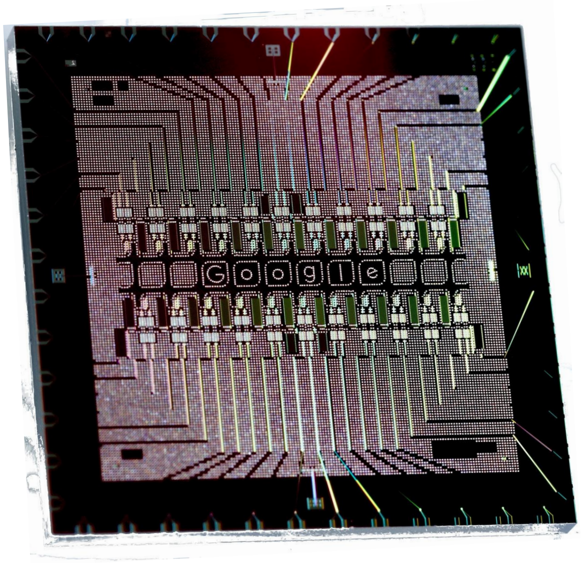
Forum Teratec

An Update on Google's Quantum Computing Initiative

20 June, 2018

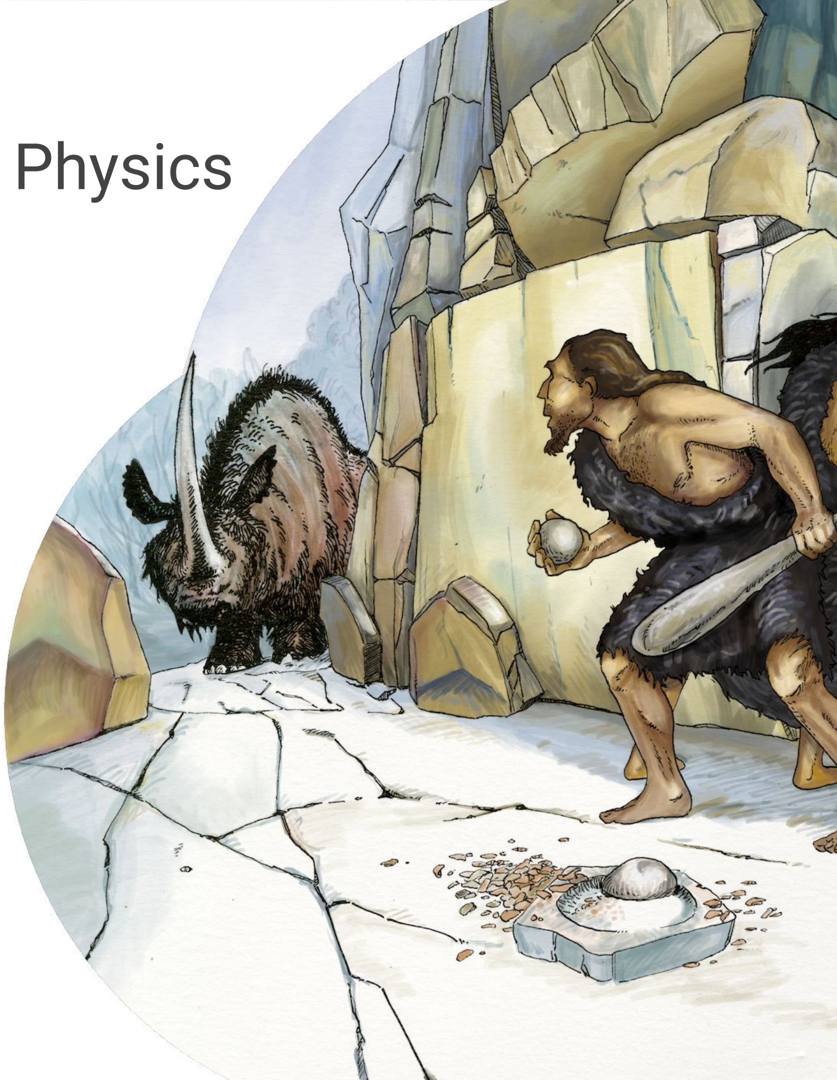


Google Cloud

Our Brains are Wired for Newtonian Physics

Brains that recognize and anticipate behaviors of Heat, Light, Momentum, Gravity, etc. have an Evolutionary Advantage.

Quantum phenomena contradict our intuition.



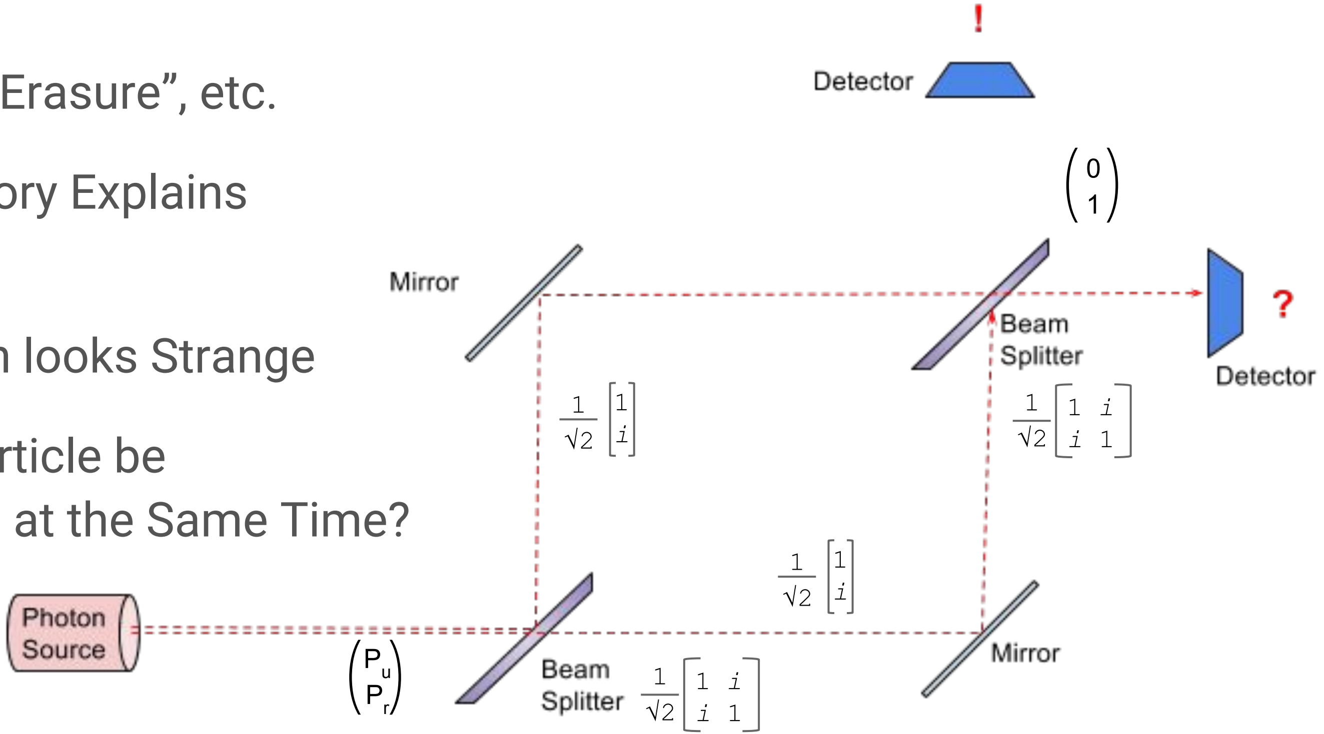
Quantum Phenomena Contradict Intuition

Interference, “Erasure”, etc.

Quantum Theory Explains Cleanly…

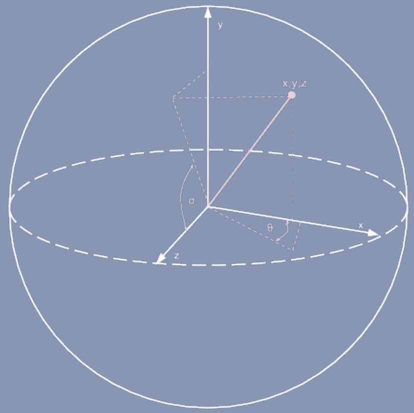
…but the Math looks Strange

How can a Particle be
On Two Paths at the Same Time?



