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Superconducting Qubits

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Introduction

To design a qubit, or to physically realize a quantum computing system, it is important to fulfill certain requirements such as:

- DiVincenzo criteria (Long coherence time, scalability)
- Ease of design and manufacturing
- Ease of control

Superconducting qubits satisfy these criteria to a level

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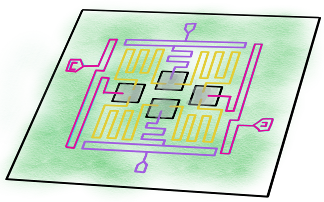
Introduction

Superconducting quantum computing

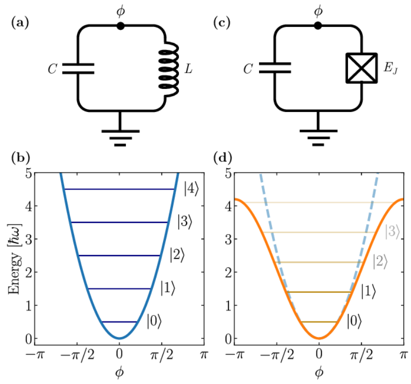
- Circuits which are designed to act as 2-level systems at low temperatures
- At this condition, the circuits have almost infinite conductivity and zero resistance.
- The charge carriers are Cooper pairs of electrons, which are bosons.
- At low temperatures, the cooper pairs collapse to the ground state to form BE condensates
- Sine there are less interactions among bosons, they act as a superconductor.



Introduction

Superconducting quantum computing

- The circuits are composed of semiconductor circuit elements (LC circuit, Capacitor, Inductor)
- From an LC circuit, we get the standard Quantum Harmonic oscillator with equally spaced discrete levels.
- In order to reduce to a 2-level quantum system, the Josephson junction helps with the process

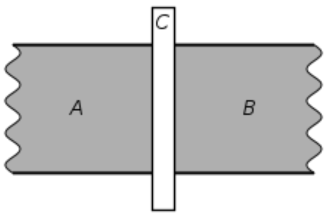


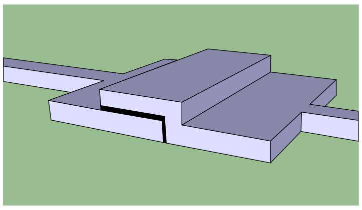
Josephson Effect

- When 2 superconductors are restricted with a barrier, a supercurrent flows through the junction
- Given that the 2 superconductors A & B have wave functions of Cooper pairs given by

$$\psi_A = \sqrt{n_A} e^{i\phi_A}$$

$$\psi_B = \sqrt{n_B} e^{i\phi_B}$$





Josephson Effect

The Schrodinger equation is given by

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}=\begin{pmatrix}eV & K\\ K & -eV\end{pmatrix}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix},$$

Where K is the characteristic of the junction.
Solving the equation by taking the time derivative for A,

$$\frac{\partial}{\partial t}(\sqrt{n_A}e^{i\phi_A})=\dot{\sqrt{n_A}}e^{i\phi_A}+\sqrt{n_A}(i\dot{\phi}_A e^{i\phi_A})=(\dot{\sqrt{n_A}}+i\sqrt{n_A}\dot{\phi}_A)e^{i\phi_A},$$

This allows to rewrite the equation as

$$\dot{\sqrt{n_A}}+i\sqrt{n_A}\dot{\phi}_A=\frac{1}{i\hbar}(eV\sqrt{n_A}+K\sqrt{n_B}e^{i\varphi}),$$

