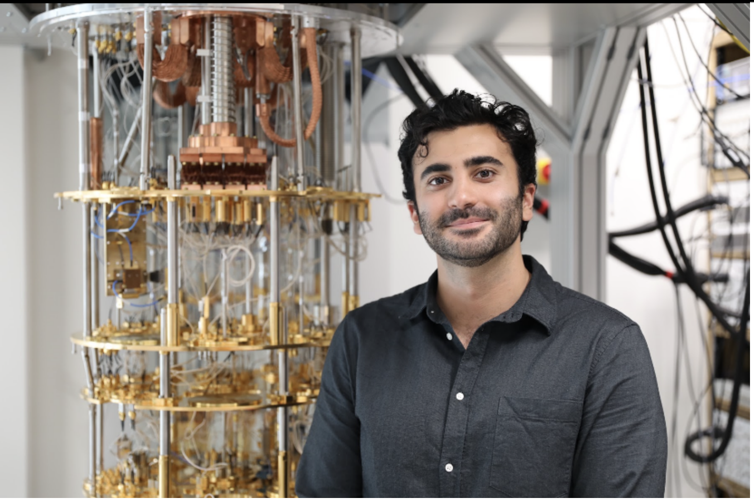
Superconducting Circuits for Quantum Computing

QEDi Day 1 Lecture 3
15/09/2025
Kian Jansepar

Outline

- Superconductivity
- Quantum Harmonic Oscillator
- Josephson Junctions
- Transmon Qubit
- Superconducting Qubit Industry



Kian Jansepar

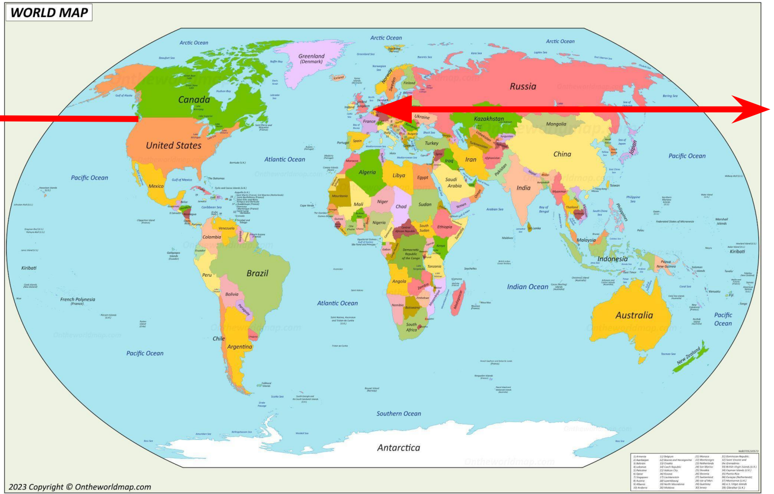
- Coming from a quantum hardware background, designing and characterizing superconducting circuits for quantum computing.
- 2nd year PhD Student at UCL

Berkeley
UNIVERSITY OF CALIFORNIA

BERKELEY LAB

deepSight™

Lawrence Livermore National Laboratory



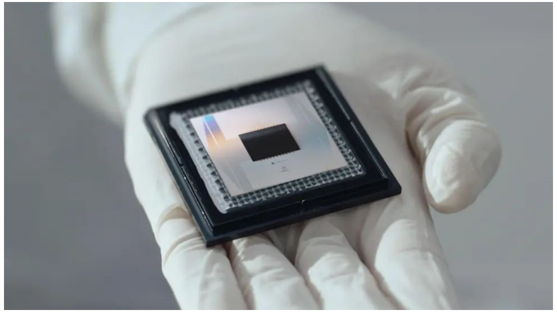
Imperial College London

QUANTUM MOTION

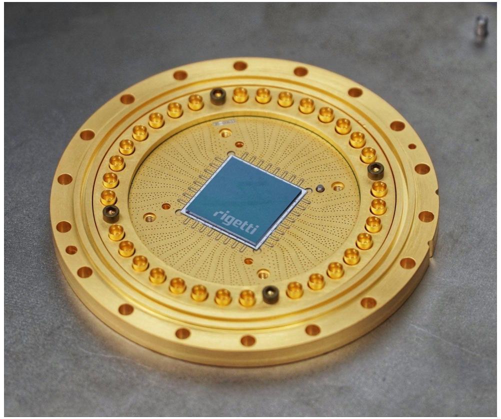
EVOTRACK™

Who uses superconducting quantum qubits?

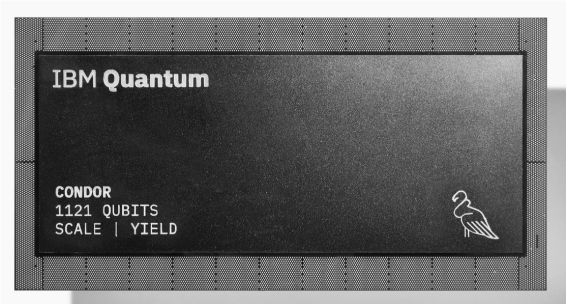
Google



Rigetti



IBM



QUANTWARE

OQC

IQM

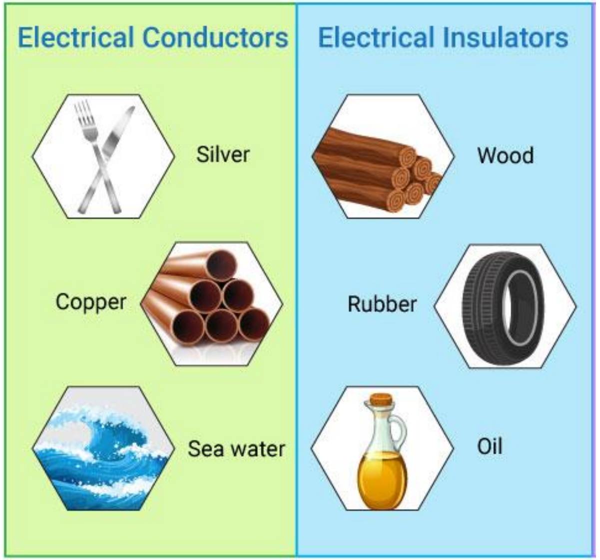
D:Wave
The Quantum Computing Company™

aws

Most popular platform for qubits at the moment:

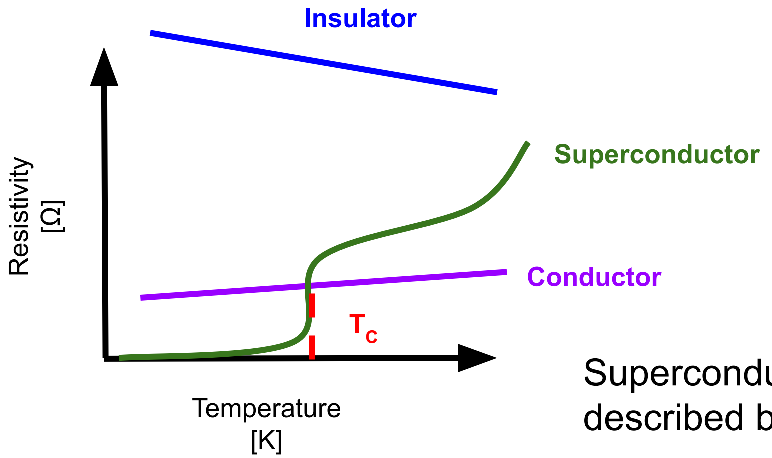
- High fidelity operations
- Long coherence times
- Offers degrees of freedom for tunability

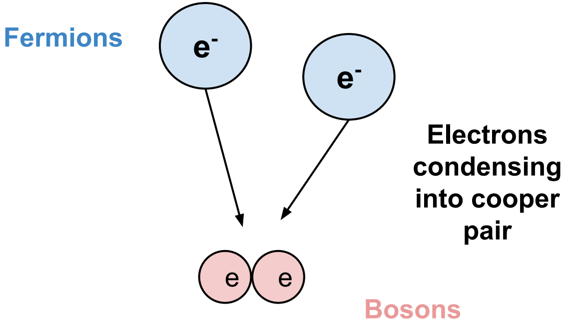
Superconductivity
Critical Temperature



https://ksa.mytutorsource.com/blog/electrical-conductor-electrical-insulator-and-thermal-conductor/

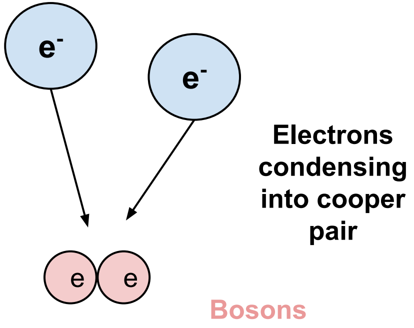
T_C: Critical Temperature

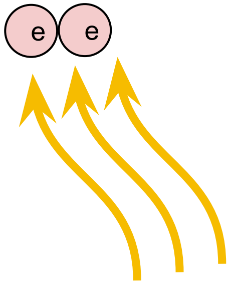




Superconductivity is best described by BCS theory.

Superconductivity

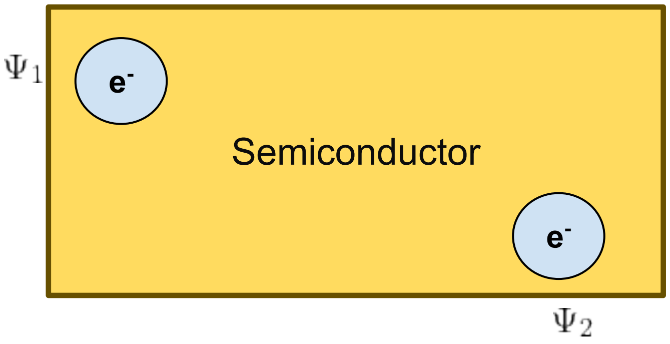


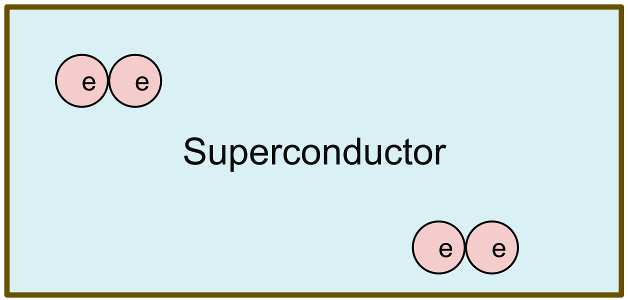


- Cooper pairs in superconductor behave as macroscopic entity with bosonic behavior
- 2Δ is the energy needed to break cooper pair

$$\Psi(r,t) = \Psi_0 e^{i\phi(r,t)}$$

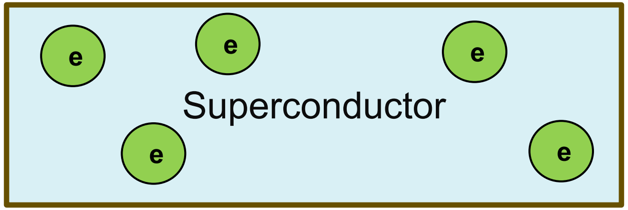
Macroscopic wavefunction (Order Parameter)



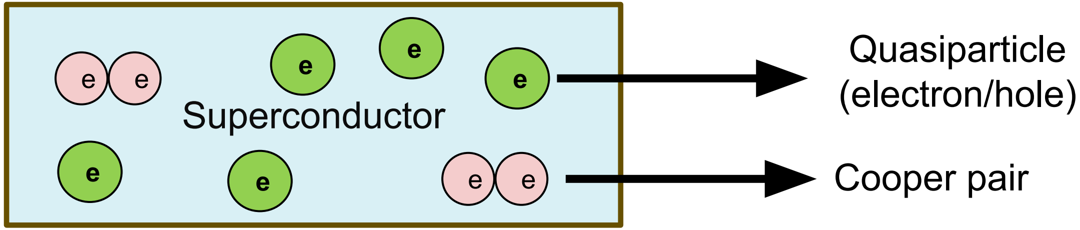


Superconductivity

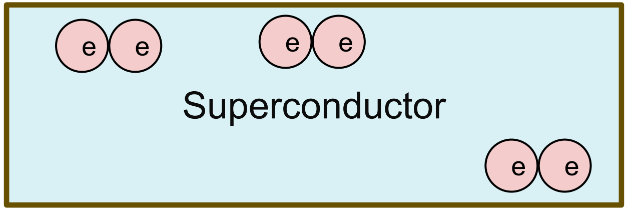
T > Tc
As you approach Tc, the density of quasiparticles increases, and the Cooper pair density goes to zero.