Quantum Data

$$|0\rangle + |1\rangle$$



Quantum Data

$$(|0\rangle+|1\rangle)^2$$
$$= |00\rangle+|01\rangle+|10\rangle+|11\rangle$$

Really Big Data

$$(|0\rangle + |1\rangle)^n$$

n=50: supercomputer

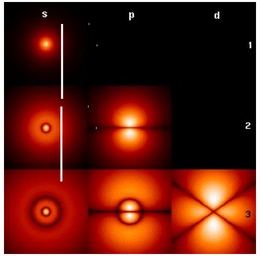
n=300: more states than atoms in universe

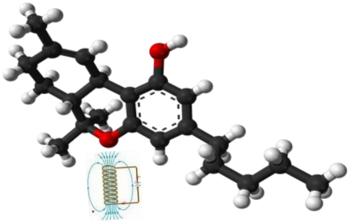
Macroscopic QM Enables New Physics

Control of single quantum systems, to quantum computers

1 nm

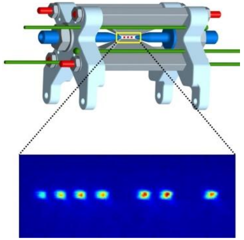
H atom wavefunctions:

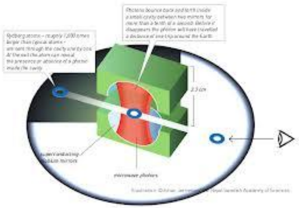


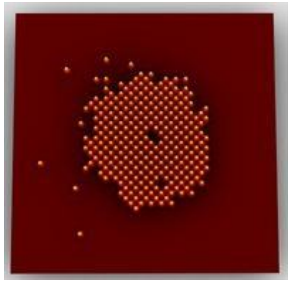


Problem:
Light is 1000x larger

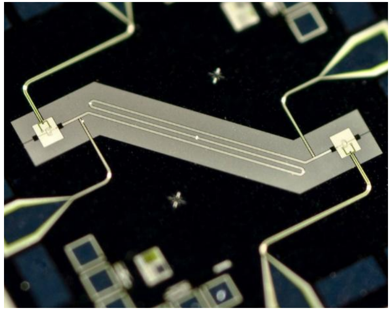
1 μm

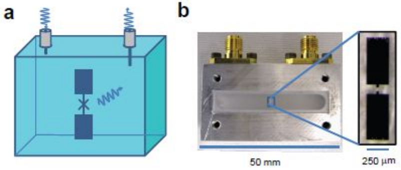






1 mm

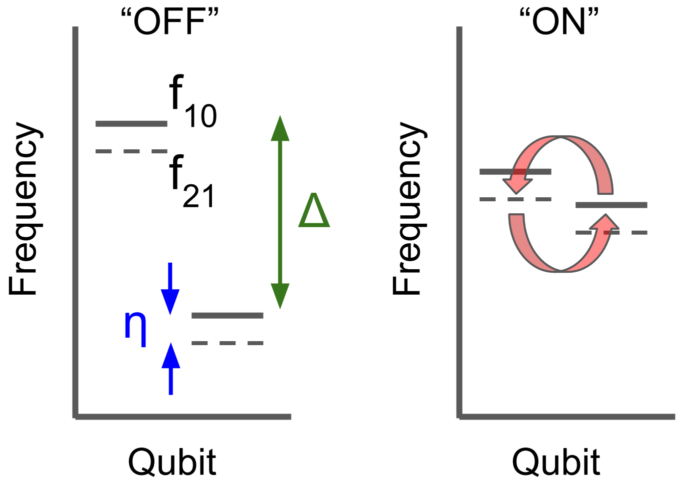


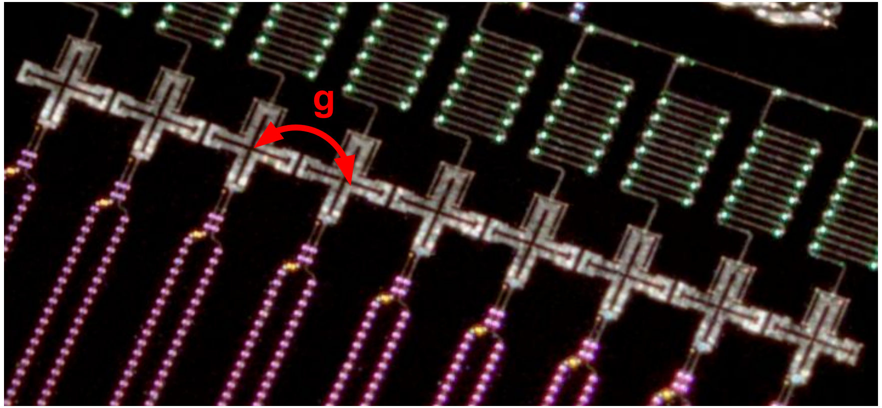


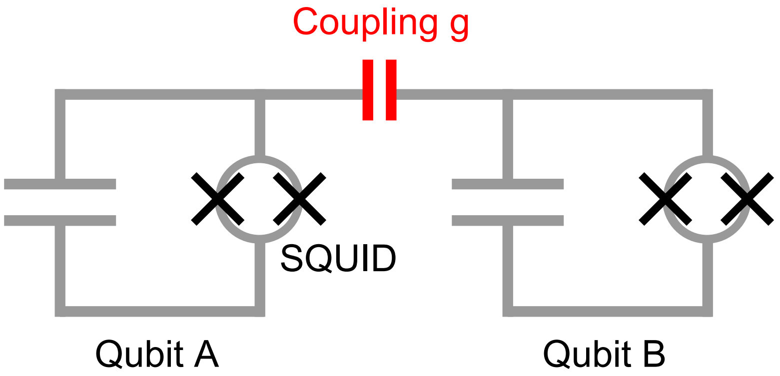
Large “atom” has room for complex control

Xmon: Direct coupling + Tunable Transmons

- Direct qubit-qubit capacitive coupling
- Turn interaction on and off with frequency control







Coupling rate $\Omega_{zz} \approx 4\eta g^2 / \Delta^2$

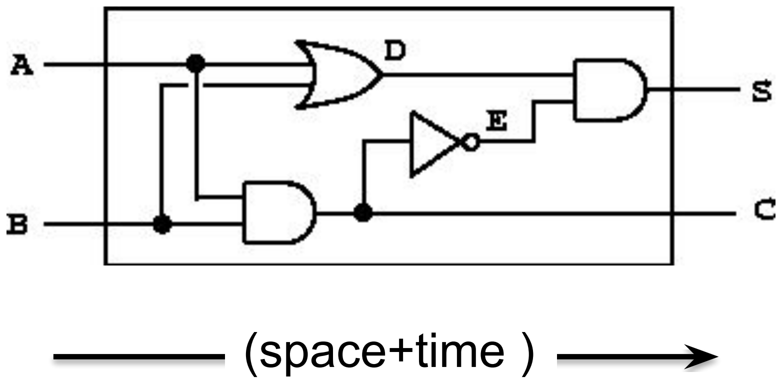
Logic Built from Universal Gates

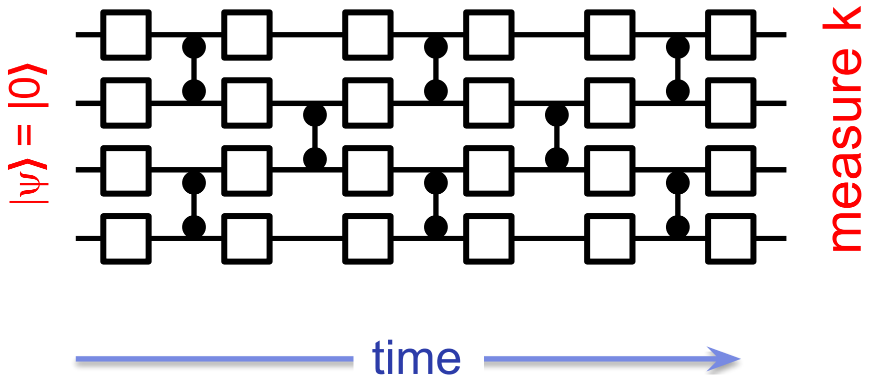
Classical circuit:

1 bit NOT
2 bit AND
Wiring fan-out

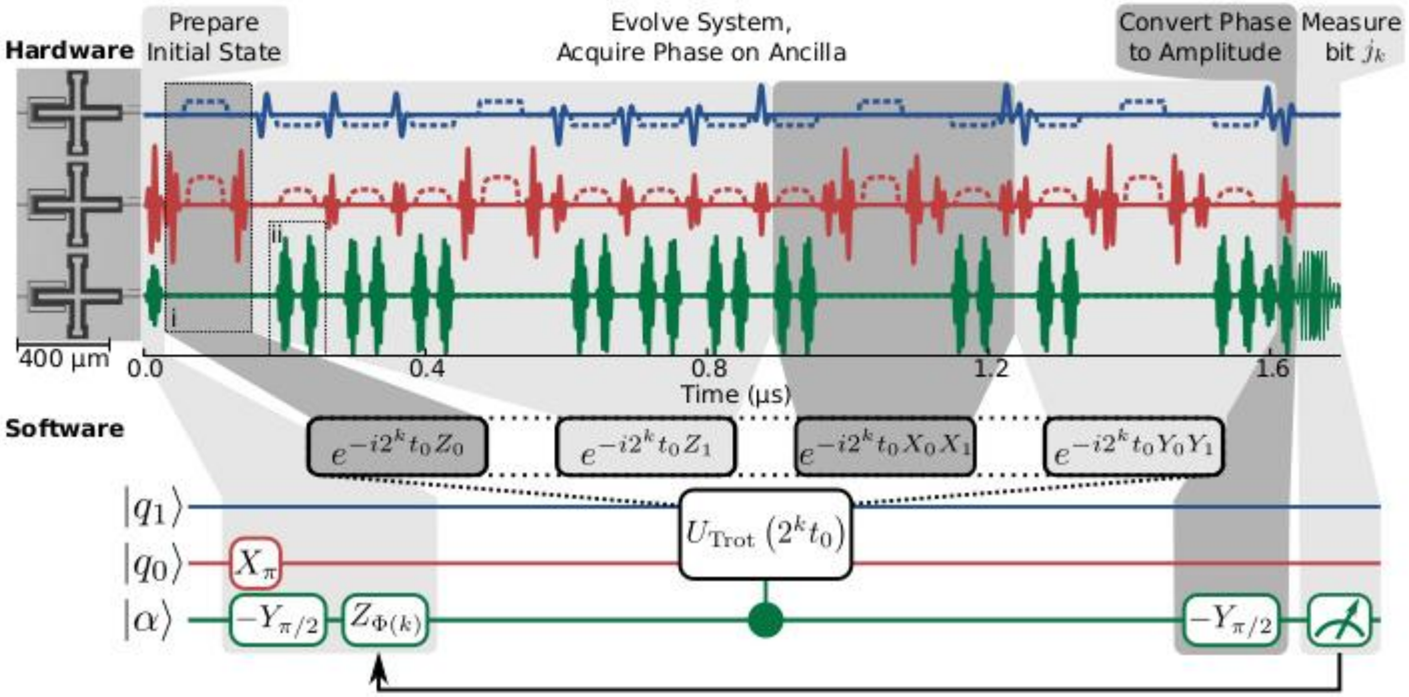
Quantum circuit:

1 qubit rotation
2 qubit CNOT
No copy





Execution of a Quantum Simulation

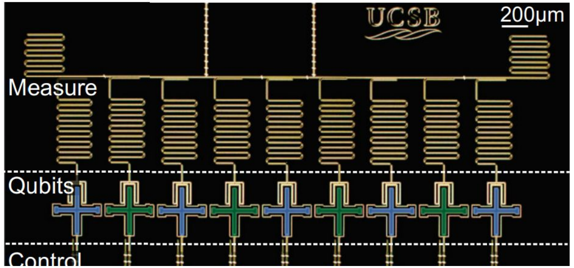


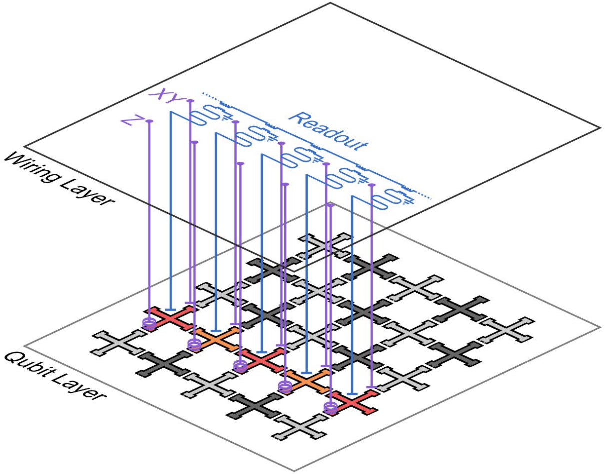
9 Qubit: Good performance, Limited Scaling

9 qubit device has good performance

- Err_{CZ} down to 0.6%
- Err_{SQ} < 0.1%
- Err_{RO} = 1%

Limited to 1D connectivity (planar geometry)

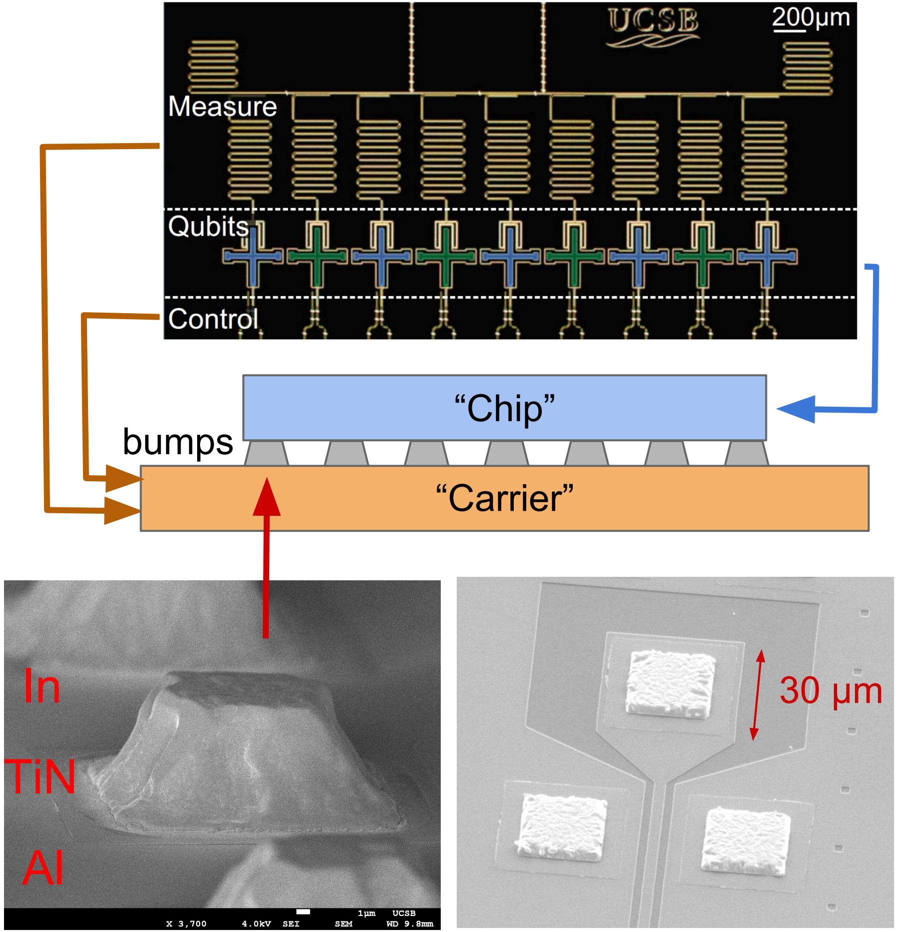




Scale-up strategy: move qubits, control to different planes

Bump-Bond Architecture

- Bond together two separate chips
  - Qubits → “Chip”
  - Control → “Carrier”
- Superconducting interconnect
- Use lossless vacuum as dielectric



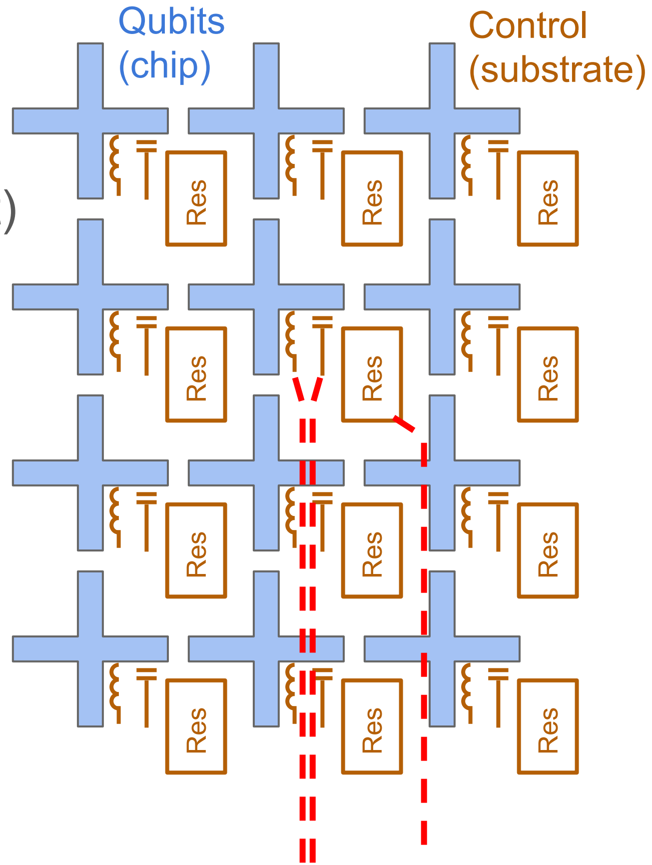
Scaling to 2D

Design must be "tileable" (control fits in qubit footprint)

