INTRO TO QUANTUM COMPUTING

LECTURE #23

Quantum Hardware: Superconducting qubits

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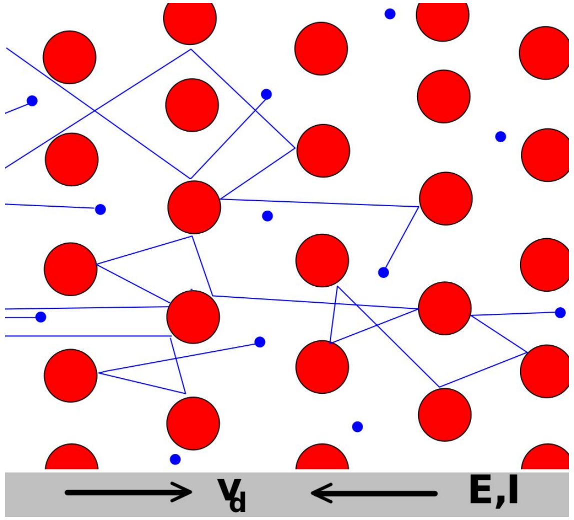
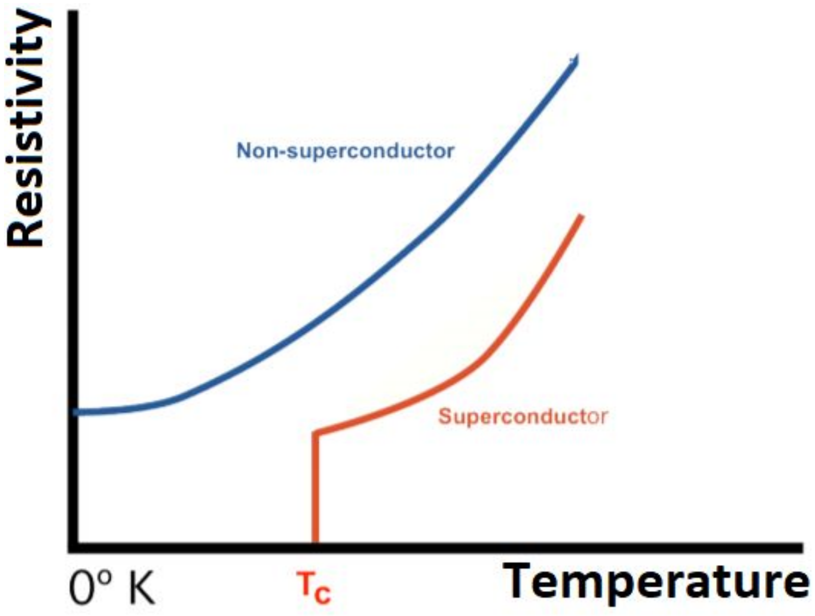
tldr: Superconducting qubits

Engineer artificial atoms using superconducting material that can be used a qubit

What is a superconductor

- As electricity moves through normal material it experiences resistance
- A superconductor conducts electricity without any resistance

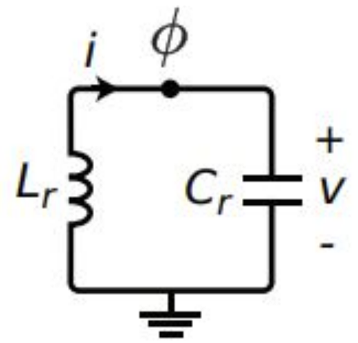




- Material resistance drops as the temperature gets lower
- For some material, the resistance sharply drops to 0 at a critical temperature (Tc).
- Example: Aluminum becomes superconducting at Tc=1.75K