T < Tc
Thermally excited quasiparticles prevents having a coherent macroscopic wavefunction

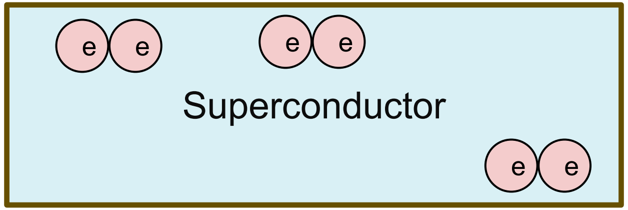


T << Tc
Quasiparticle number is exponentially reduced.



Superconductivity

T << Tc
Quasiparticle number is exponentially reduced.
Coherent macroscopic wavefunction is observed.



Below Tc, a moving Cooper pair condensate cannot dissipate energy through individual scattering, and slowing the entire condensate would require extremely large energy

Well defined macroscopic wavefunction
describing a **quantum system.**

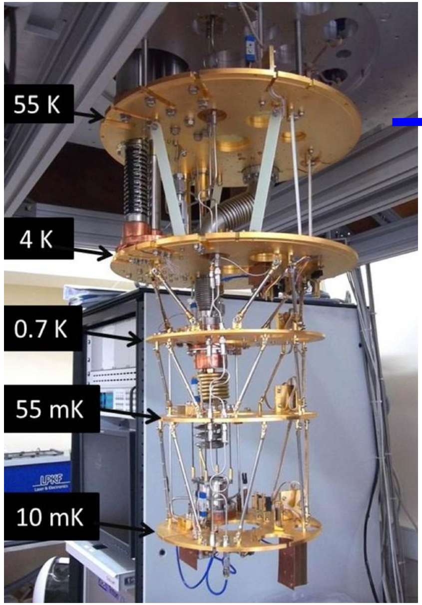
$$\Psi(r,t) = \Psi_0 e^{i\phi(r,t)}$$

Macroscopic wavefunction (Order Parameter)

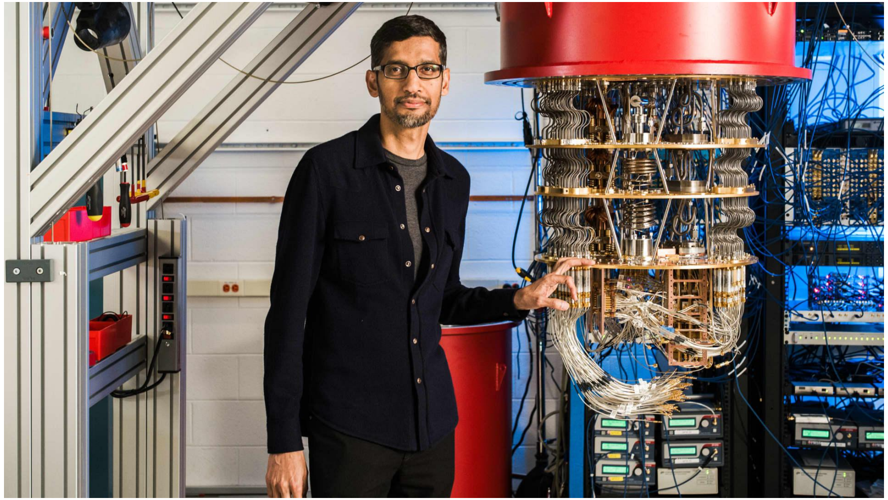
Most widely used superconductors for quantum circuits:

- Nb (Tc~ 9 K)
- Al (Tc~1.2 K)

Superconductivity
Critical Temperature



Dilution fridge used to cool down superconducting circuits



Google CEO Sundar Pichai stands with a quantum computer a Google laboratory in Santa Barbara, California

Google

https://www.tifr.res.in/~quantro/facilities.html

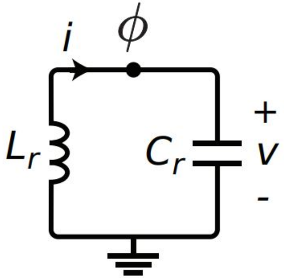
Quantum Harmonic Oscillator

$$Q(t) = \int I(t)dt$$

$$\Phi(t) = \int V(t)dt$$

$$E(t) = \int_{-\infty}^{t} V(\tau)I(\tau)d\tau$$

$$\Phi = LI$$



$$Q = CV$$

$$E_{inductor} = \int \dot{\Phi} I(t)dt = \int \dot{\Phi}\frac{\Phi}{L}dt = \int \frac{\Phi}{L}d\Phi = \frac{\Phi^2}{2L}$$

$$E_{capacitor} = \int CV(t)dV = C\frac{V^2}{2} = \frac{Q^2}{2C} = \frac{1}{2}CV^2 = \frac{1}{2}C\dot{\Phi}^2$$

$$\mathcal{L} = \frac{1}{2}C\dot{\Phi}^2 - \frac{\Phi^2}{2L}$$

Equations of motion $$\frac{d}{dt}\frac{\delta\mathcal{L}}{\delta\dot{\Phi}} = \frac{\delta\mathcal{L}}{\delta\Phi}$$

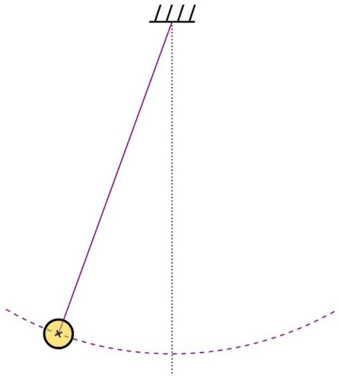
$$C\ddot{\Phi} + L^{-1}\Phi = 0$$

Energy in the circuit oscillates between **magnetic field within an inductor** and the **electric field between the capacitor**

P. Krantz, A Quantum Engineer’s Guide to Superconducting Qubits, 2021

Quantum Harmonic Oscillator

Classical Harmonic Oscillator



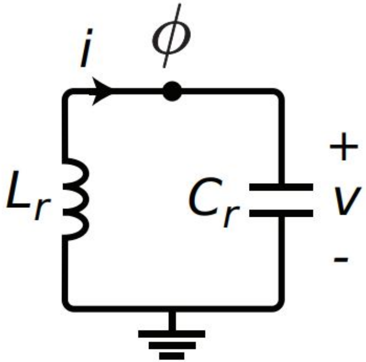
https://commons.wikimedia.org/wiki/File:Pendulum-no-text.gif

$$F = ma = T\sin(\theta) \approx T\theta$$

$$T \approx mg \to F = ma = mg\theta$$

$$\theta \approx \frac{g}{l} \to F = -m\frac{g}{l} \to \boxed{F = m\ddot{x} = -kx}$$

Quantum Harmonic Oscillator

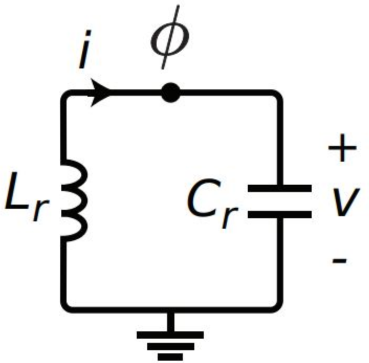


https://arxiv.org/pdf/1904.06560

$$C\ddot{\Phi} + L^{-1}\Phi = 0$$

$$\boxed{C\ddot{\Phi} = -L^{-1}\Phi}$$

Quantum Harmonic Oscillator Hamiltonian



Energy of each component

$$E_{inductor} = \int \dot{\Phi} I(t)dt = \int \dot{\Phi}\frac{\Phi}{L}dt = \int \frac{\Phi}{L}d\Phi = \frac{\Phi^2}{2L}$$

$$E_{capacitor} = \int CV(t)dV = C\frac{V^2}{2} = \frac{Q^2}{2C}$$

$$H_{LC} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

Defining some new variables:

$n = \dfrac{Q}{2e}$ Reduced charge

$\phi = \dfrac{2\pi\Phi}{\Phi_0}$ Reduced flux

$E_C = \dfrac{e^2}{2C}$ Charging energy

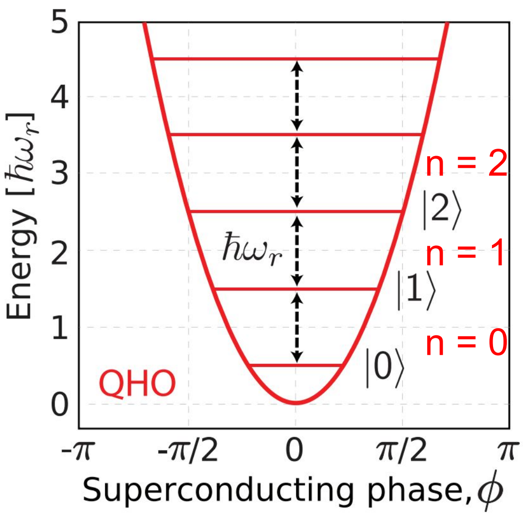
$E_L = (\Phi/2\pi)^2/L$ Inductive energy

$\Phi_0 = \dfrac{h}{2e}$

$$H = 4E_C n^2 + \frac{1}{2}E_L\phi^2$$

$$\boxed{H = \hbar\omega_r(\underbrace{a^\dagger a}_{\text{Number of cooper pairs}} + \frac{1}{2})}$$

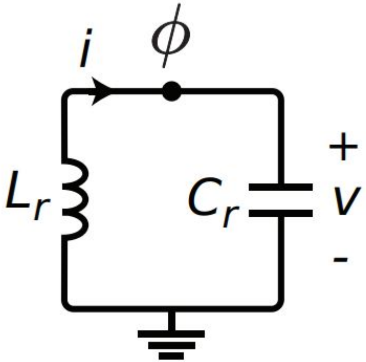
QHO energy in terms of cooper pair number

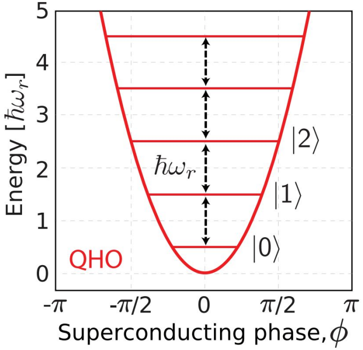


https://arxiv.org/pdf/1904.06560

Quantum Harmonic Oscillator

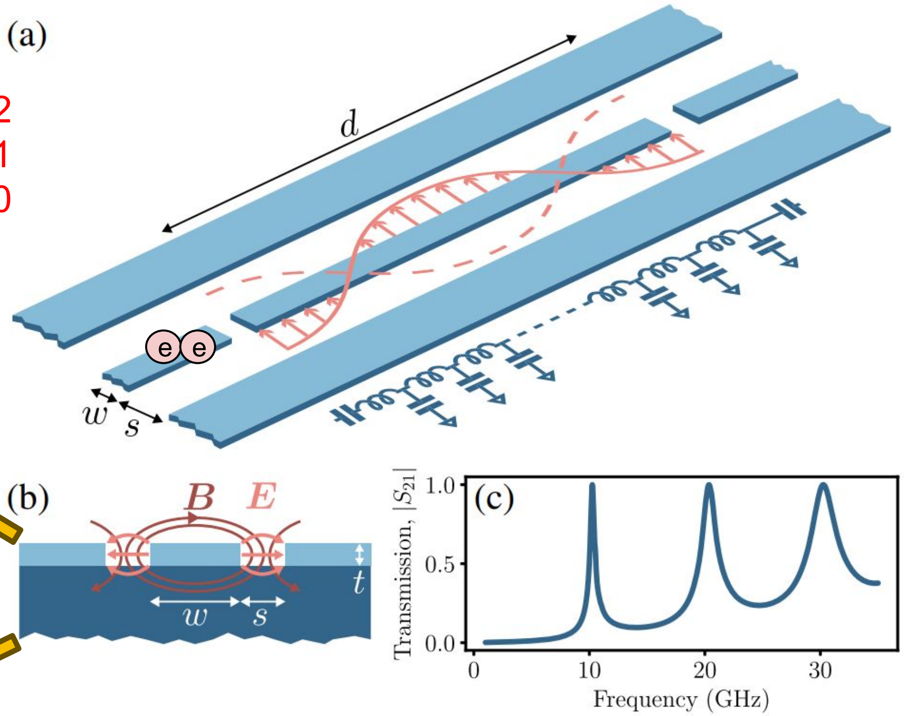
Circuit Diagram





n = 2
n = 1
n = 0

Device Design



Superconducting film
(Al, Nb, Ta)

Substrate
(Si, Sapphire)

$n = \frac{Q}{2e}$ Reduced charge

$\phi = \frac{2\pi\Phi}{\Phi_0}$ Reduced flux

$E_C = \frac{e^2}{2C}$ Charging energy

$E_L = (\Phi/2\pi)^2/L$ Inductive energy

$\Phi_0 = \frac{h}{2e}$

M. Göppl and A. Fragner and M. Baur and R. Bianchetti and A. Wallraff. Coplanar waveguide resonators for circuit quantum electrodynamics (2008)

Quantum Harmonic Oscillator

Schrödinger Equation

$$H\left|\psi(t)\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle$$

Time independent Hamiltonian

$$\left|\psi(t)\right\rangle = U(t)\left|\psi(0)\right\rangle = e^{-iHt/\hbar}\left|\psi(0)\right\rangle$$

Time evolution operator

$$H = 4E_C n^2 + \frac{1}{2}E_L\phi^2$$

QHO Hamiltonian

Do we have everything for a qubit?