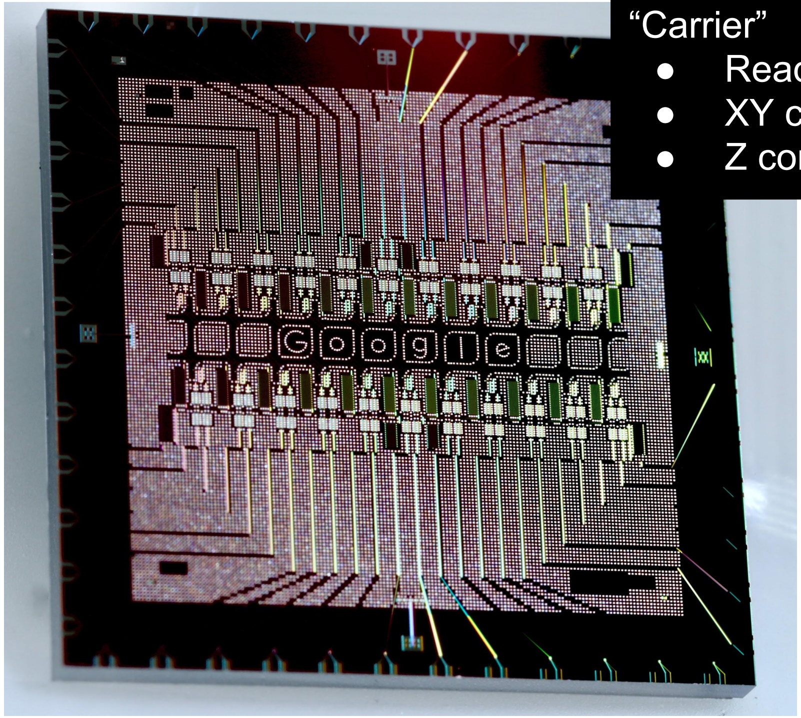
- Readout resonator
- XY coupler
- SQUID coupler

Need to shield qubits from interior wire routing

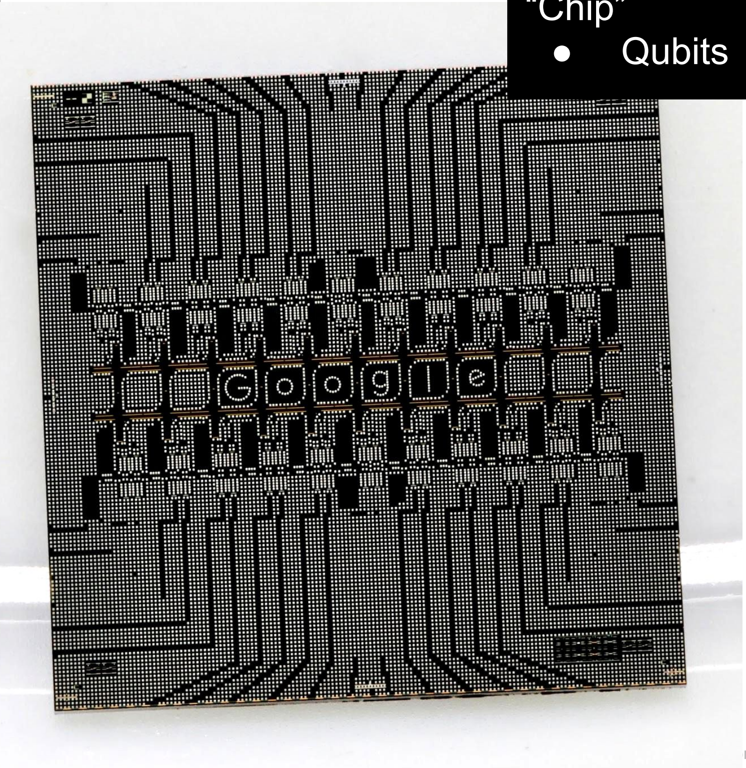
- Small coupling to 50Ω line will decohere qubit



“Foxtail” 22 Qubit Device



“Carrier”
- Readout
- XY control
- Z control



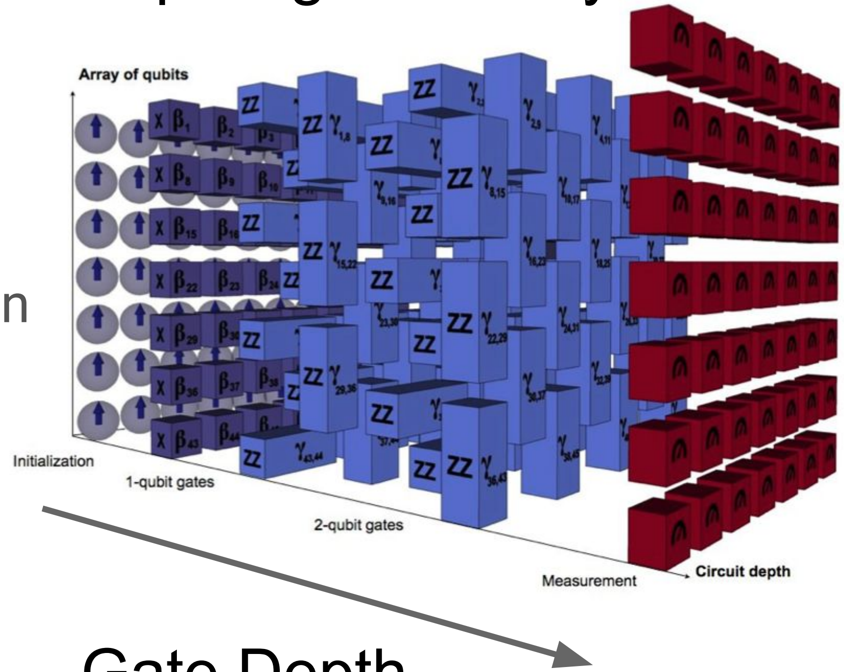
“Chip”
- Qubits

Space-Time Volume of a Quantum Gate Computation

Uncorrected Gate "Circuits" Limited by Fidelity of Operations and Decoherence Times

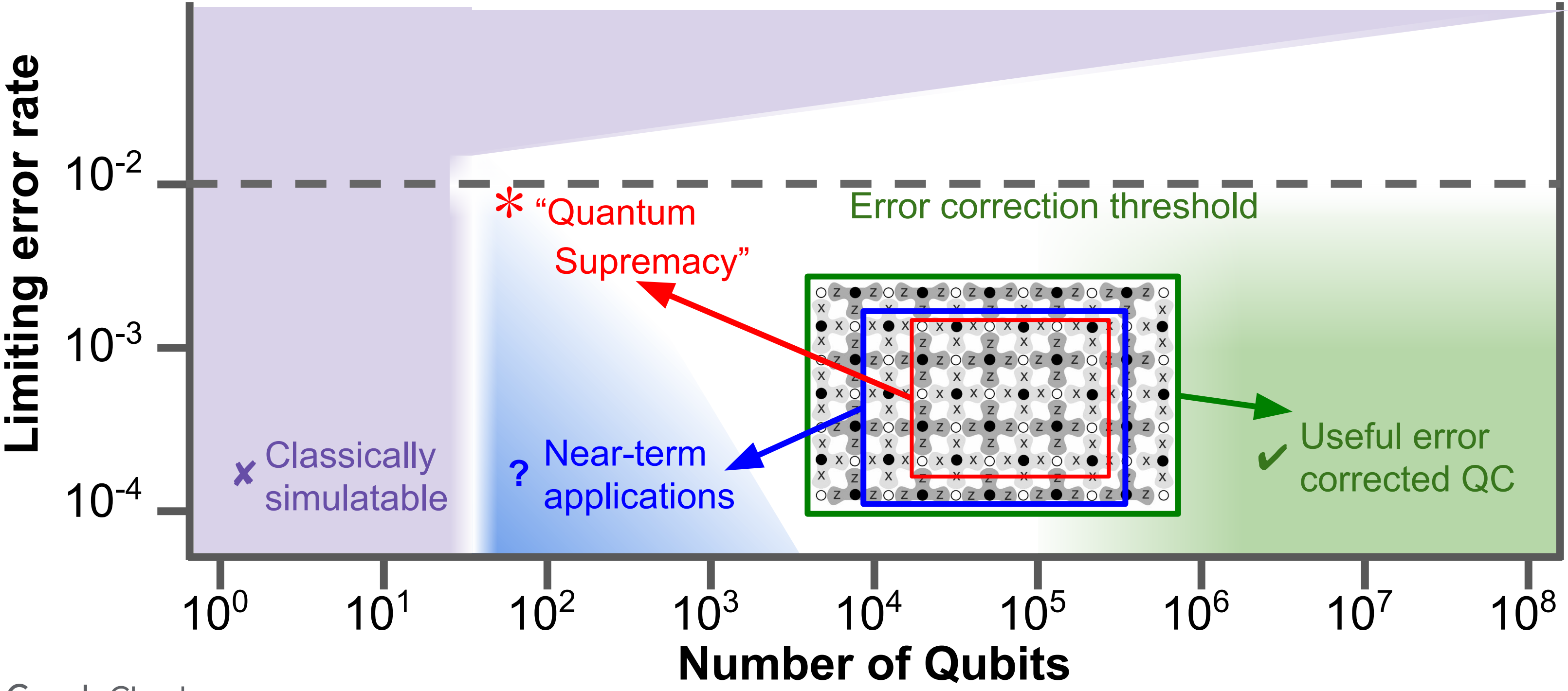
Fidelity is the Third Dimension

2 qubit gate fidelity = 99.5%



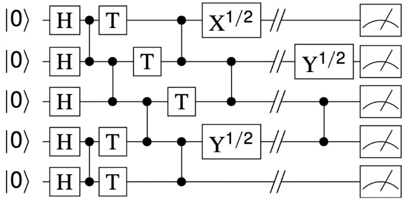
Gate Depth

Goals for Near-Term Scaling



Quantum “Supremacy”