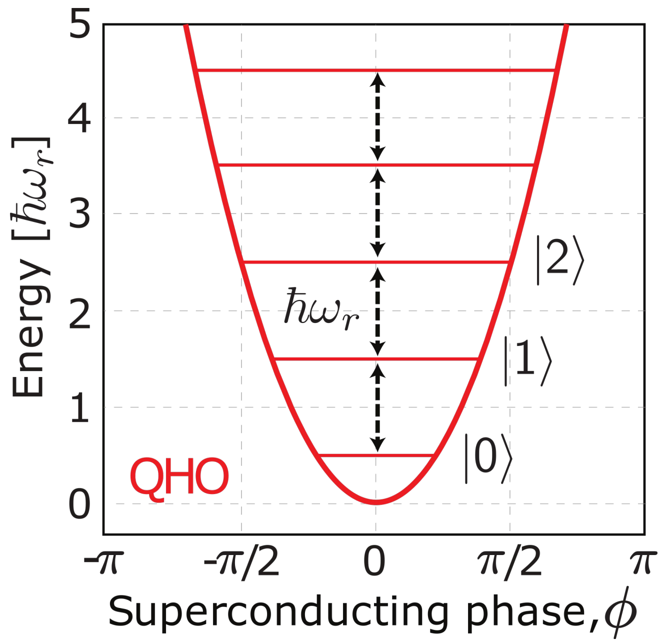
What is a superconducting qubit

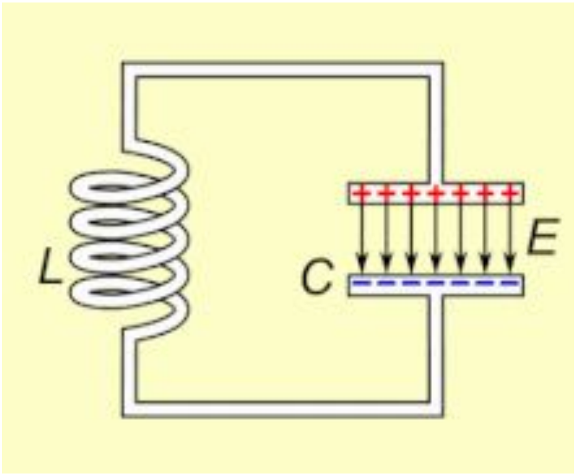
Let’s build a superconducting circuit with a capacitor an inductor



- Capacitor: stores electrical energy
- Inductor: stores magnetic energy

What do the energy levels of this system look like:





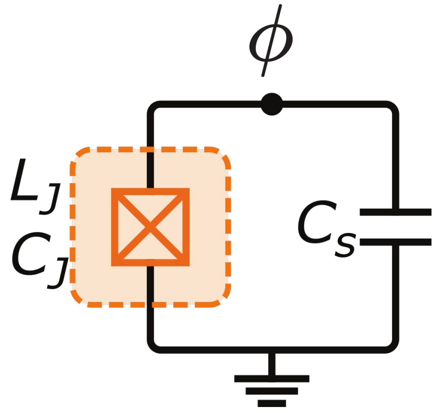
Can we use this system as a qubit?