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Josephson Effect

Taking the complex conjugate and subtracting we can get the time derivative of phase Φ_A’

$$2i\sqrt{n_A}\dot{\phi}_A=\frac{1}{i\hbar}(2eV\sqrt{n_A}+K\sqrt{n_B}e^{i\varphi}+K\sqrt{n_B}e^{-i\varphi}),$$

$$\dot{\phi}_A=-\frac{1}{\hbar}(eV+K\sqrt{\frac{n_B}{n_A}}\cos\varphi).$$

Likewise, for B

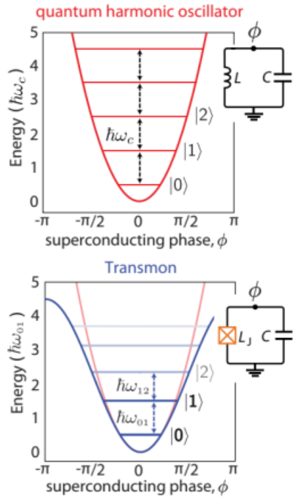
$$\dot{\phi}_B=\frac{1}{\hbar}(eV-K\sqrt{\frac{n_B}{n_A}}\cos\varphi).$$

The Josephson phase is the difference between Φ_B and Φ_A

$$\varphi=\phi_B-\phi_A$$

Josephson Effect

- Here, the Josephson junction with different phases on both sides causes current flow to occur by quantum tunneling
- This causes non-linear inductance which produces anharmonic oscillators with non-uniform spacing between energy levels
- Compared to QHO, this allows to access only 2 levels



Josephson Effect

For the given phase difference, the Josephson relations are

$$I_J = I_0 \sin\phi \qquad\qquad V = \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

where
I_J is the Josephson current and
Φ_0 is the flux quantum

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Types

Based on different degrees of freedom, there are mainly 2 categories of superconducting qubits

- Charge
- Flux

Other variants can be hybridized versions of the above 2 main types

The differentiating factor is the ratio EJ/EC where EJ is the Josephson energy and EC is the charging energy

Another means of comparison is via the number of Cooper pairs that are allowed to tunnel through the junction, therefore Charge < Flux

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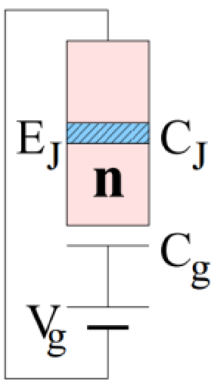
Charge Qubit

- $EJ \ll EC$
- Control gate voltage V_g is coupled to the system via a gate capacitor C_g
- Junction capacitance can be designed to Femtofarad range values (10^{-15} F)
- Charging energy $E_C = e^2/2(C_G+C_J)$
- The 2 states of 0 and 1 differ by one Cooper pair charge
- Gates can be applied by tweaking the gate voltage or magnetic fields



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Charge Qubit

The Hamiltonian is given by

$$H = 4E_c(n - n_g)^2 - E_J cos\Phi$$

n = number of (excess) Cooper pairs on the island that tunnel through the junction
Φ = Josephson phase difference parameter
n_g = gate charge which acts as an opposing control parameter = $C_gV_g/2e$

Considering a 2 level system and the number of Cooper pairs, the Hamiltonian rephrases to

$$\mathcal{H} = \sum_n \Big\{ 4E_\mathrm{C}(n - n_\mathrm{g})^2 |n\rangle\langle n| - \frac{1}{2}E_\mathrm{J}\Big(|n\rangle\langle n+1| + |n+1\rangle\langle n| \Big) \Big\} .$$

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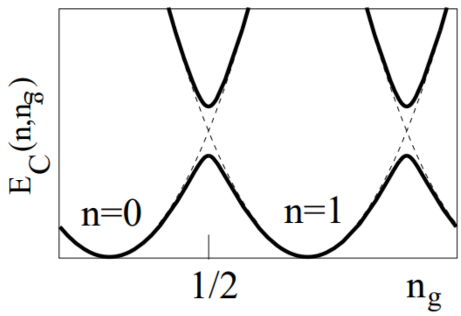
Charge Qubit