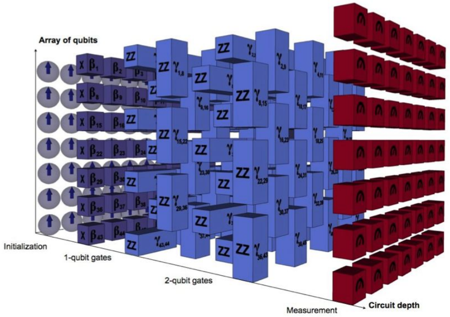
Do what classical CPUs Cannot do:

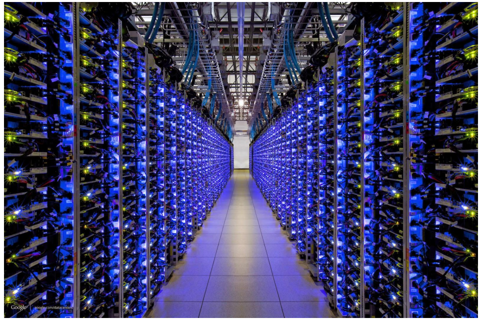


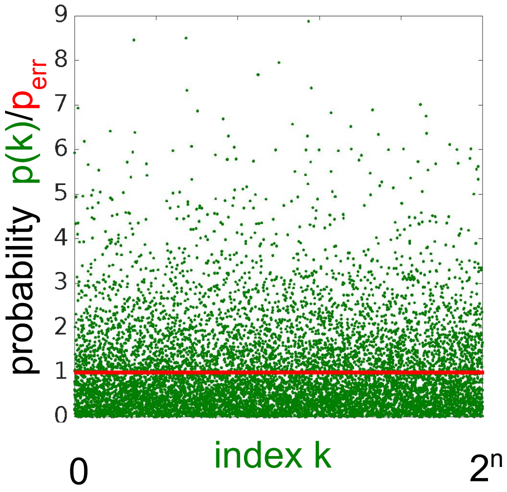
$$|0\rangle^{\otimes n} \mapsto H^{\otimes n}|0\rangle^{\otimes n} = \left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)^{\otimes n} \mapsto U\left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)^{\otimes n} = \sum_{i=1}^{2^n} c_i|x_i\rangle$$

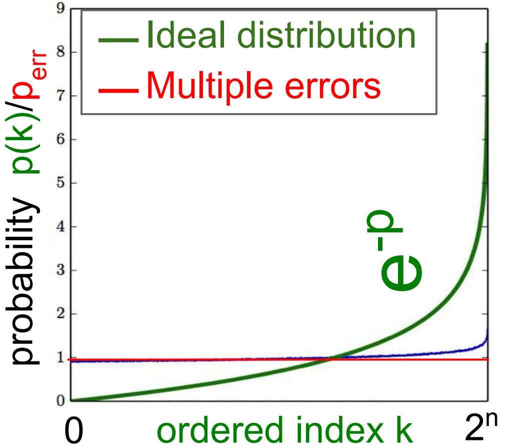
$$p_U(x_i) = |c_i|^2$$

>50 Qubits, >40 Steps



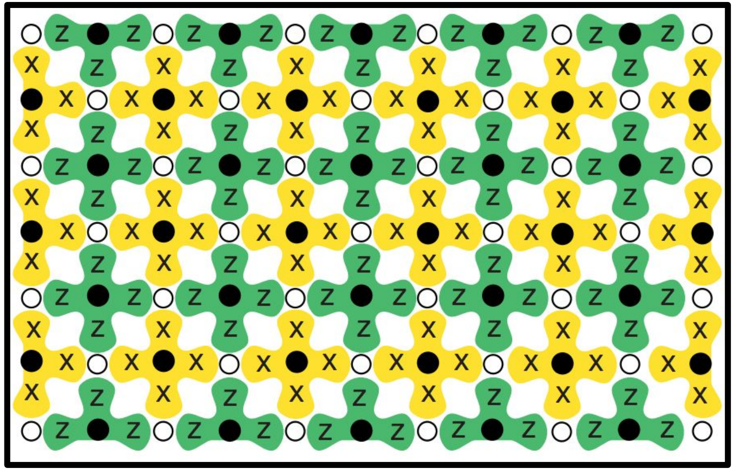






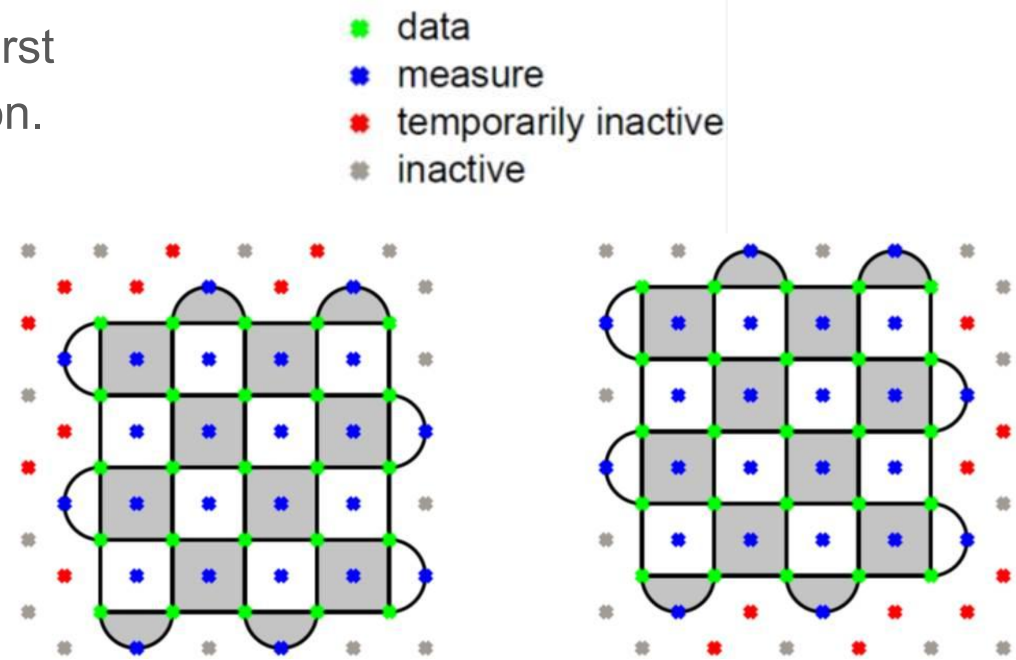
Toward Universal Fault-Tolerant QC

- 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 (n.n. coupling)
  - Modest error rates (1% threshold, 0.1% target)
  - Useful at 10^6 physical qubits

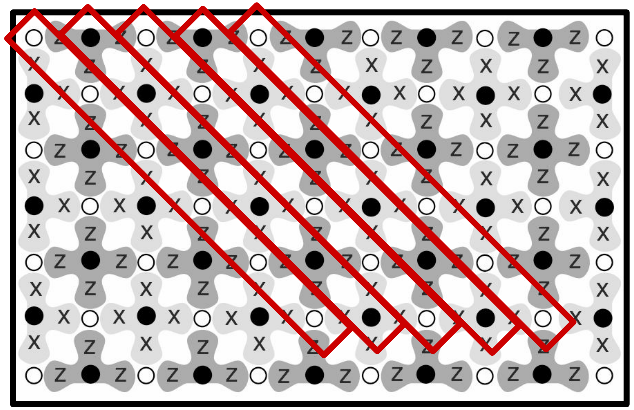


2D Grid Topology for O(100) Qubits

- The right shape and size to do first and second order error correction.
- X, Z, and leakage errors supressable.
- Hopefully prove Nature permits robust quantum computation.