What is a superconducting qubit

Challenge: Ideally we want a purely two-level system

In reality: Most physical systems have many energy levels :(

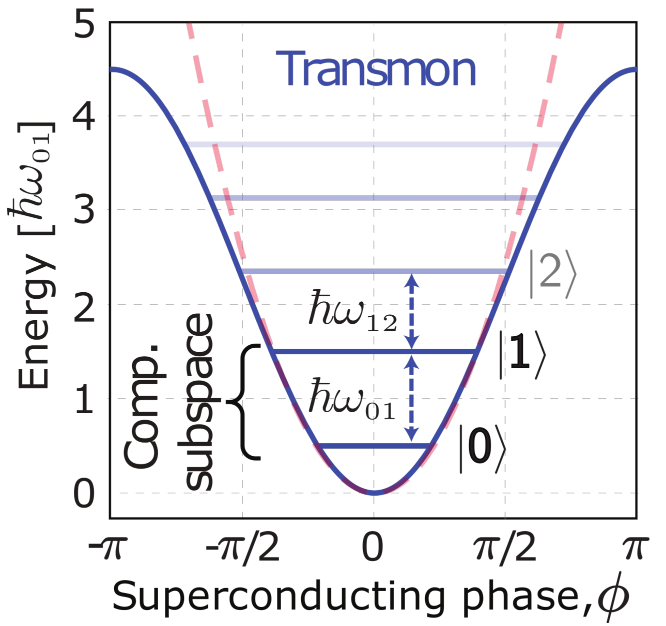
What is a superconducting qubit

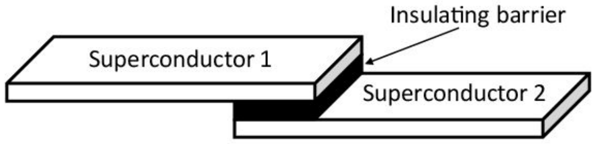


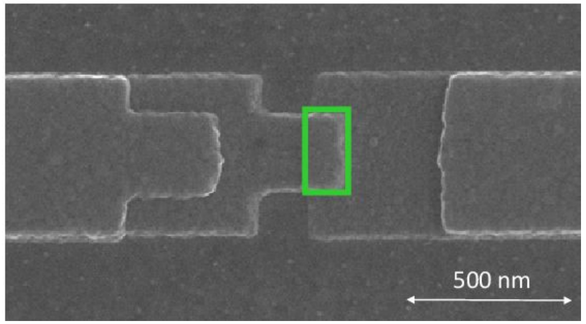
Solution: replace the inductor with a Josephson Junction

What's a Josephson Junction?

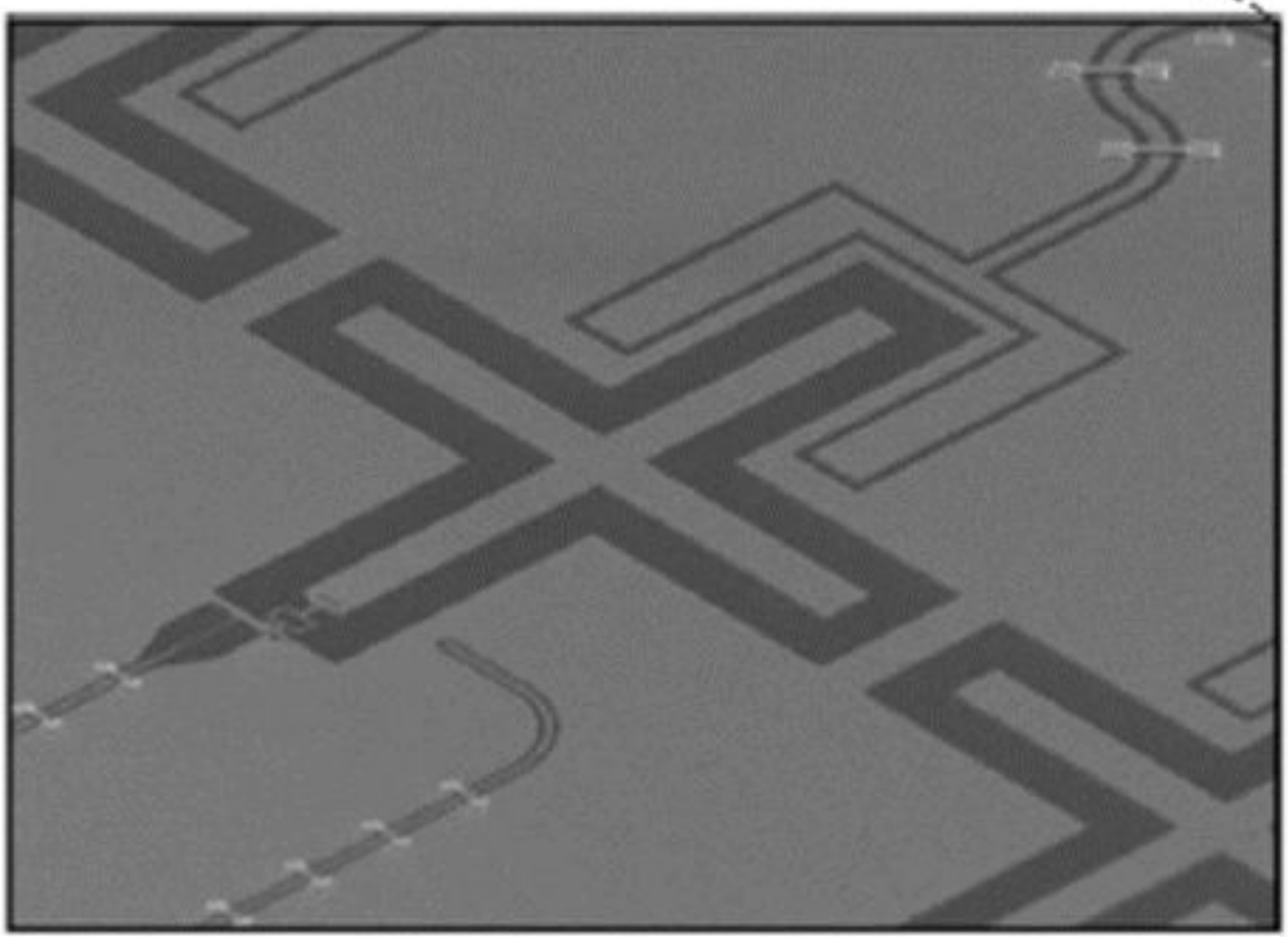
- Two superconductors coupled by a thin insulating barrier
- Current tunnels through the insulator