- Initially, the system is similar to a quantum harmonic oscillator
- However, with the Josephson junctions, there is over lapping at ½ integer values of n_g
- For the sake of 2-level system, only 2 states can be considered.
- In essence, the Josephson junctions act as valves for Cooper pairs to restrict movement within only 2 levels which is needed for a qubit



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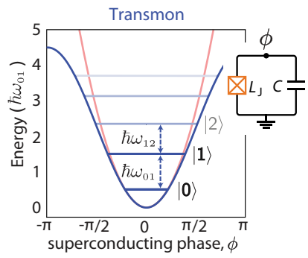
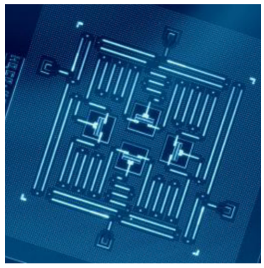
Transmon

- As mentioned, the addition of Josephson junctions produces anharmonicity $\alpha \equiv \omega_{12}/2\pi - \omega_{01}/2\pi$
- However, this qubit is still vulnerable t environment charge noise and other external factors
- The addition of a shunt capacitor gives us the transmon qubit
- This qubit aside from decreased charge noise sensitivity also gives increase in EJ/EC ratio and increased coherence time





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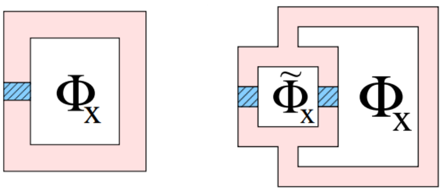
Flux Qubit

- $1 \ll EJ/EC \ll 100$
- $EJ \gg EC$
- Loops of superconducting wire fitted with a number of Josephson junctions
- Since the Josephson energy is greater, Cooper pairs flow continuously around the loop
- High coherence time ranging between 10 µs to 23 µs
- The only drawback is the lack of device-to device reproducibility



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Flux Qubit

The Hamiltonian is given by

$$\mathcal{H} = -E_J \cos\left(2\pi\frac{\Phi}{\Phi_0}\right) + \frac{(\Phi - \Phi_x)^2}{2L} + \frac{Q^2}{2C_J}$$

Where
L is the self-inductance of the loop
C_J is the capacitance of the junction
Φ_X is the external applied flux
Q is the charge on the leads which is canonically conjugate to Φ

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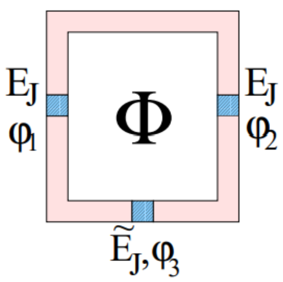
Flux Qubit

- When the external flux Φ_X applied is close to a ½ integer number of flux Φ, the first 2 terms of the Hamiltonian forms a double well potential where $\Phi = \Phi_0/2$
- Since this qubit functions at low temperatures, this allows for the lowest energy states to contribute.
- The superposition of the 2 classical states from the clockwise and counterclockwise currents form the 2 level system
- Due to the fact that the product of critical current and self inductance was high, this would lead to requiring larger loop area. This could be rectified by multiple junctions



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Challenges faced

- Maintenance of high coherence
- Requires low temperatures (mK) for proper functioning, thus requiring advances in cryogenic technology first
- Fabrication of large scale circuits
- Verification/ Benchmarking of circuits becomes tougher with scale
- Requires specialized hardware that is hard to find and is also highly expensive

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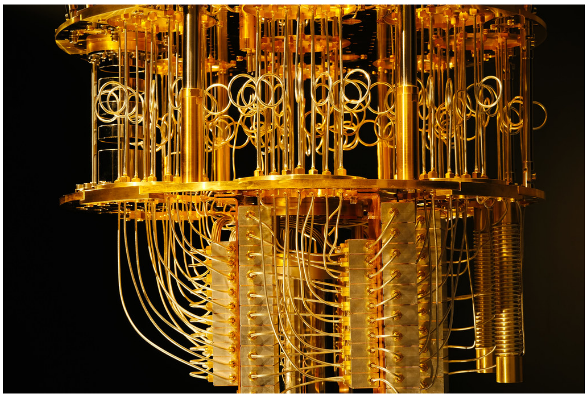
Challenges faced

- Dilution refrigerators are custom-designed by few companies
- Helium-3 is required to operate at supercooled temperatures.
- Superconducting cables are specially designed and manufactured by only one Japanese company (Coax Co.)