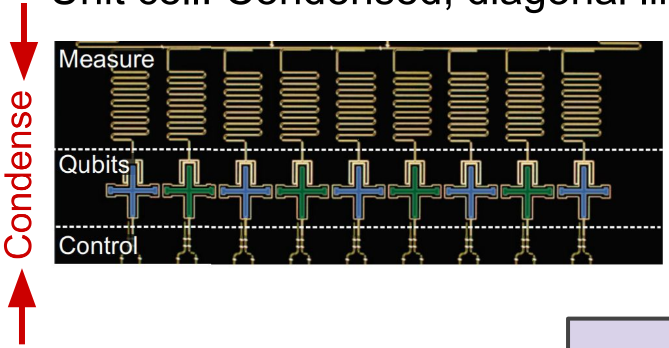


2D Unit Cell

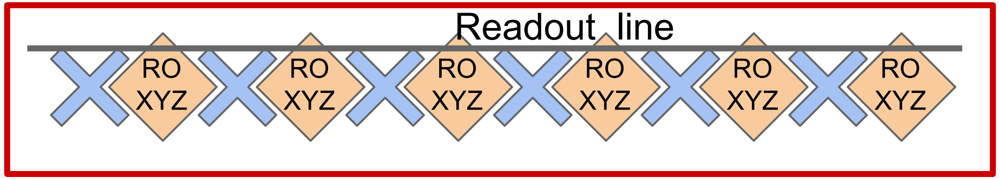


- Diagonal for surface code:
  all “measure” qubits on same line
- Condense footprint across 2 chips
- Introduce shielded wiring between qubits
- Tile unit cell for 2D array

Unit cell: Condensed, diagonal linear chain



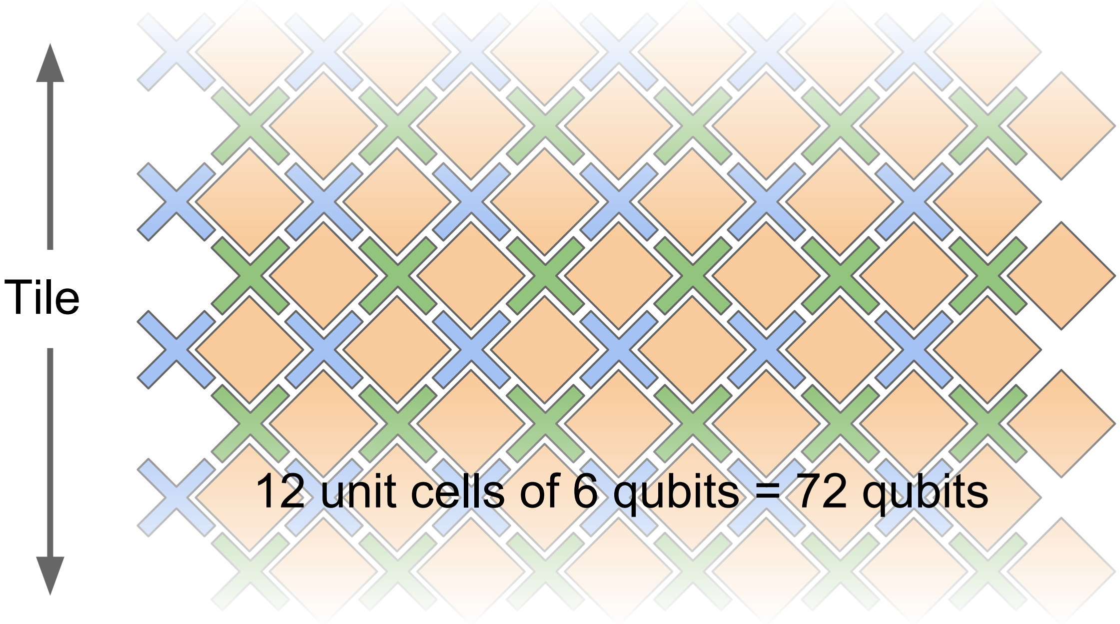
rotate



Unit cell designed for surface code

"Bristlecone" Architecture

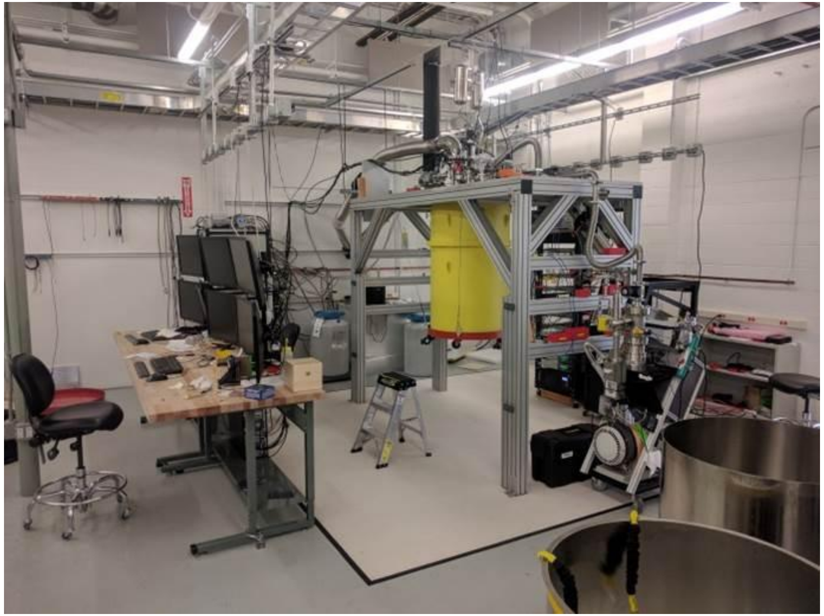
Bristlecone

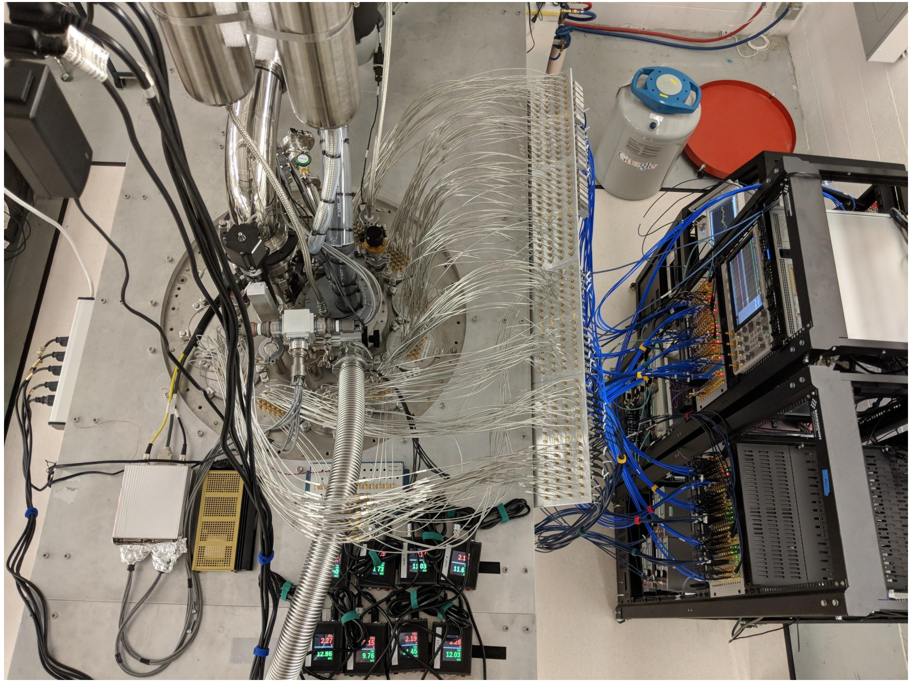


Tile for a 2D grid of n.n. coupled qubits
Bonus: Looks like a pine cone!

Photo: Erik Lucero

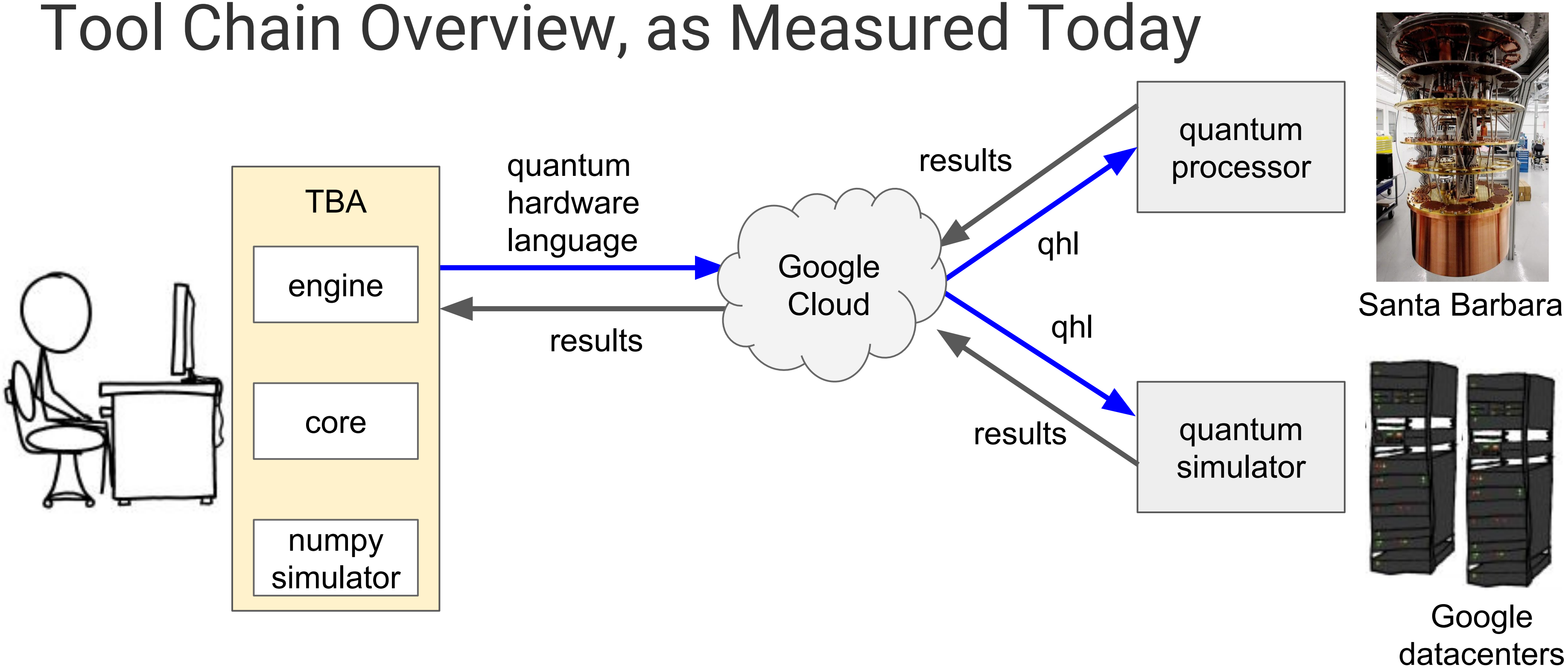
“72 qubits cold in fridge”