What is a superconducting qubit

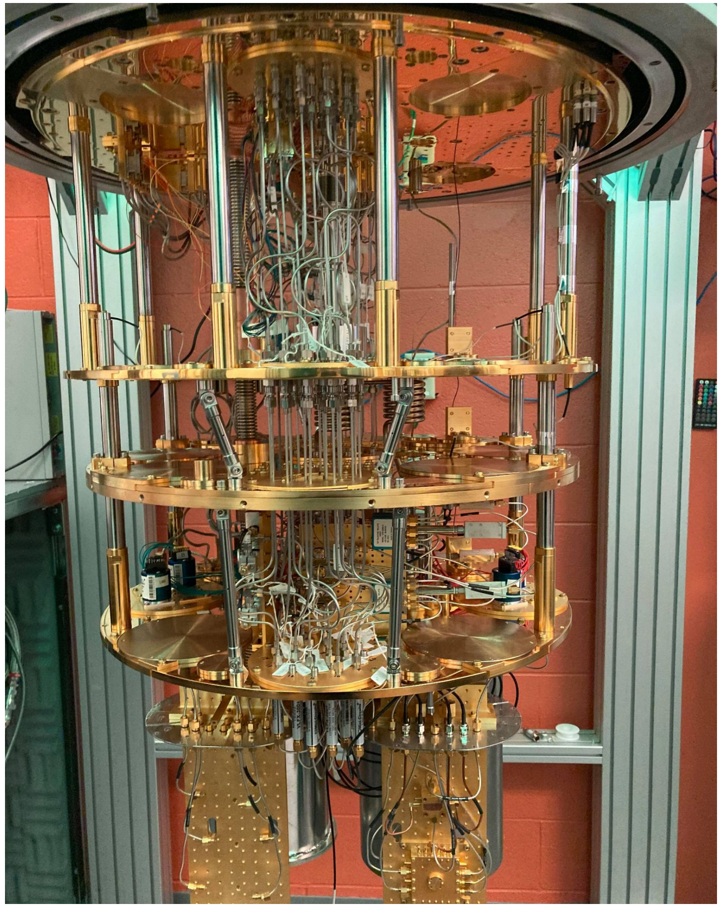


How do we operate the qubits?

Equipment:

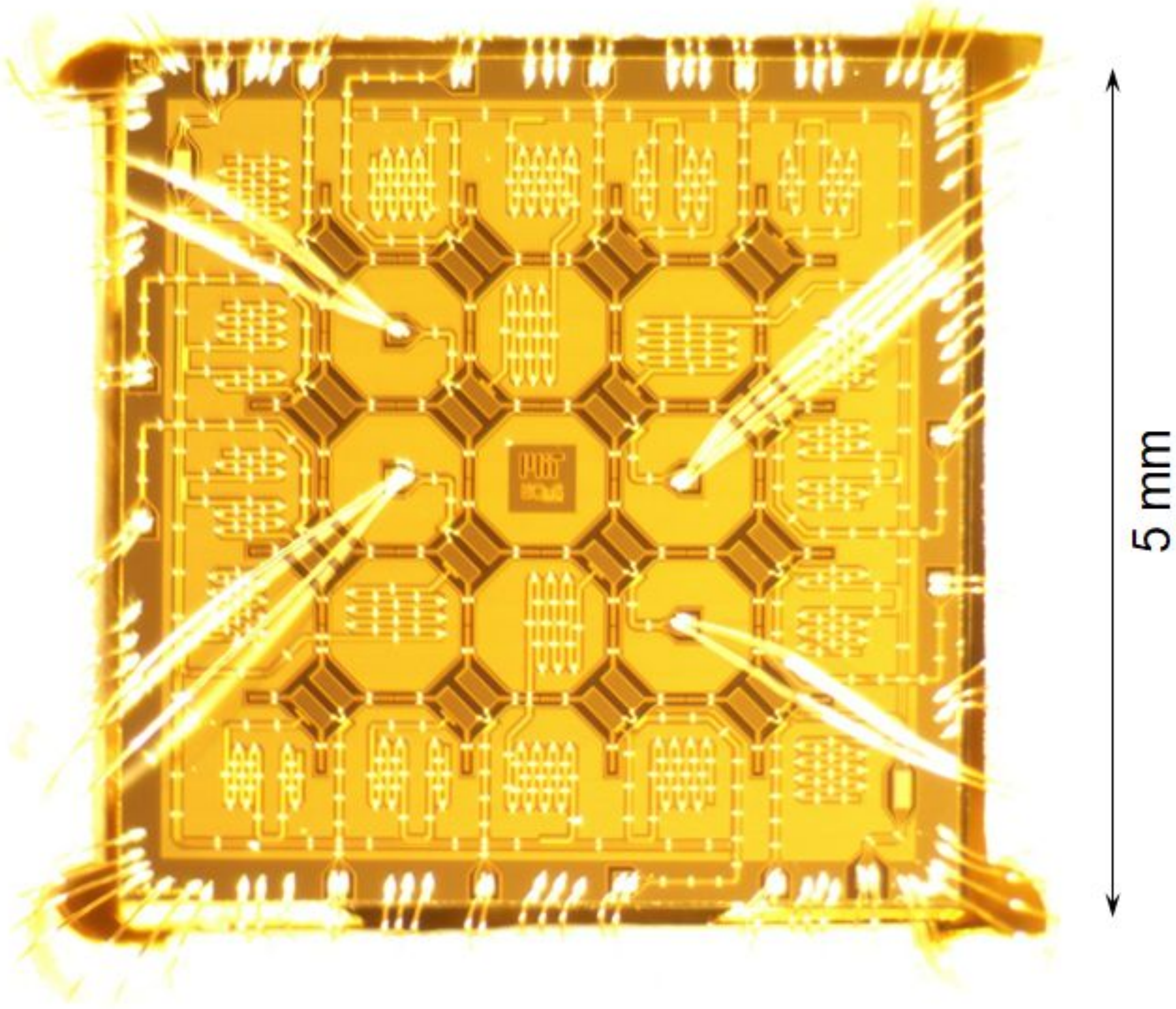
Dilution refrigerator

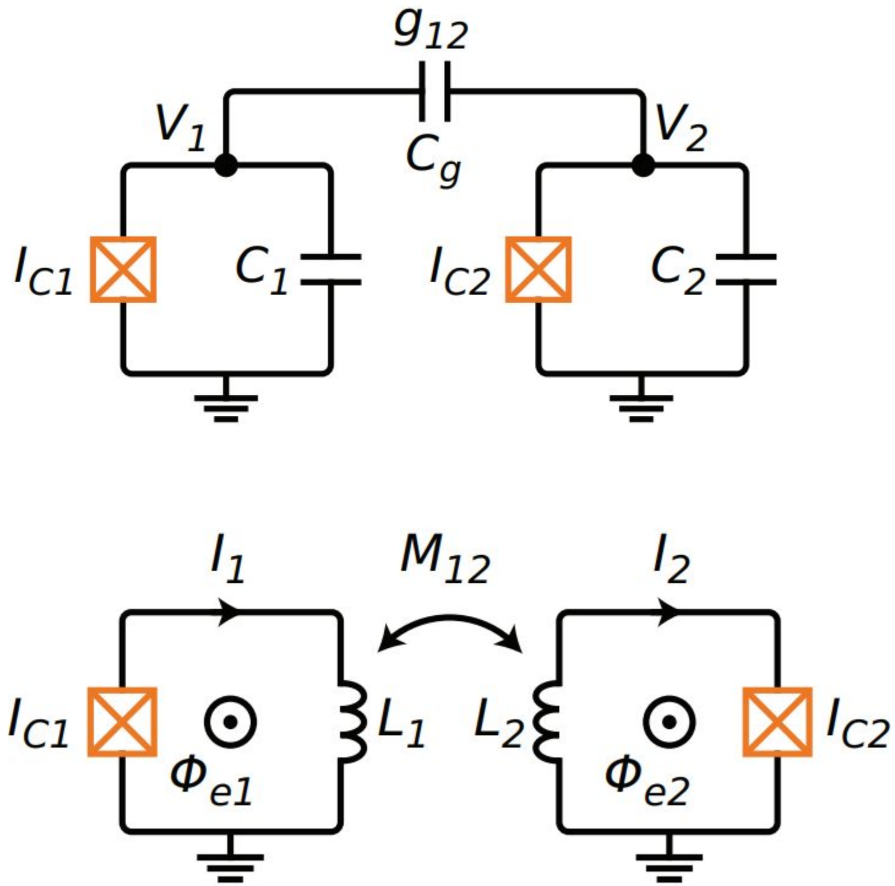
Dilution refrigerator (inside)



