Superconducting Quantum Computing Hardware

qLearn Lecture Series

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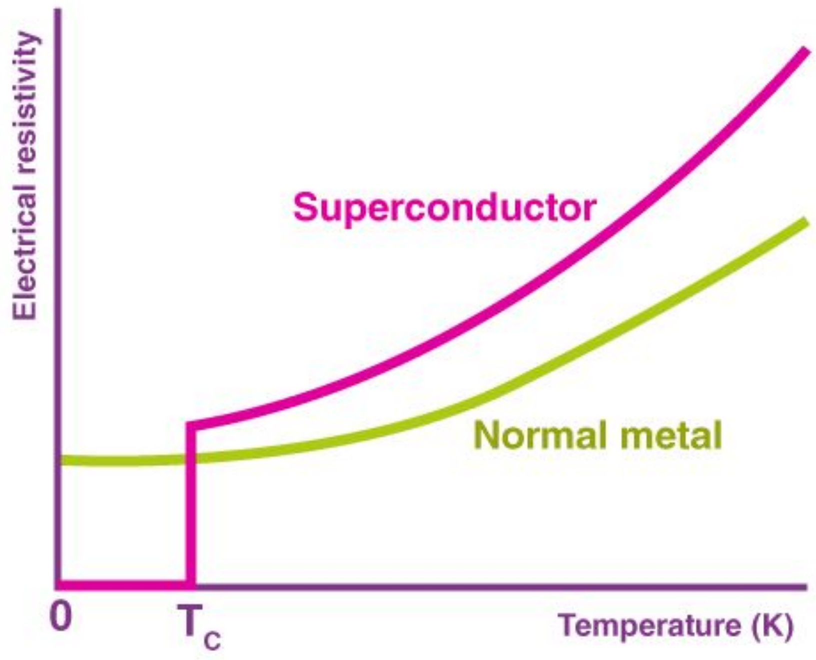
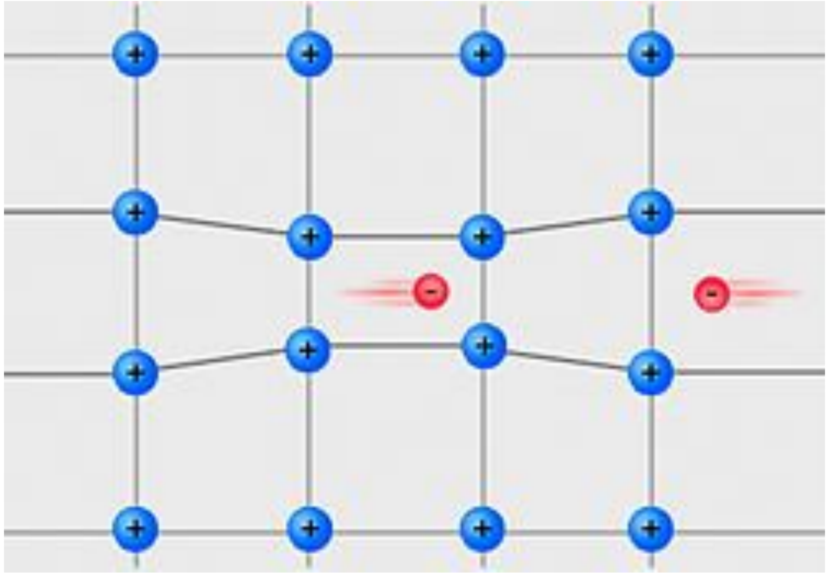
What is a superconductor?



- Limiting resistances allows for persistent current and coherence
- Prevents losing energy to resistance

Cooper Pairs: The Particles Behind Superconductivity



- Two electrons weakly bind together in a lattice
- They move as a single quantum object

$$\Psi = |\Psi| e^{i\phi}$$

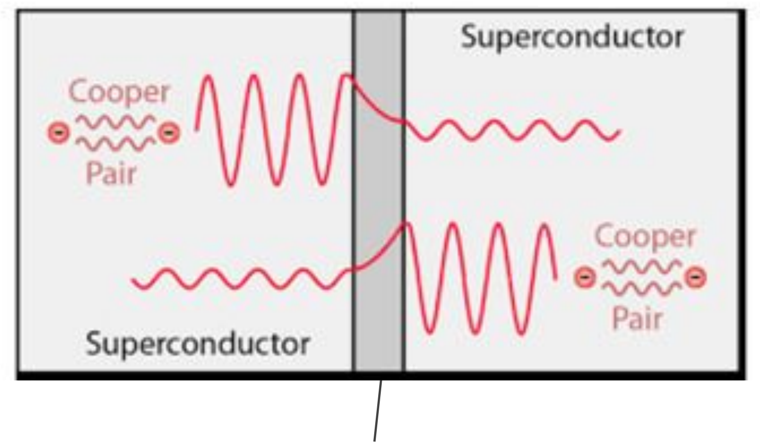
$|\Psi|^2$: density

ϕ: phase

- Billions of pairs form one giant quantum wave that moves without resistance
- Groups share a single function in superconductor