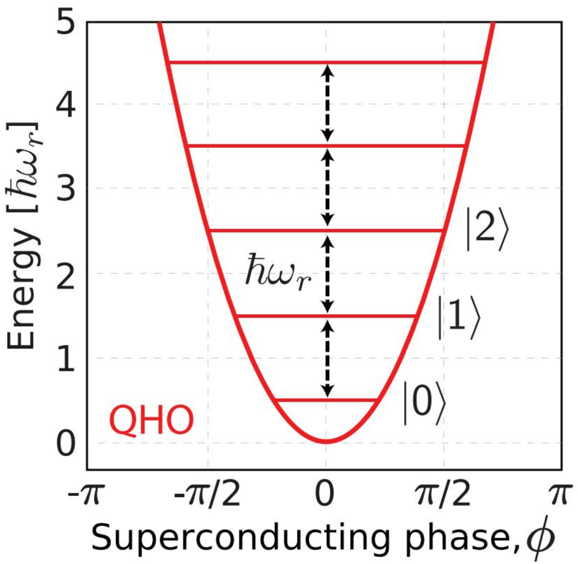
Classical bit 0 / 1

quantum bit (qubit) |0⟩ / |1⟩ → α|0⟩ + β|1⟩

At the core of a qubit is a well-defined
two-level system

Quantum Harmonic Oscillator

At the core of a qubit is a well-defined
two-level system



Is the QHO a two-level system?

No! We need Anharmonicity!

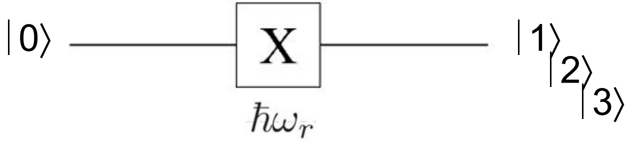
n = 2

n = 1

n = 0

- **Equally spaced energy levels** → The transition frequency between any two neighboring states is the same, so you can't isolate just two levels without unintentionally exciting higher ones.
- **No natural two-level truncation** → QHO doesn't provide a "forbidden" or energetically distinct subspace for a qubit.
- **Leakage errors** → Driving the $|0\rangle \leftrightarrow |1$ transition also couples strongly to $|1\rangle \leftrightarrow |2$, leading to population leakage outside the qubit manifold.

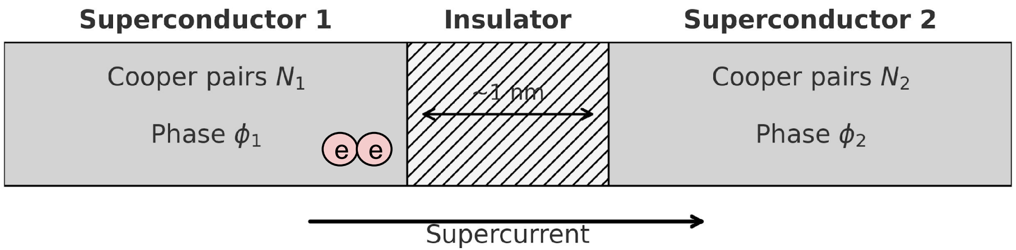
Example of shortcoming



How can we define a Two-Level System with superconducting circuits?

Towards Anharominicty
Josephson Junctions

$\Psi(r,t) = \Psi_0 e^{i\phi(r,t)}$ $\Psi(r,t) = \Psi_0 e^{i\phi(r,t)}$

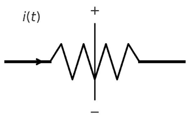


Dynamical Variables: $n = N_1 - N_2, \quad \varphi = \phi_1 - \phi_2$

Josephson Equations:

$$I_s = I_c \sin(\varphi)$$
$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$$

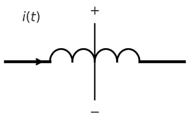
Resistor



$v(t) = R\,i(t)$

$i(t) = \frac{v(t)}{R}$

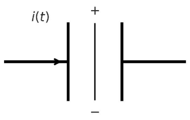
Inductor



$v(t) = L\frac{di(t)}{dt}$

$i(t) = \frac{1}{L}\int v(t)\,dt + i(0)$

Capacitor



$i(t) = C\frac{dv(t)}{dt}$

$v(t) = \frac{1}{C}\int i(t)\,dt + v(0)$

Josephson Junction

Josephson Equations:

$$I_s = I_c \sin(\varphi)$$
$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$$

$$E(t) = \int_{-\infty}^{t} V(\tau) I(\tau) d\tau$$

Towards Anharominicty
Josephson Junctions

The Josephson Effect is described by 2 equations:

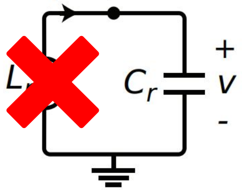
supercurrent, $\boldsymbol{I_s = I_c \sin\phi}$ (more generally just needs to be 2π periodic)

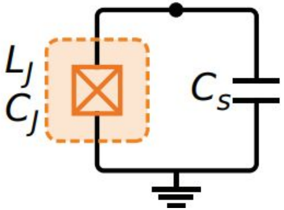
rate of change of phase, $\boldsymbol{\frac{d\phi}{dt} = \frac{2e}{\hbar} V}$

$$\mathrm{E}_{JJ} = \int I_C \sin(\phi) \frac{\hbar}{2e} \frac{d\phi}{dt} dt = -\frac{\hbar I_C}{2e} \cos(\phi) = -\frac{\Phi_0 I_C}{2\pi} \cos(\phi) = -E_J cos(\phi)$$

$\mathrm{E}_{JJ} = -E_J cos(\phi)$ **Josephson Energy**

QHO

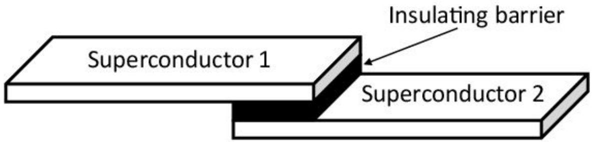


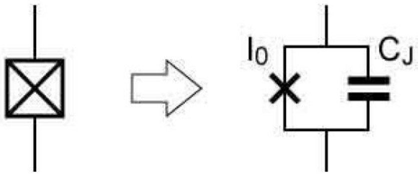


$$H = 4E_C n^2 + \cancel{\frac{1}{2}E_L}\phi^2$$

$$H = 4E_C n^2 \boxed{- E_J \cos(\phi)}$$

Josephson Junctions



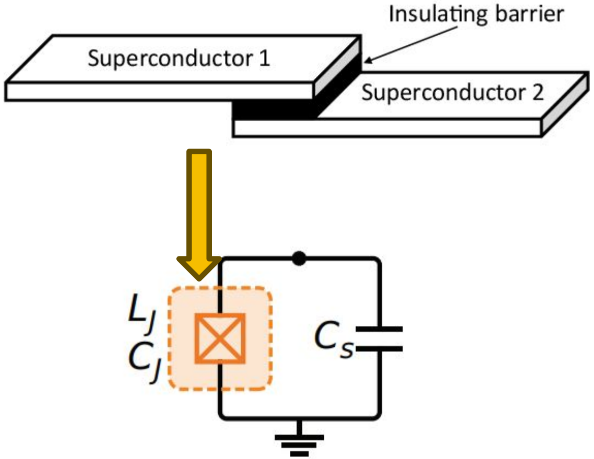


Josephson Junction have self capacitance

M.H. Devoret et al, Superconducting Qubits: A Short Review (2004)

Towards Anharominicty

Josephson Junction

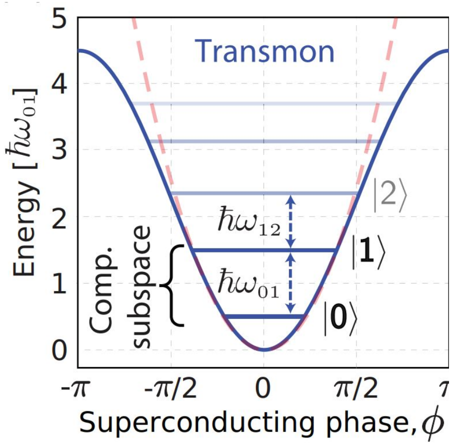


- **Nonlinear inductance:** Josephson junction provides a tunable, nonlinear inductance that depends on the superconducting phase difference across it.
- **Potential energy landscape:** This nonlinearity creates anharmonic energy levels instead of evenly spaced harmonic oscillator states.

$$H = 4E_C n^2 - \boxed{E_J \cos(\phi)}$$

Josephson Junction have self-capactiance!

$$\mathrm{E}_C = \frac{e^2}{2C_\Sigma} = \boxed{\frac{e^2}{2(C_S + C_J)}}$$

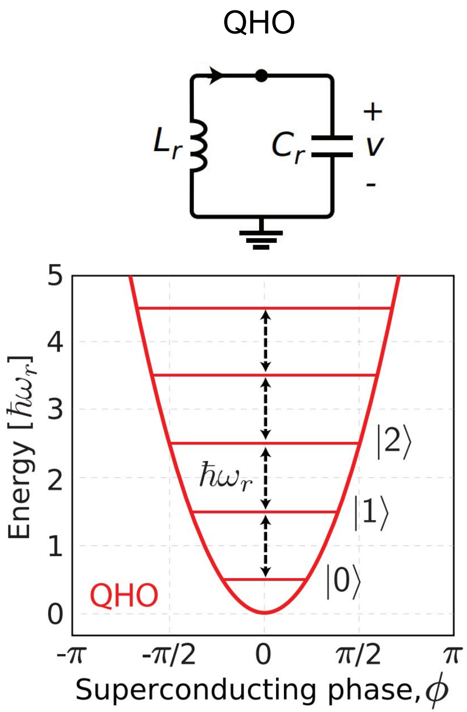


Anharmonic is related to charging energy

$$\alpha \propto E_C$$

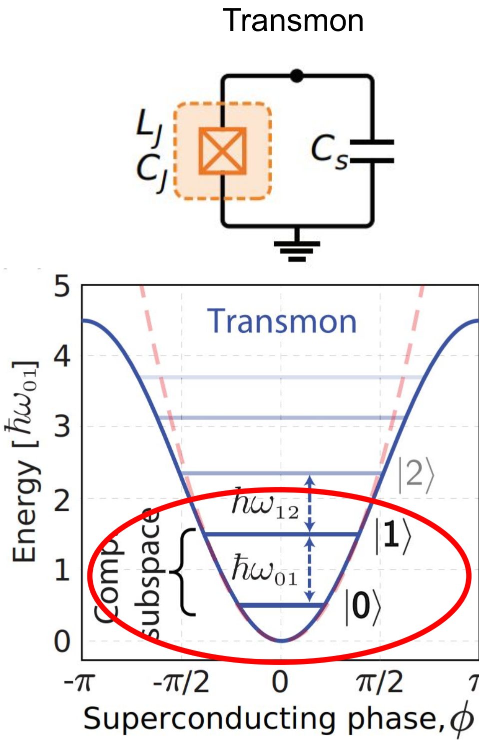
Transmon

Creating well-defined two-level systems



- **Nonlinear energy spacing**
- **Higher order energy states are removed**
- **Robust two-level system can be defined (ground & excited state)**