Microwave equipment

How are the qubits connected

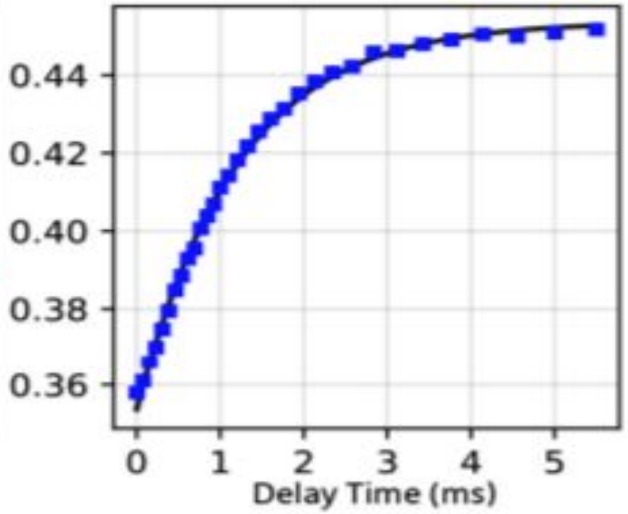


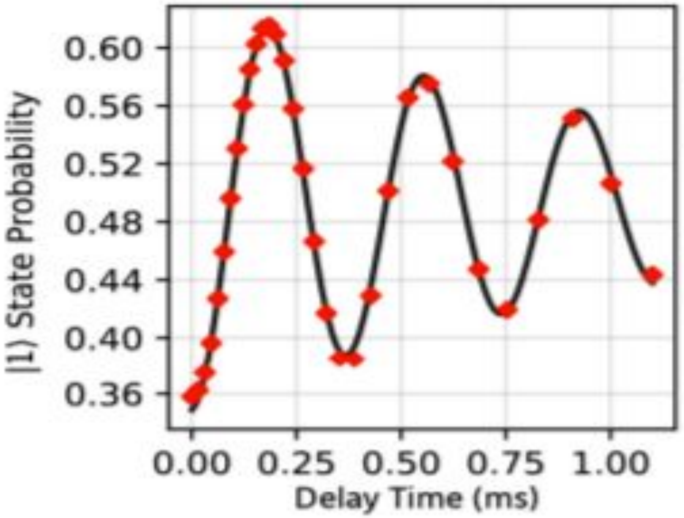


What are the coherence properties?

- State of the art T1 in quantum processors: ~100 us
- State of the art T2 in quantum processors: ~ 100 us
- Individual qubit T1s and T2s have been shown to go as high as 1ms