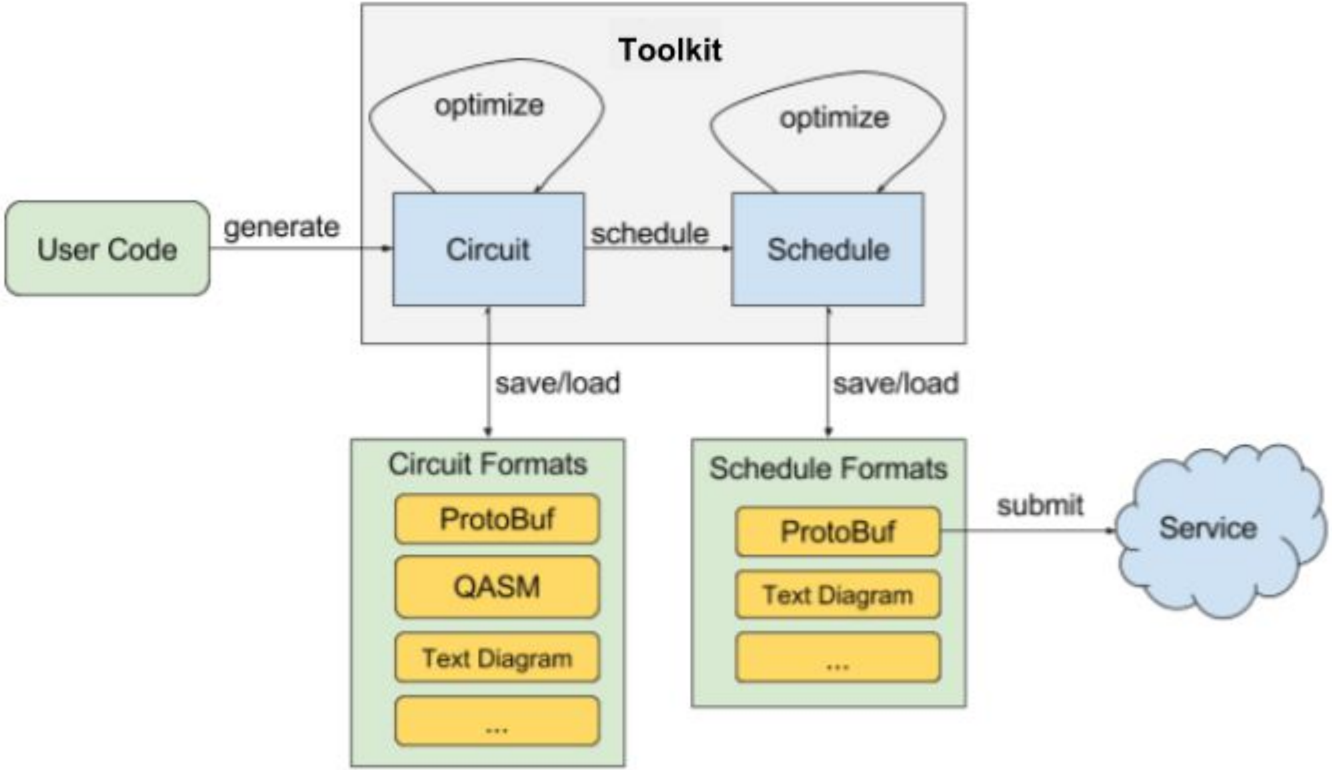


Oh, Yeah, the Software...