We have a Qubit!
(aka artifical atom)

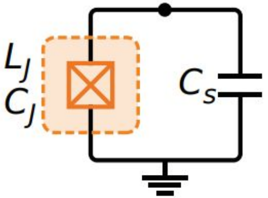


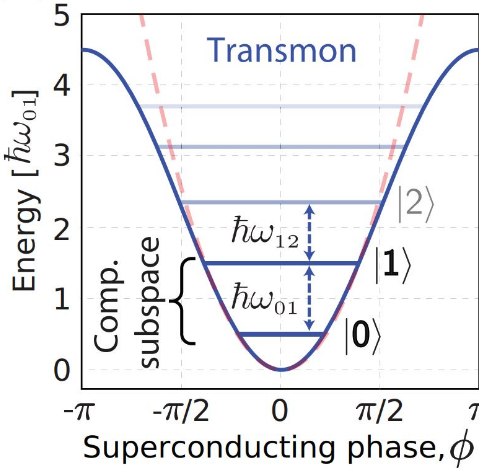
P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021

Transmon

Creating well-defined two-level systems

Transmon





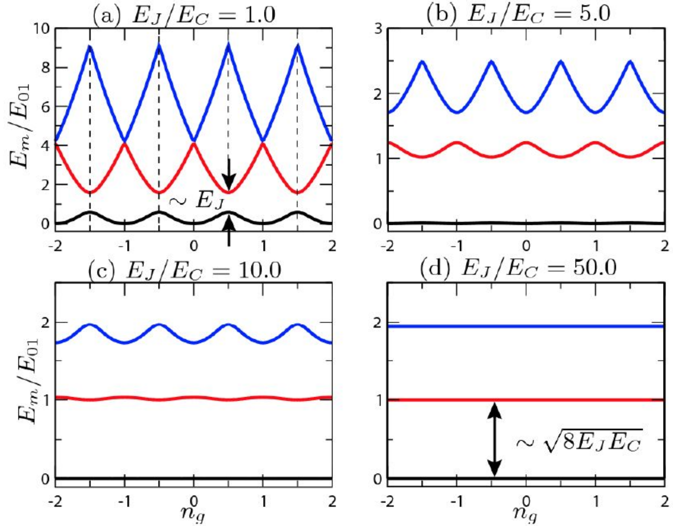
Ideal: $H = 4E_C n^2 - E_J \cos(\phi)$

Realistic:

$$\hat{H} = 4E_C\left(\hat{n} - \boxed{n_g}\right)^2 - E_J \cos\hat{\varphi}$$

Offset charge

Energy sensitivity vs offset charge

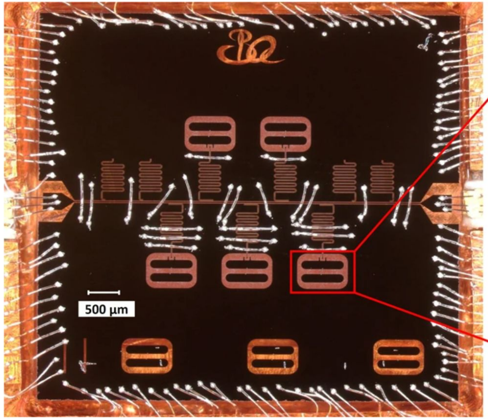


- Qubit dynamics depend on the ratio EJ/EC.
- Designs use **EJ≫ EC** for stable, **coherent operation**.
- If **EJ≤EC**, the qubit becomes very sensitive to **charge noise**.
- Charge noise is harder to mitigate than flux noise → coherence suffers.

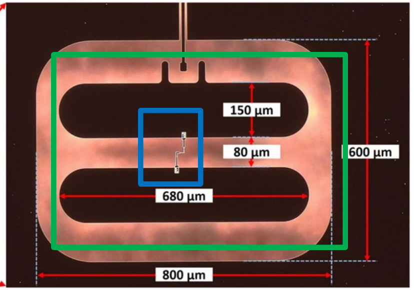
P. Krantz, A Quantum Engineer’s Guide to Superconducting Qubits, 2021
J. Koch et al, Charge insensitive qubit design derived from the Cooper pair box (2007)

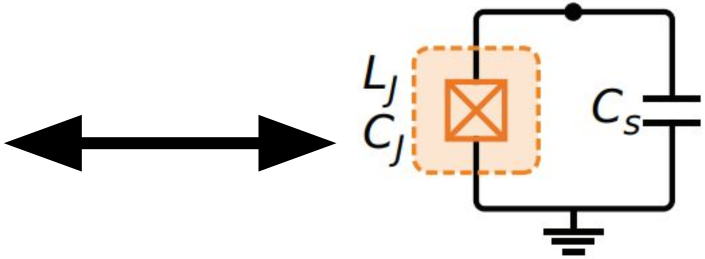
Transmon
Geometry

$$H = 4\boxed{E_C}n^2 - \boxed{E_J}\cos(\phi)$$



Transmon



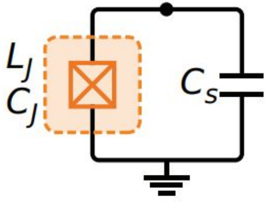


P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021
C. Wang et al, Towards practical quantum computers: transmon qubit with a lifetime approaching 0.5 milliseconds, 2022

Superconducting Quantum Interference Device (SQUID)

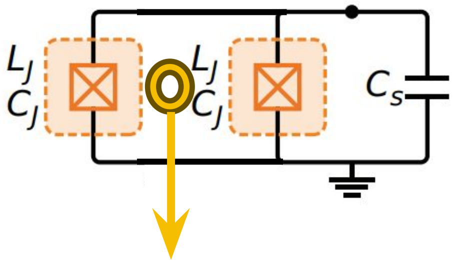
Can we make a tunable Transmon?

Transmon



$$H = 4E_C n^2 - E_J \cos(\phi)$$

Tunable Transmon



$$\mathrm{H} = 4\mathrm{E}_C n^2 - E_J \cos(\phi_1) - E_J \cos(\phi_2)$$

Caveat: Fluxoid quantization condition states that the total branch flux from all inductive elements in a loop, plus the applied external flux, must equal an integer multiple of the superconducting flux quantum.

$$\varphi_1 - \varphi_2 + 2\varphi_e = 2\pi k$$

$$\varphi_e = \pi \Phi_{\mathrm{ext}} / \Phi_0$$

Trig Identities

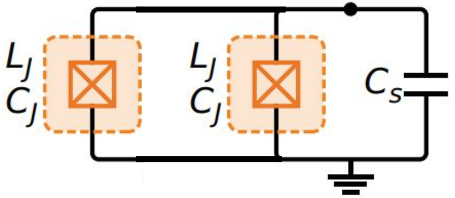
$$H = 4E_C n^2 - \underbrace{2E_J \left|\cos\left(\varphi_e\right)\right|}_{E'_J(\varphi_e)} \cos(\phi)$$

The effective Josephson Energy , EJ', can be tuned via externally magnetic field!

P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021

Flux-Tunable Transmon

Tunable Transmon



Qubit frequency can be tuned!

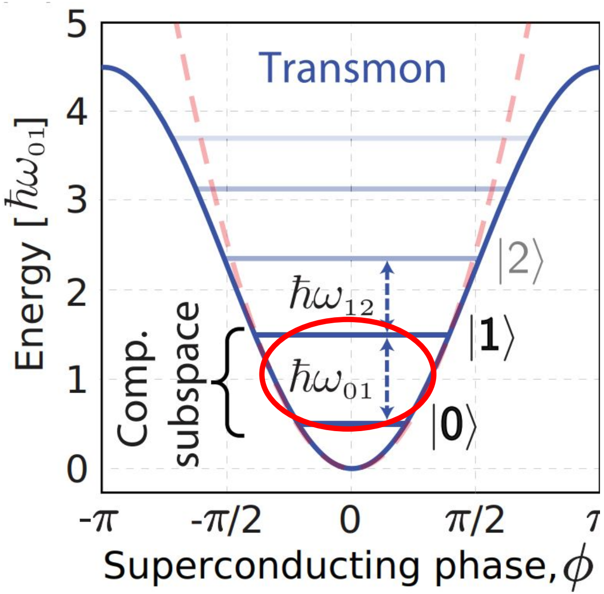
$$H = 4E_C n^2 - \underbrace{2E_J\left|\cos\left(\varphi_e\right)\right|}_{E'_J(\varphi_e)}\cos(\phi)$$

The effective Josephson Energy , EJ', can be tuned via externally magnetic field!

$$\hbar\omega_{qubit} = \sqrt{8E_J E_C} - E_C$$

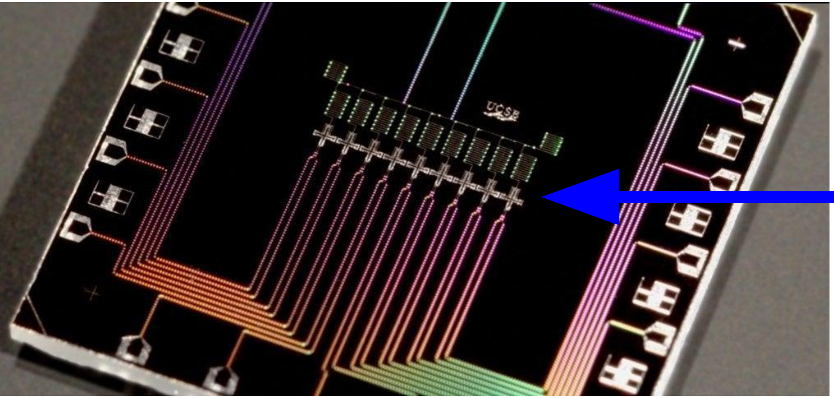
Energy needed to excite $|0\rangle$ □ $|1\rangle$

Qubit Frequency (energy) can be tuned!