The Josephson Junction

$\Psi_1 = e^{i\phi_1}$ insulator $\Psi_2 = e^{i\phi_2}$



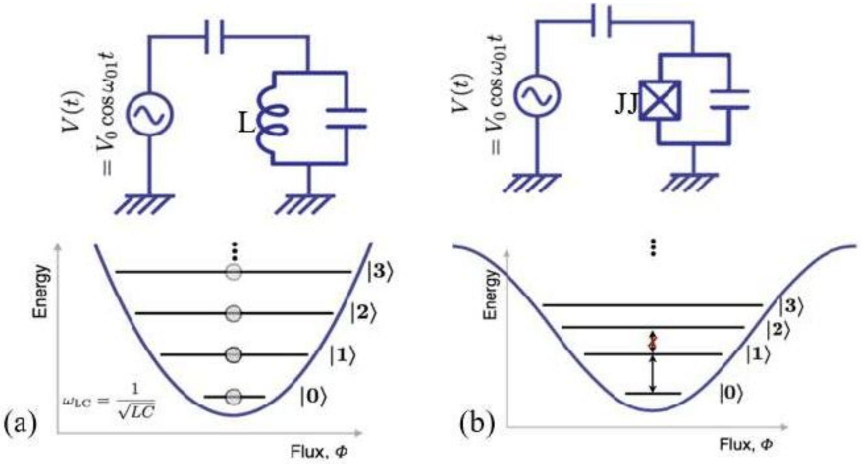
Quantum Tunneling Effect

- Cooper pairs can tunnel through the insulating barrier
- Current depends on **phase difference** between superconductors

$$I = I_c \sin(\phi_1 - \phi_2)$$

- Introduces nonlinearity into circuits

From Josephson Junctions to Superconducting Qubits



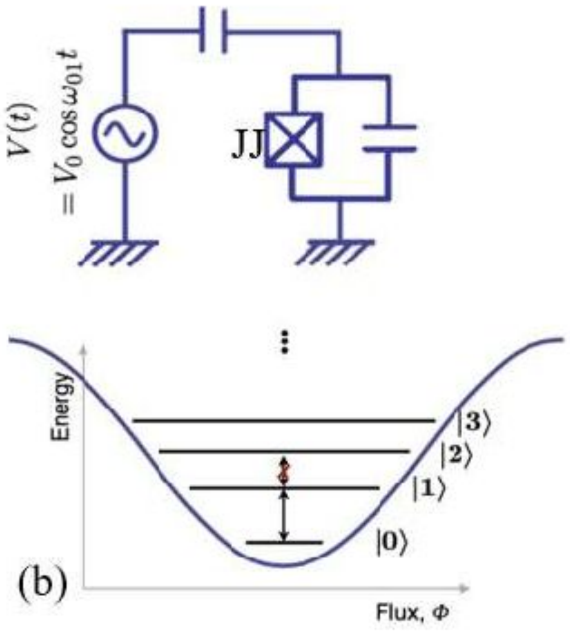
LC vs. 'Transmon' Circuits & Energy levels

- LC Circuits act as a resonator/oscillator
- Josephson junction acts as a nonlinear inductor -> makes circuit quantum
- Cooper pairs now occupy discrete energy levels of 0 and 1
- Energy spacing is uneven; we can excite 0 to 1 without hitting higher levels

Quantum Operations with Transmon Qubits

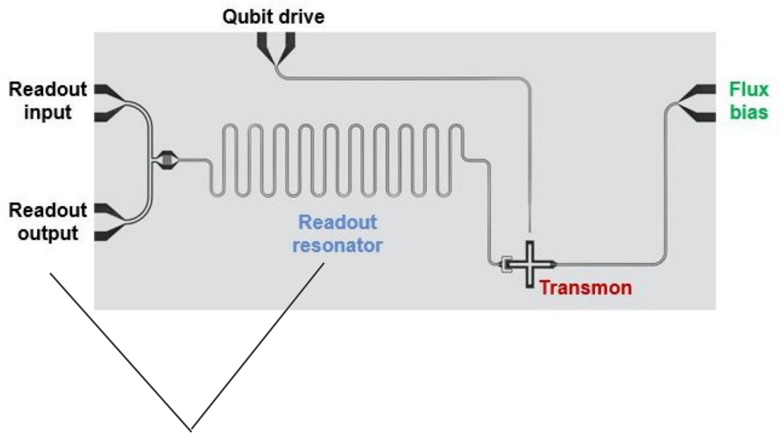
- Done using microwave pulses
  - They essentially change the phase difference across the Josephson junction
  - This changes the wavefunction (controlled oscillation)
- Specific to Z rotations, we don't need to perform quantum operations, but instead changes future microwave pulses to accommodate for the phase change