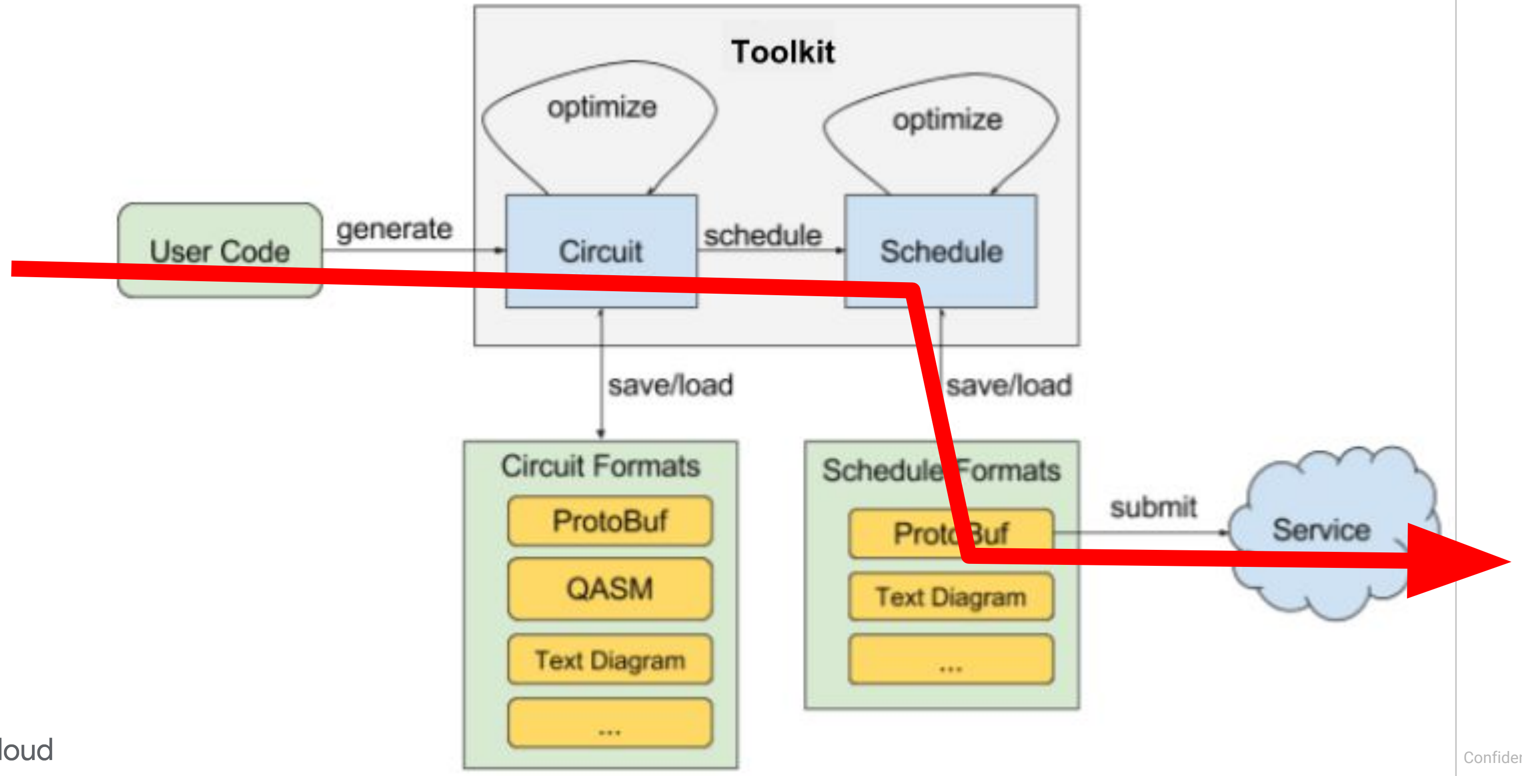
Tool Chain Overview, as Measured Today



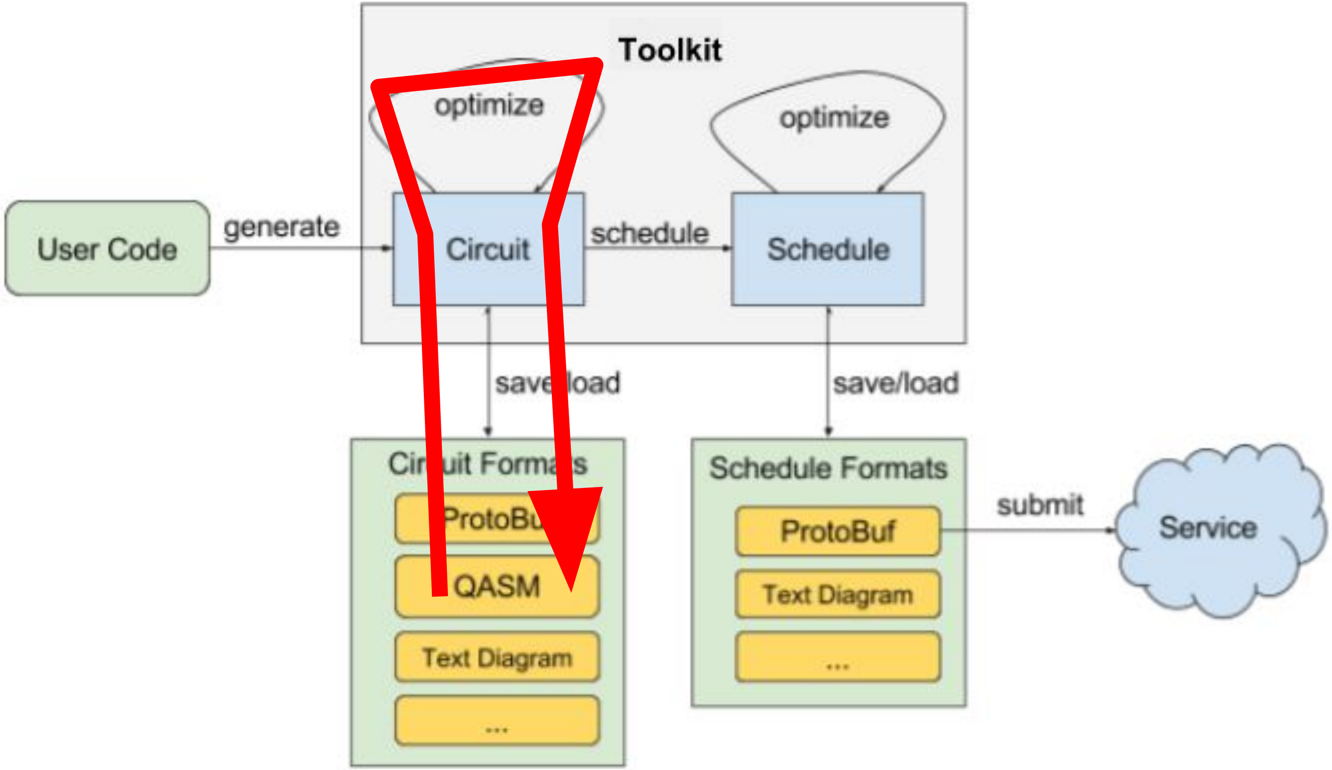
Tool Structure



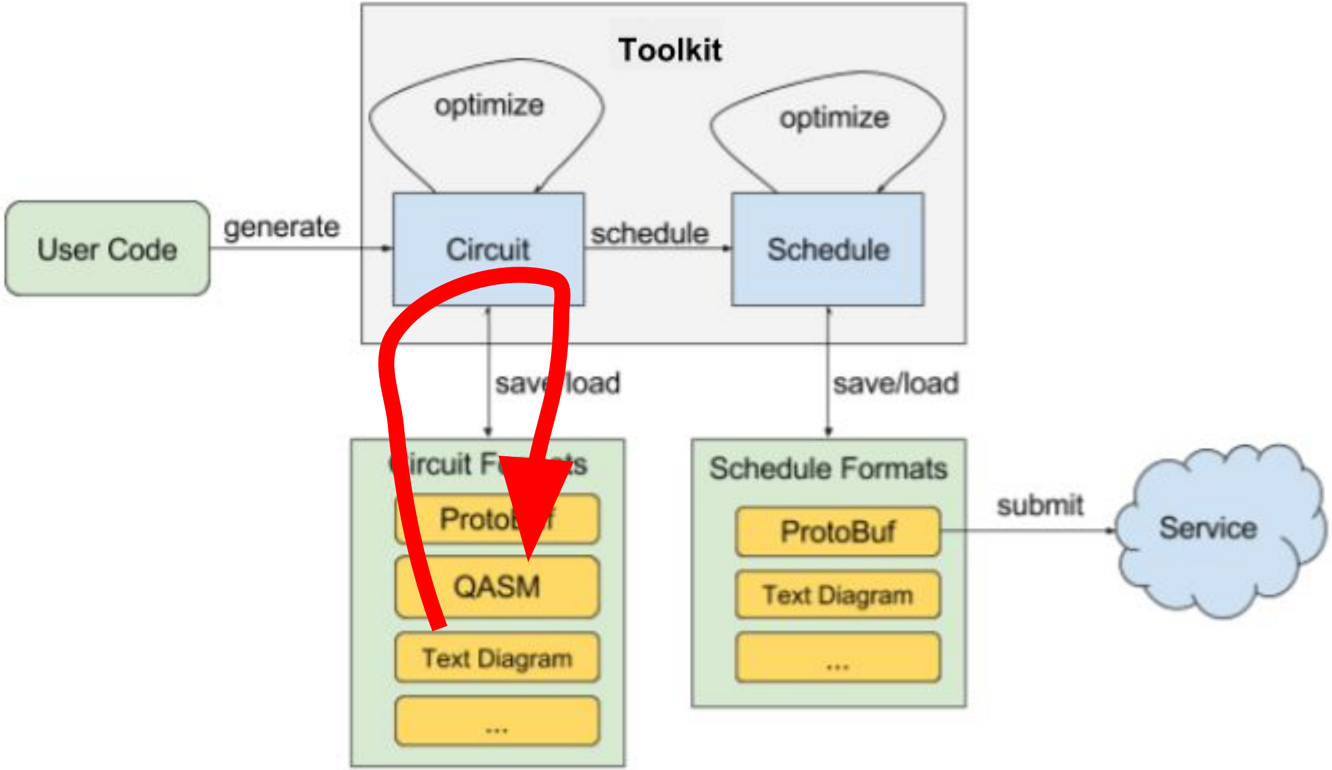
Use Case: Quantum Program Writer



Use Case: Optimizer



Use Case: Transcoder



Hello Qubit

namespacing: most commands accessible as tool.X

```
import tool
```

```
# Define a qubit.
qubit = tool.google.XmonQubit(0, 0)

# Create a circuit (qubits start in the |0> state).
circuit = tool.Circuit()
circuit.append([
    # Square root of NOT.
    tool.X.on(qubit)**0.5,

    # Measurement.
    tool.MeasurementGate('result').on(qubit)
])
```

Hello Qubit (Continued)

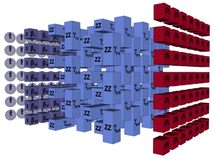
```
print(circuit)
```

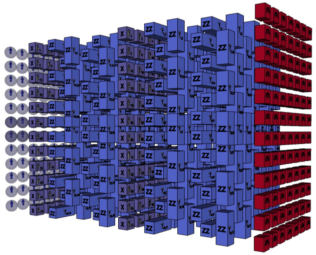
```
(0, 0): ───X^0.5───M───
```

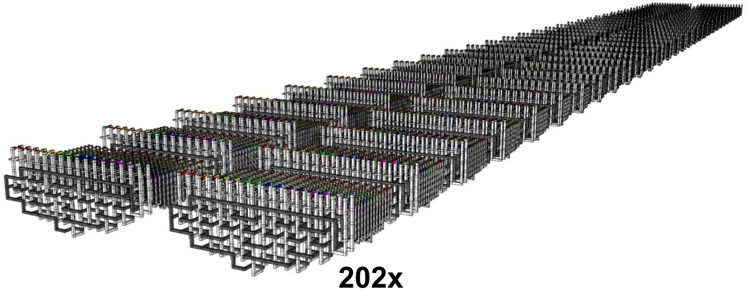
```
# Now simulate the circuit and print out the measurement result.

# Create a simulator.
simulator = tool.google.Simulator()

# Run the simulation 10 times.
result = simulator.run(circuit, repetitions=10)

# Mangle the results to a list of 0/1 results.
results = [str(int(b)) for b in result.measurements['result'][:, 0]]
print("Simulated measurement results:")
print(''.join(results))
```

```
Simulated measurement results:
1101010111
```

Quantum Computer Timeline







201x | **202x**

49 qubits @ 0.5 Error | ~10^6 qubits @ 0.1 Error

Quantum Supremacy

Beyond classical computing capability demonstrated for a select computational problem

NISQ - "Noisy Intermediate Scale Quantum": Pre-error-corrected quantum processors

Potential applications

- Simulation of Quantum Systems
- Optimization
- Sampling
- Machine Learning

Error corrected quantum computer

Growing list of quantum algorithms for wide variety of applications with proven speedups

- Unstructured Search
- Factoring
- Semi-definite Programming
- Solving Linear Systems
- ...

Thanks for Your Attention!

Google Cloud