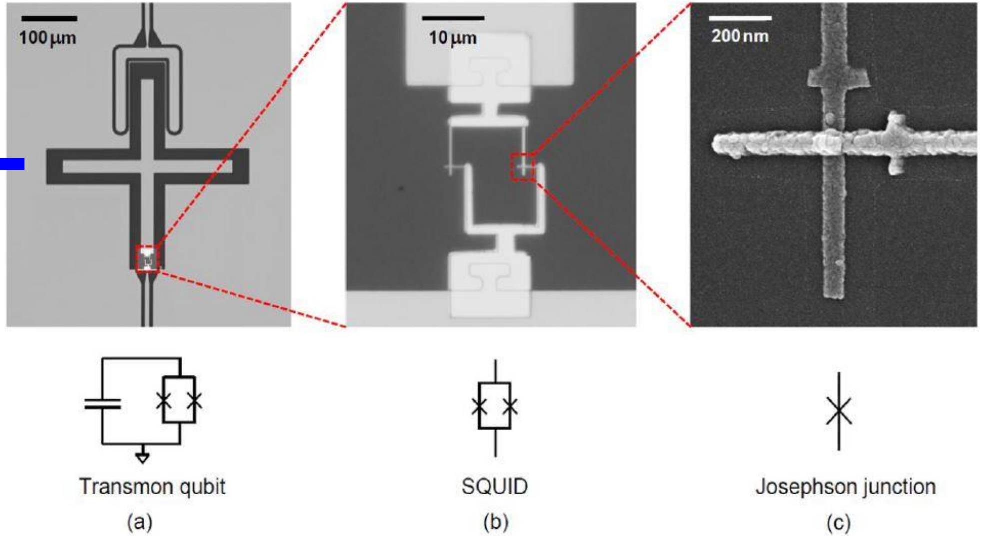


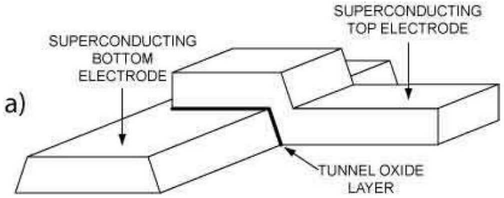
P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021

Tunable Transmon



Early superconducting qubit chip from UCSB and Google

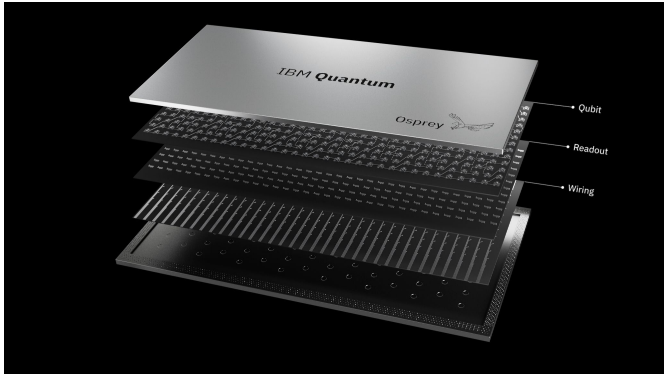


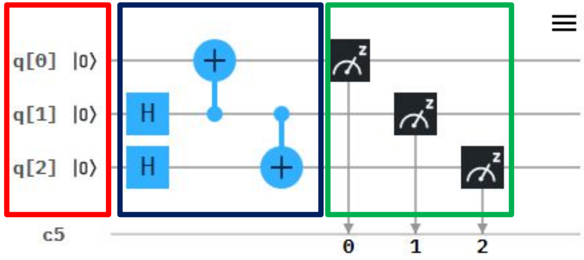


Thomas E. Roth, An Introduction to the Transmon Qubit for Electromagnetic Engineers.

DiVincenzo Criteria
(5 requirements for Quantum Computers)

- **Scalable physical system with well-defined qubits**
  A system must allow the definition of two-level quantum states (qubits) that can be scaled up.
- **Ability to initialize qubits to a known state**
  You need a reliable way to prepare qubits in a simple starting state.
- **Long decoherence times compared to gate times**
  Qubits must maintain coherence long enough to perform operations before errors from the environment dominate.
- **A universal set of quantum gates**
  There must be physical mechanisms to implement a set of gates.
- **Qubit-specific measurement capability**
  It must be possible to measure individual qubits with high fidelity without disturbing others unnecessarily.





≡

Prof DiVincenzo at SQA conference in August

D. P. DiVincenzo, The physical implementation of quantum computation (2000)

Superconducting Qubit Industry

IQM Quantum Computers Raises over $300 Million in Series B Funding Round Led by U.S. Investor Ten Eleven Ventures with strong support from Tesi

03 Sep 2025

Google AI Quantum

intel

rigetti

IQM

D-Wave
The Quantum Computing Company™

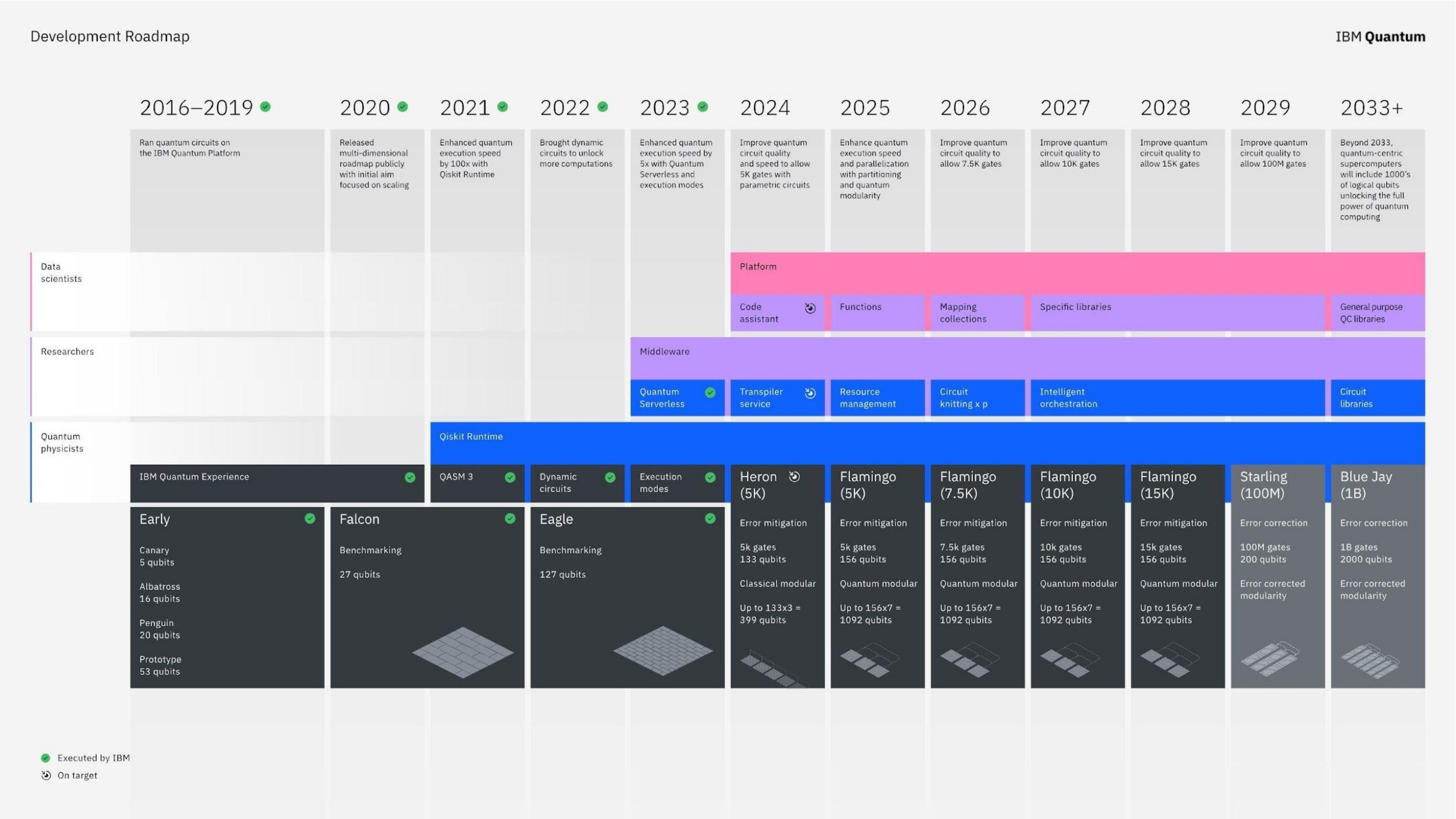
IBM Q™

aws
Amazon Braket

Home » News

Delft's QuantWare extends Series A to €23.3M to unlock the path to million-qubit quantum processors

Roadmap towards Fault-taulerant Quantum Computing



https://www.ibm.com/quantum/blog/ibm-quantum-roadmap-2025

Entire Quantum Industry

Fresh off the press

ZACKS

Nvidia Just Invested in this Quantum Computing Stock

Ethan Feller
Thu, September 4, 2025 at 6:32 PM GMT+1 • 3 min read

In this article:

QBTS +4.73% · QBTS-WS · IONQ +7.29% · IONQ-WS · NVDA +1.46%

Over the past year, **Nvidia** (NVDA) CEO Jensen Huang has dramatically shifted his view on quantum computing. Once framing the technology as a breakthrough for the distant future, Huang now believes commercialization may be much sooner. Reflecting that conviction, Nvidia has begun actively positioning itself in the quantum space, and this week the company appeared to double down. Reports indicate that Nvidia has invested in **Quantinuum**, a leading quantum computing startup majority-owned by **Honeywell International** (HON).

Quantum computing company raises a record $1bn

PsiQuantum backed by BlackRock, Temasek and Baillie Gifford as investment race intensifies

Maybell Quantum closes $40m funding round for quantum computing fridges

Company looks to disrupt cryostat industry

September 08, 2025 By: Dan Swinhoe Have your say

Infleqtion to go public in SPAC deal valuing quantum computing firm at $1.8 billion

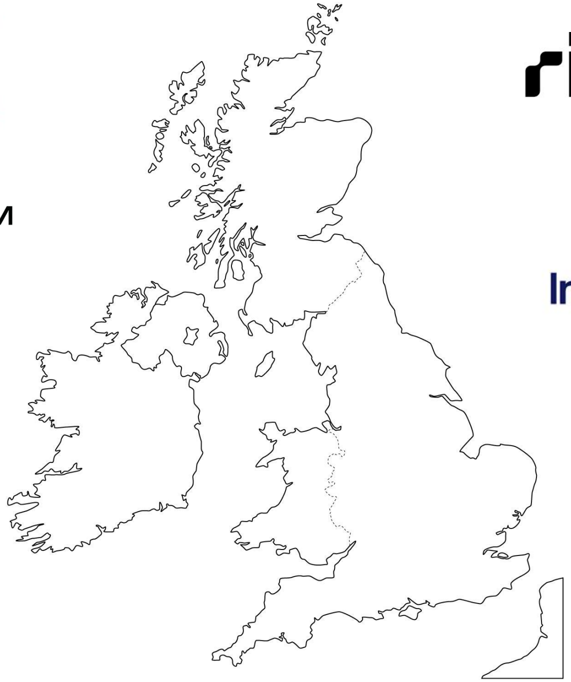
By Jaspreet Singh
September 8, 2025 9:02 PM GMT+1 · Updated September 8, 2025

Aa

UK's Quantum Industry

Startups founded in the UK

- nu QUANTUM
- riverlane
- Universal Quantum
- QUANTINUUM
- oxford ionics
- QUANTUM MOTION
- PHASECRAFT
- OQC



Companies with HQs in the UK

- rigetti
- MULTIVERSE COMPUTING
- Infleqtion
- Ψ PsiQuantum
- TOSHIBA
- CLASSIQ
- seeqc

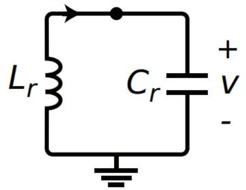
Thank you!

Superconducting Circuits for Quantum Computing

QEDi Day 2 Lecture 4
16/09/2025
Kian Jansepar

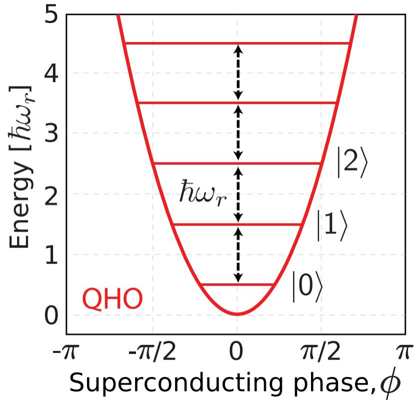
Recap

Quantum Harmonic Oscillator



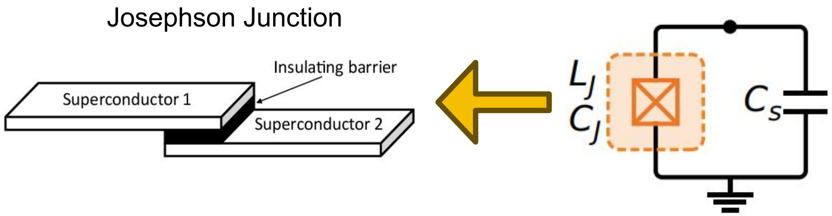
$$H = 4E_C n^2 + \frac{1}{2}E_L\phi^2$$

$$H = \hbar\omega_r(\underbrace{a^\dagger a}_{\text{Number of photons}} + \frac{1}{2})$$

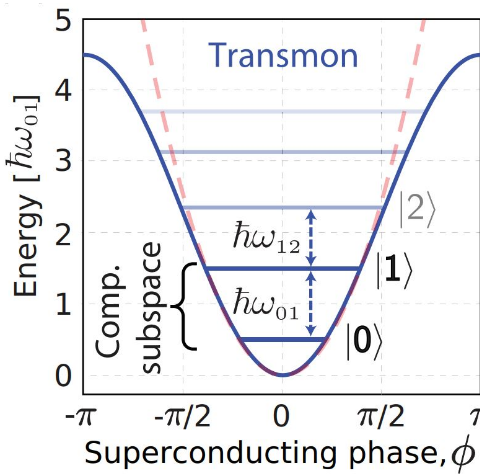


Not a well-defined two-level system for a qubit!