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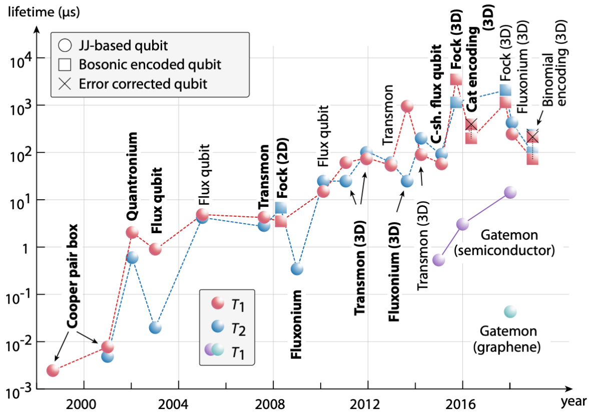
Current progress

- Over time, the coherence and thus lifetime of various iterations of SC qubits has shown to improve with further research and development
- While there are a lot of challenges to be solved, currently SC quantum computing is seen as the most common manufacturing approach taken by companies
- Industries such as Google, IBM, D-Wave are implementing such means of quantum computing



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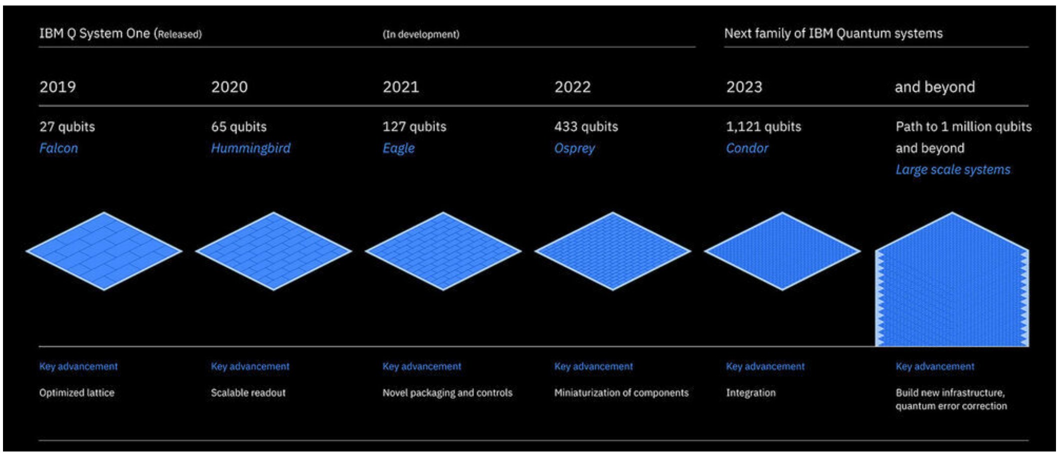
Current progress



IBM roadmap for Quantum processor

References

- *“Superconducting Qubits: Current State of Play”* Morten Kjaergaard, Mollie E. Schwartz, Jochen Braumuller, Philip Krantz, Joel I-J Wang, Simon Gustavsson, and William D. Oliver
- “*Quantum-state engineering with Josephson-Junction devices*” Yuriy Makhlin, Gerd Schon, Alexander Shnirman
- *“Superconducting Quantum Computing: A Review”* He-Liang Huang, Dachao Wu, Daojin Fan, Xiaobo Zhu
- *“A Quantum Engineer's Guide to Superconducting Qubits”* Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, William D. Oliver