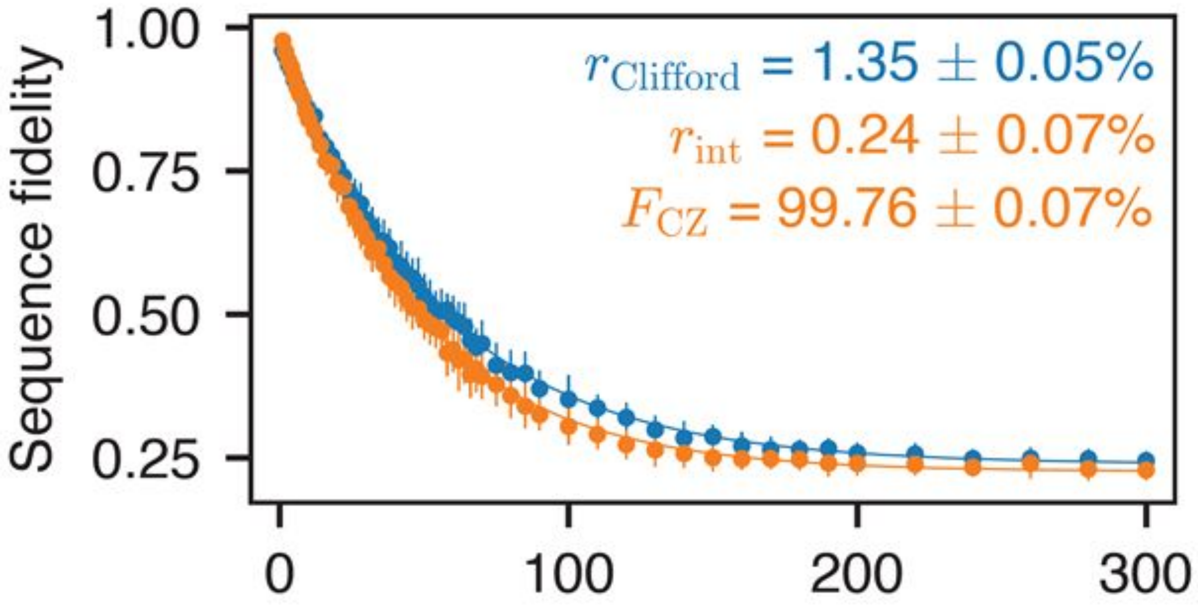
Average gate time: 10-100ns





What is the gate fidelity?

- Gates can be engineered using:
  - Microwave pulse
  - Using natural hardware interactions
- Single-qubit gates: ~99.99%
- Two-qubit gate: >99.7%



Pros and Cons

Pros:

- Comes on a chip
- Compatible with existing fabrication infrastructure
- Uses microwave technology which is well developed
- High quality gates and readout

Cons:

- Loss to substrate material
- Requires cooling to mK temperatures
- Need bigger dilution fridges for larger processors

Breakthroughs

Article

Quantum supremacy using a programmable superconducting processor

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Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5]*

QUANTUM COMPUTING

Hartree-Fock on a superconducting qubit quantum computer

Google AI Quantum and Collaborators*†

The simulation of fermionic systems is among the most anticipated applications of quantum computing. We performed several quantum simulations of chemistry with up to one dozen qubits, including modeling the isomerization mechanism of diazene. We also demonstrated error-mitigation strategies based on *N*-representability that dramatically improve the effective fidelity of our experiments. Our parameterized ansatz circuits realized the Givens rotation approach to noninteracting fermion evolution, which we variationally optimized to prepare the Hartree-Fock wave function. This ubiquitous algorithmic primitive is classically tractable to simulate yet still generates highly entangled states over the computational basis, which allowed us to assess the performance of our hardware and establish a foundation for scaling up correlated quantum chemistry simulations.

Millisecond coherence in a superconducting qubit

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(Dated: March 16, 2021)

Article

Control and readout of a superconducting qubit using a photonic link

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F. Lecocq[1,2]✉, F. Quinlan[1]✉, K. Cicak[1], J. Aumentado[1], S. A. Diddams[1,2] & J. D. Teufel[1]✉

Delivering on the revolutionary promise of a universal quantum computer will require processors with millions of quantum bits (qubits)[1–3]. In superconducting quantum processors[4], each qubit is individually addressed with microwave signal lines that connect room-temperature electronics to the cryogenic environment of the quantum circuit. The complexity and heat load associated with the multiple coaxial lines per qubit limits the maximum possible size of a processor to a few thousand qubits[5]. Here we introduce a photonic link using an optical fibre to guide modulated laser light from room temperature to a cryogenic photodetector[6], capable of delivering shot-noise-limited microwave signals directly at millikelvin temperatures. By demonstrating high-fidelity control and readout of a superconducting qubit, we show that this photonic link can meet the stringent requirements of superconducting quantum information processing[7]. Leveraging the low thermal conductivity and large intrinsic bandwidth of optical fibre enables the efficient and massively multiplexed delivery of coherent microwave control pulses, providing a path towards a million-qubit universal quantum computer.

Ongoing research

- Scaling to more qubits
- Higher coherence times (T1, T2)
    - New designs
    - Improvement in material
- Engineering better quantum gates
- Achieving error correction and fault tolerance