Transmon

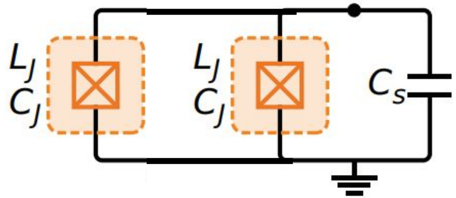


$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}$$



Recap

Tunable Transmon

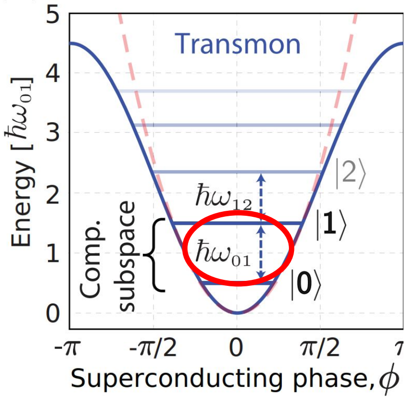


$$H = 4E_C n^2 - \underbrace{2E_J \left|\cos\left(\varphi_e\right)\right|}_{E'_J(\varphi_e)} \cos(\phi)$$

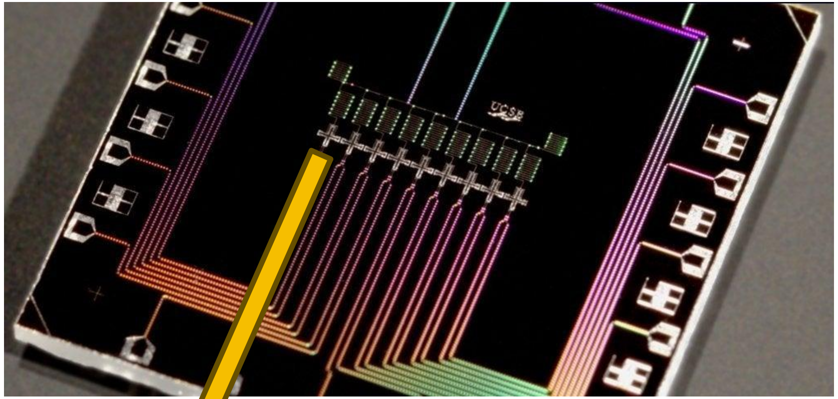
The effective Josephson Energy , EJ', can be tuned via externally magnetic field!

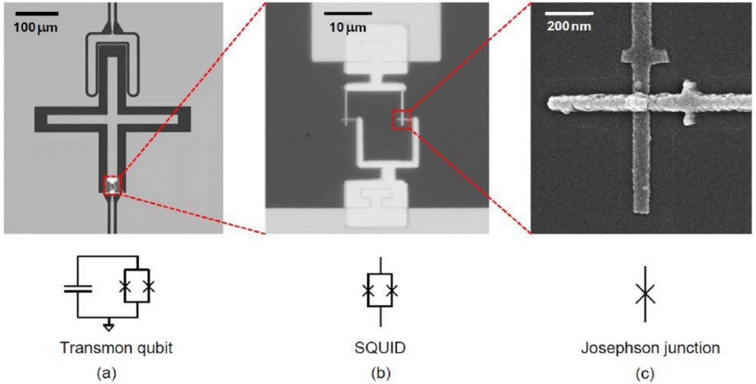
$$\hbar\omega_{qubit} = \sqrt{8E_J E_C} - E_C$$

Energy needed to excite $|0\rangle$ □ $|1\rangle$



Google 9 qubit chip

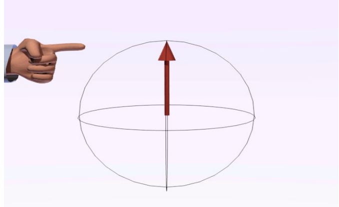


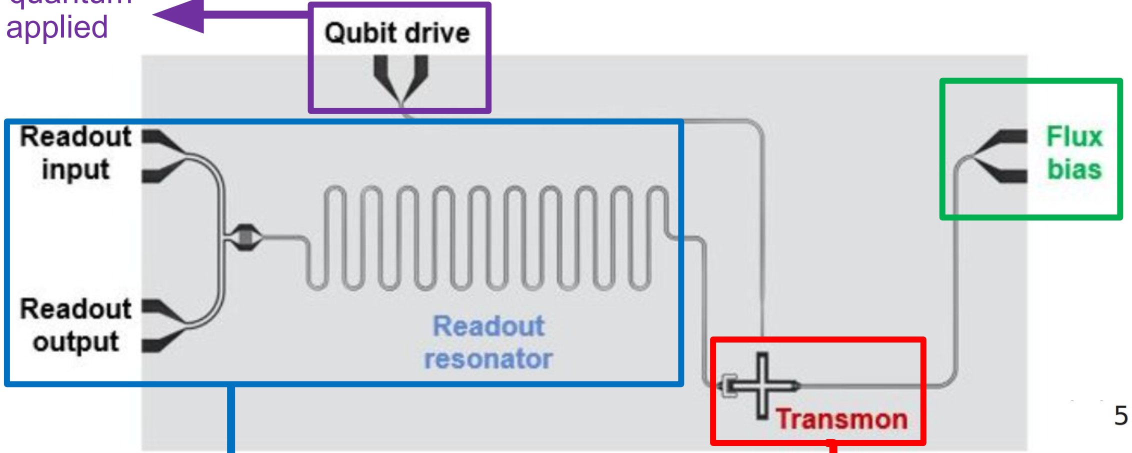


What else do we need for a single qubit?

Controlling a Tunable Transmon

This is how quantum gates are applied

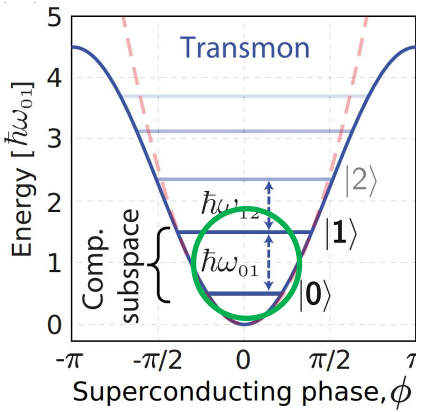




This is what we use to readout the qubit state (measurement)

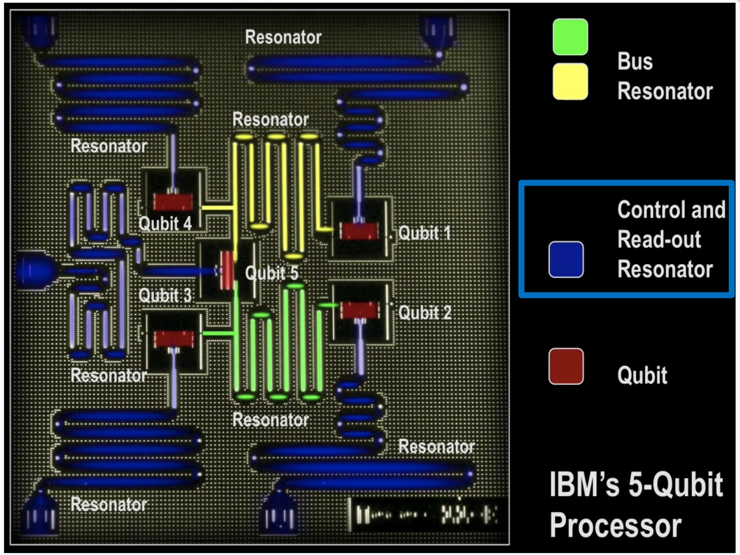
We can tune the energy needed to excite the qubit

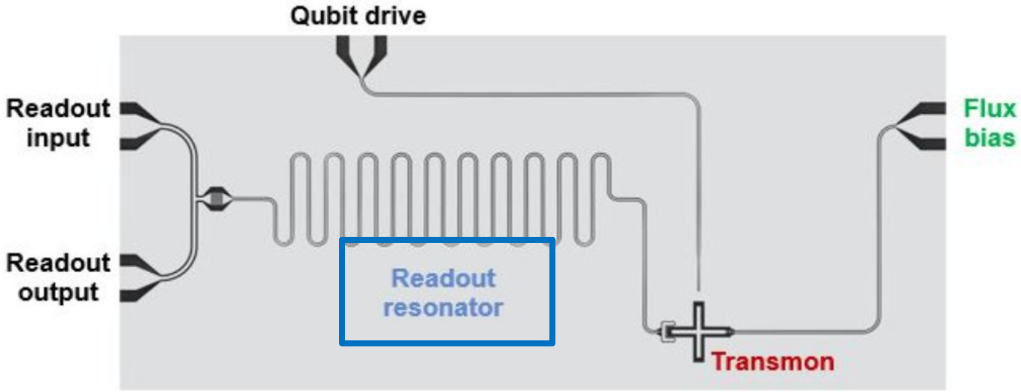
We have our Quantum Two-Level System: $|0\rangle, |1\rangle$, superposition states



Thomas E. Roth et al, An Introduction to the Transmon Qubit for Electromagnetic Engineers (2021)

Readout Resonator





•Qubit state cannot be probed directly. Various methods are used to readout qubit state
•For superconducting Quantum Processors, qubits are often readout using a resonator
•Qubit and resonator are effectively coupled, and in particular operating points, quantum non-demolition measurements (QND) are taken

Thomas E. Roth et al, An Introduction to the Transmon Qubit for Electromagnetic Engineers (2021)
https://www.researchgate.net/figure/An-image-of-IBMs-five-qubit-processor-with-its-main-elements-highlighted-including-the_fig4_358153899

Readout Resonator
Hamiltonian

Recall the qubit Hamiltonian: $H = 4E_C n^2 - E_J \cos(\phi)$

In the regime where $E_J >> E_C$, system is a two-level system (TLS) with states $|0\rangle$, $|1\rangle$, $|2\rangle$, etc. We truncate the two lowest energy state :

$$H_{TLS} \approx \frac{\omega_q \sigma_z}{2}$$

Qubit frequency (~$E_J E_C$)

Pauli-Z operator ($|0\rangle$, $|1\rangle$ are its eigenstates)

Resonator (Quantum Harmonic Oscillator) $H = \hbar\omega_r(\overbrace{a^\dagger a}^{\text{Number of photons}} + \frac{1}{2})$

Jaynes-Cummings Hamiltonian (Light matter interaction)

$$H_{JC} = \underbrace{\omega_r\left(a^\dagger a + \frac{1}{2}\right)}_{\text{Resonator}} + \underbrace{\frac{\omega_q}{2}\sigma_z}_{\text{Qubit}} + \underbrace{g\left(\sigma_+ a + \sigma_- a^\dagger\right)}_{\text{Interaction}}$$

Readout Resonator

Quantum Non-demolition Measurements (QND)

Jaynes-Cummings Hamiltonian (Light matter interaction)

$$H_{\mathrm{JC}} = \underbrace{\omega_r \left(a^\dagger a + \frac{1}{2} \right)}_{\text{Resonator}} + \underbrace{\frac{\omega_{\mathrm{q}}}{2}\sigma_z}_{\text{Qubit}} + \underbrace{g\left(\sigma_+ a + \sigma_- a^\dagger\right)}_{\text{Interaction}}$$

Dispersive limit: $\Delta = |\omega_{\mathrm{q}} - \omega_r| \gg g$

Resonator Frequency Shifts

$$H_{\mathrm{disp}} = \left(\boxed{\omega_r + \chi\sigma_z} \right) \left(a^\dagger a + \frac{1}{2} \right) + \frac{\widetilde{\omega}_{\mathrm{q}}}{2}\sigma_z$$

Dispersive shift

$\chi = g^2/\Delta$

Dispersive shift

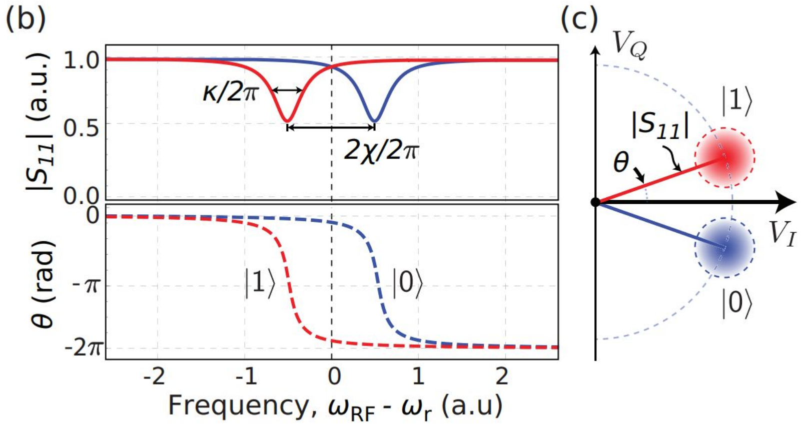
$$\chi = g^2/\Delta$$

Readout Resonator

Dispersive Readout

$$H_{\text{disp}} = \underbrace{\left(\omega_r + \chi\sigma_z\right)}_{\text{Resonator Frequency Shift}}\left(a^\dagger a + \frac{1}{2}\right) + \frac{\widetilde{\omega}_{\text{q}}}{2}\sigma_z$$

Allows you to do quantum non-demolition measurements on qubit!