Creating Superposition in Transmons



- In energy states, Cooper pairs occupy either the ground or first excited mode of the circuit
- Applying a microwave pulse at the qubit's resonant frequency drives transitions between these modes
- The Cooper pair wavefunction becomes distributed across 0 and 1, creating a superposition
- The pulse duration and amplitude control the mixture of 0 and 1

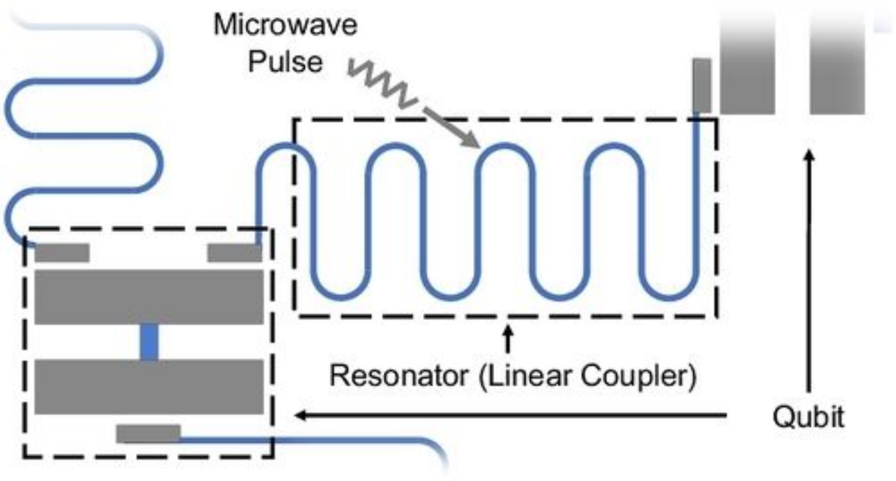
Measuring Transmon Qubits



Measurement tools

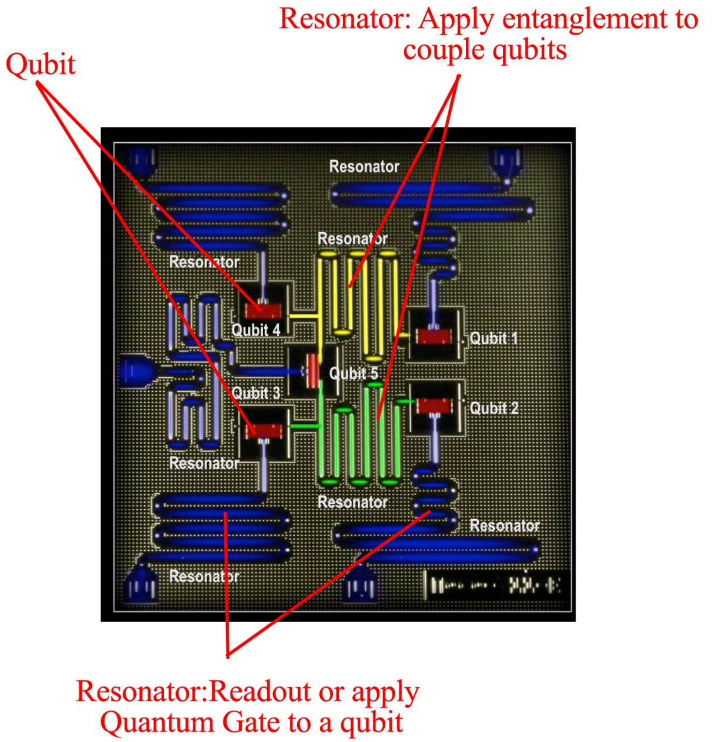
- Measurement is usually done indirectly via a readout resonator
    - Qubit is coupled to small microwave cavity
    - Qubit state slightly shifts cavity’s resonant frequency
    - Measure cavity response revealing qubit state

Creating Entanglement



- Different ways to accomplish; most common today uses a shared microwave resonator
- Qubits interact by virtually exchanging information through the resonator
- Two-qubit gates performed by tuning qubit frequencies using microwave pulses

Putting the Pieces Together



Why Superconducting Hardware?

Superconducting Hardware in the Quantum Landscape

Pros:

- Fabricated with modern transistor fab technologies
- Fast gate speeds (tens of nanoseconds)
- Mature control stack using microwave tech

Cons:

- Requires extreme cryogenics (<20mK)
- Fast decoherence times
- Tomography limitations
- Crosstalk between control lines

Who's doing it?

IBM Quantum

rigetti

Google AI Quantum

NORTHROP GRUMMAN

Superconducting mini-course!