it was the epoch of incredulity,
> it was the season of Light, it was the season of Darkness,
> it was the spring of hope, it was the winter of despair,
> we had everything before us, we had nothing before us,
> we were all going direct to Heaven,
> we were all going direct the other way.”

— A tale of two cities, Charles Dickens (1859)

“For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.”

— Richard P. Feynman (1986)