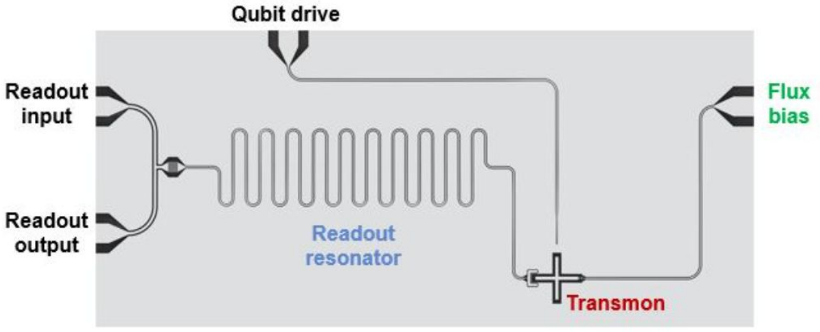


Readout of qubit states using S_{11} measurement.

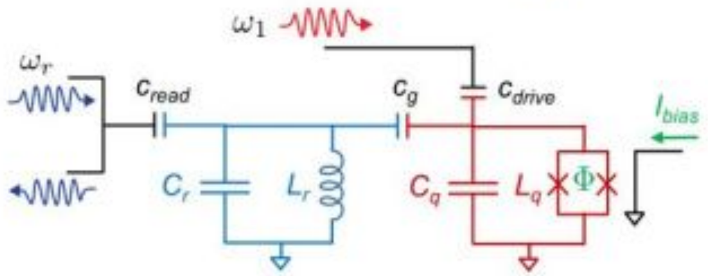
P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021

Readout Resonator
(Circuit)

Actual Design



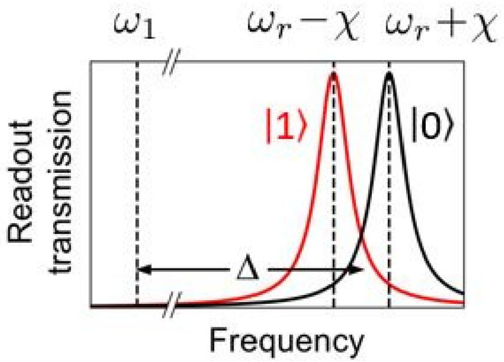
Circuit Design



Resonator Qubit Interaction

$$H_{\mathrm{JC}} = \boxed{\omega_r\left(a^\dagger a + \frac{1}{2}\right)} + \boxed{\frac{\omega_{\mathrm{q}}}{2}\sigma_z} + \boxed{g\left(\sigma_+ a + \sigma_- a^\dagger\right)}$$

Dispersive Readout



Dispersive Limit

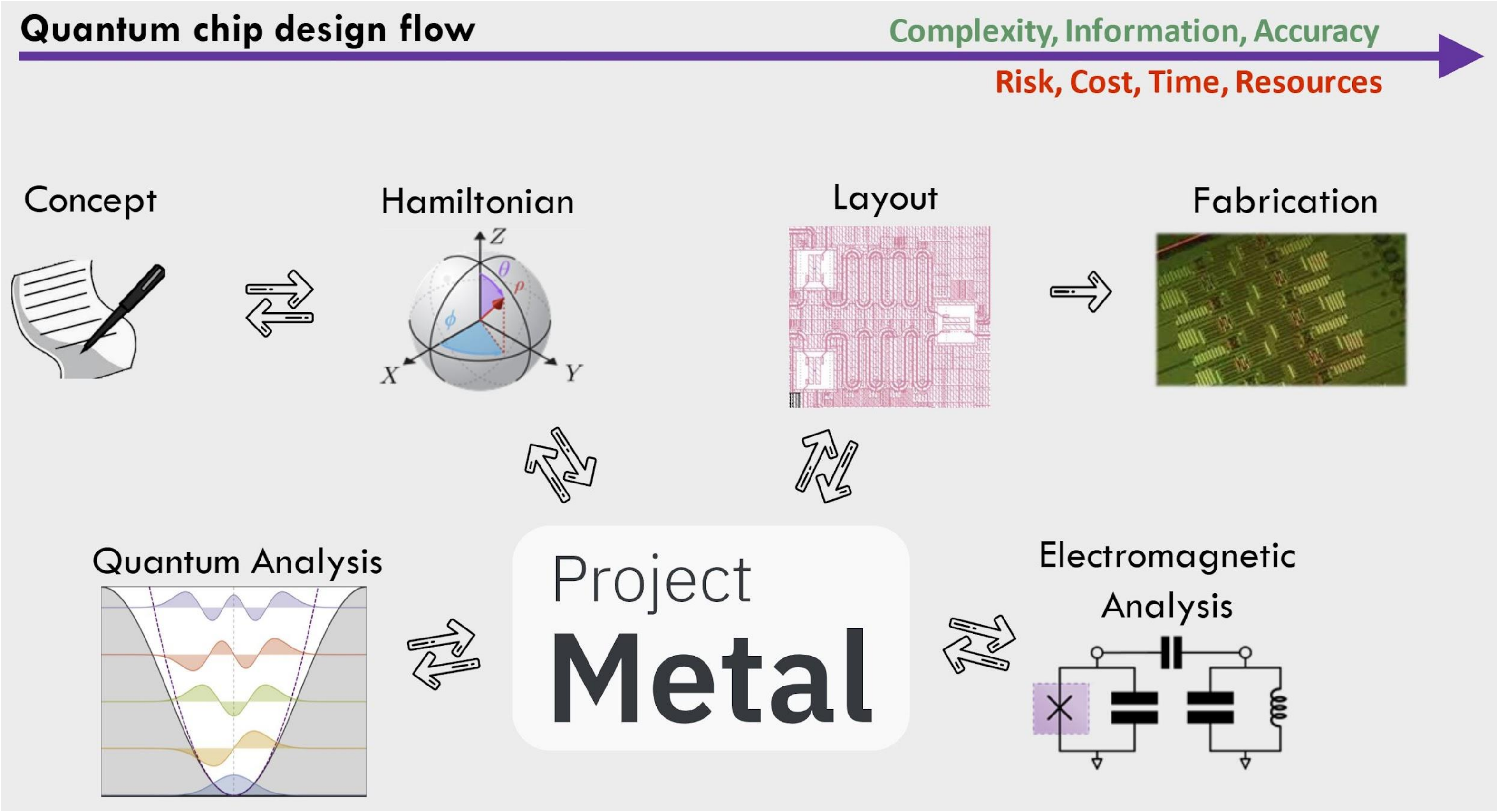
$$H_{\mathrm{disp}} = \underbrace{\left(\omega_r + \chi\sigma_z\right)}\left(a^\dagger a + \frac{1}{2}\right) + \frac{\widetilde{\omega}_{\mathrm{q}}}{2}\sigma_z$$

$$\chi = g^2/\Delta$$

g: Qubit-resonator coupling strength

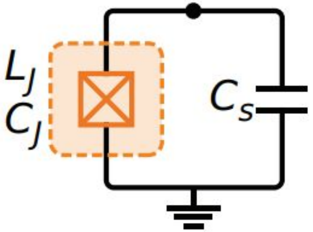
Thomas E. Roth et al, An Introduction to the Transmon Qubit for Electromagnetic Engineers (2021)
A. Blais, A. L. Grimsmo, S.M. Girvin, A. Wallraff, Circuit Quantum Electrodynamics (2021)

Next Steps


Quantum chip design flow
Complexity, Information, Accuracy
Risk, Cost, Time, Resources
Concept
Hamiltonian
Z
X
Y
θ
ρ
ϕ
Layout
Fabrication
Quantum Analysis
Project
Metal
Electromagnetic
Analysis

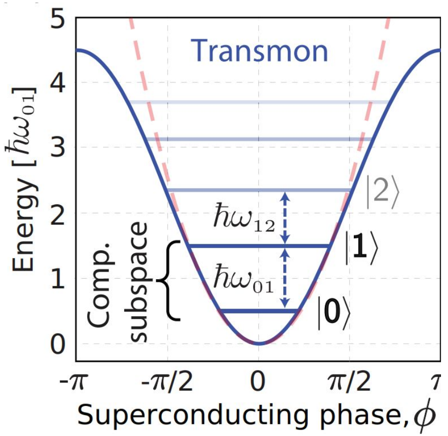
Quantum Circuit Design

Starting point



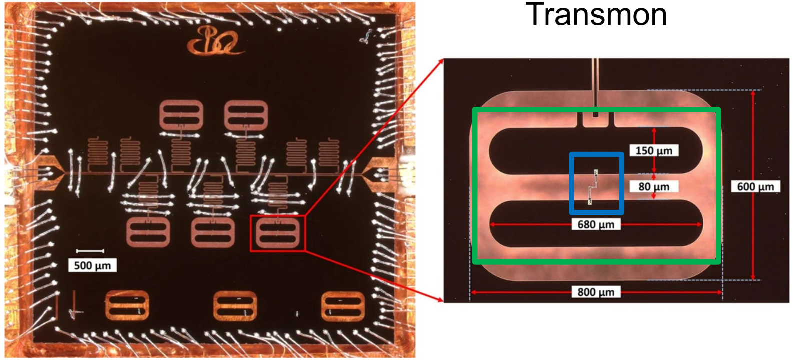
Transmon

$$H = 4\boxed{E_C}n^2 - \boxed{E_J}\cos(\phi)$$

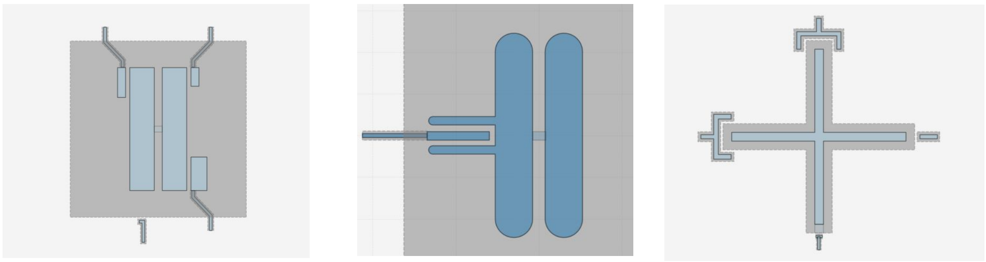


Transmon designs can look very different!

Transmon



Also Transmons



P. Krantz, A Quantum Engineer's Guide to Superconducting Qubits, 2021

C. Wang et al, Towards practical quantum computers: transmon qubit with a lifetime approaching 0.5 milliseconds, 2022

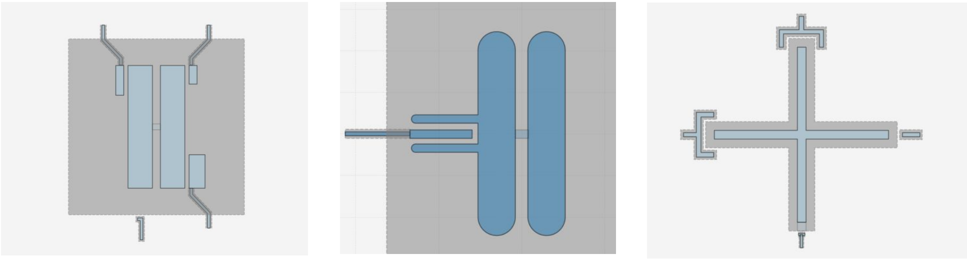
Quantum Circuit Design

Fabrication

Fabricating this will be time/resource consuming!

How can we make sure our design is giving the correct Hamiltonian values?

Transmons Designs



Fabrication (£££)

C. Wang et al, Towards practical quantum computers: transmon qubit with a lifetime approaching 0.5 milliseconds, 2022

https://angstromtechnology.com/what-are-semiconductor-cleanrooms/

Electromagnetic (EM) Simulations!

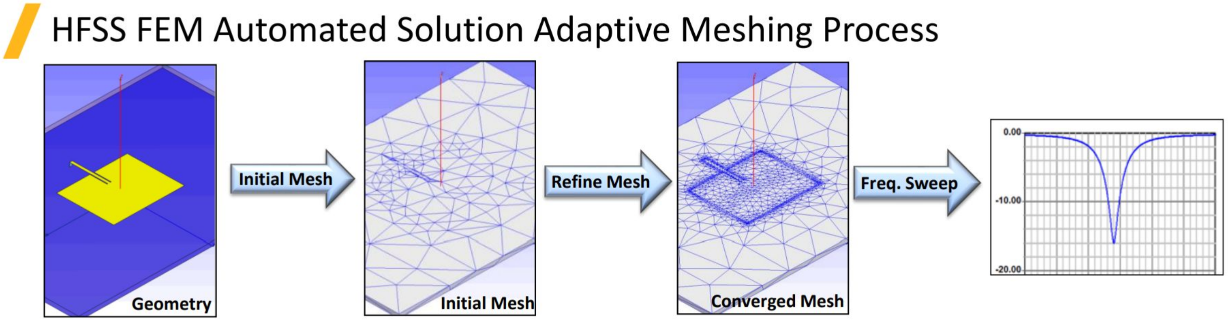
EM Simulations

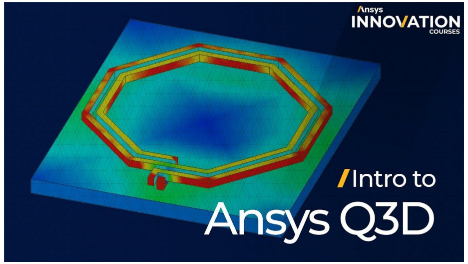
EM Simulations are a valuable approach for analyzing your chip design (classical and quantum) before fabricating it

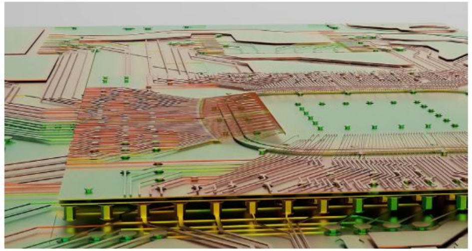
What can QPU properties can we extract using EM solvers?

1) Frequencies (qubit frequency, resonator frequency)

2) Capacitance, Inductance, Resistance, Conductance





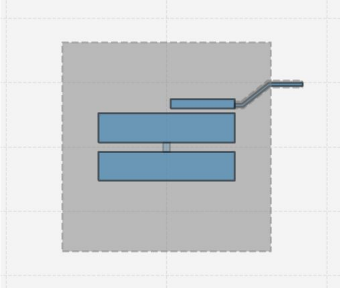


Fast, Accurate 3D Parasitic Extraction with Q3D

https://www.ansys.com/en-gb/products/electronics/ansys-hfss

EM Simulations

Transmon Design

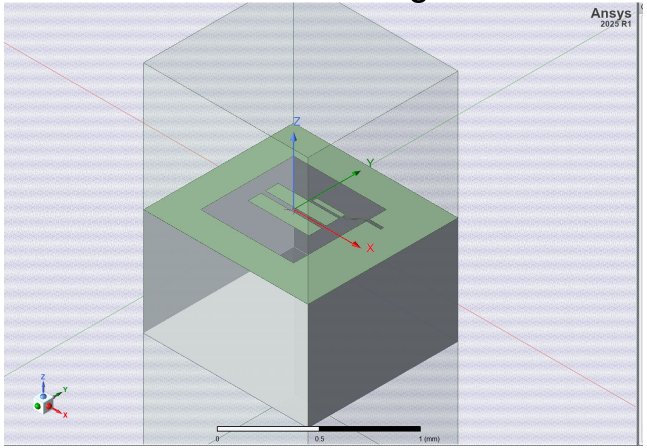


Import design

EM Simulation Software

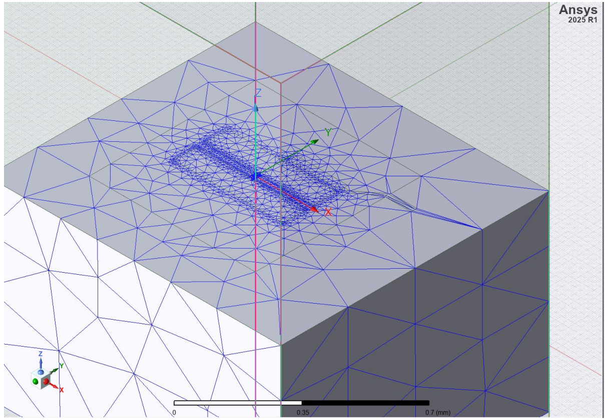
Define materials

Create 3D Design



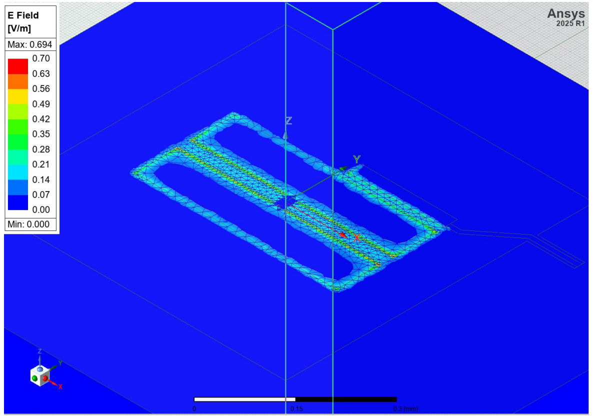
Break up design into small segments

Create Mesh



Solve Maxwell's equations for each segment (FEM)

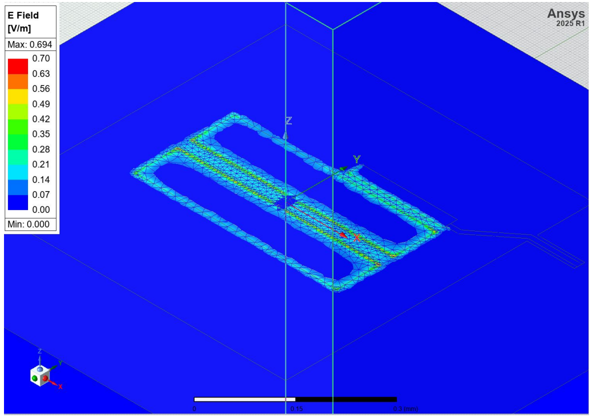
Plot Electric Field



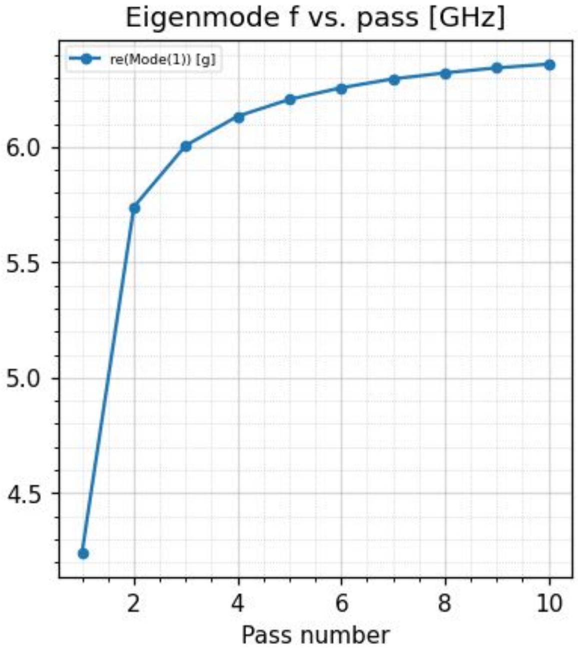
EM Simulations

Frequency

Electric field



Solve EM fields at various frequencies until converging to solution

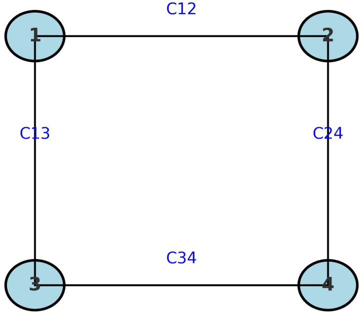


Found Transmon frequency!

$$H_{\mathrm{JC}} = \underbrace{\omega_r \left(a^\dagger a + \frac{1}{2}\right)}_{\text{Resonator}} + \underbrace{\frac{\boxed{\omega_{\mathrm{q}}}}{2}\sigma_z}_{\text{Qubit}} + \underbrace{g\left(\sigma_+ a + \sigma_- a^\dagger\right)}_{\text{Interaction}}$$

EM Simulations
Capacitance Matrix

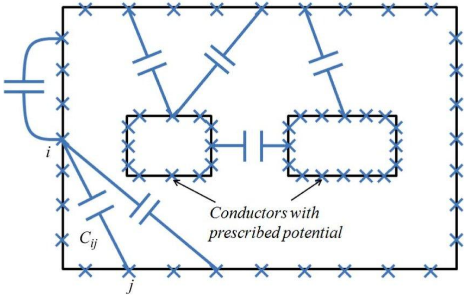
Example 4-Capacitor Configuration



Generalize to N nodes

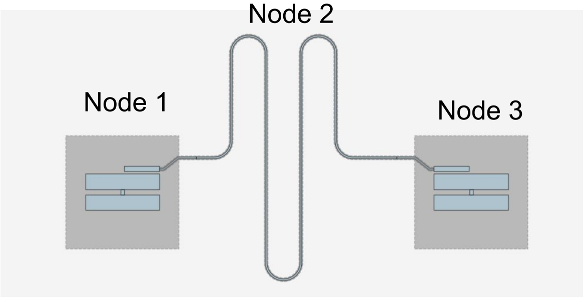
$$\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix}$$

Between every two nodes there is a capacitance



Capacitance Matrix for QPU

2 Qubit Design

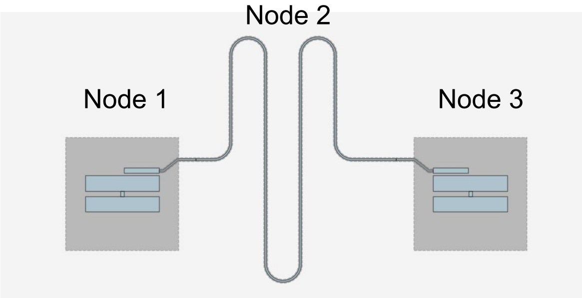


$$\begin{bmatrix} C_{11} & C_{12} & C_{12} \\ C_{21} & C_{22} & C_{22} \\ C_{31} & C_{32} & C_{32} \end{bmatrix}$$

EM Simulations

Capacitance Matrix

2 Qubit Design



$$\begin{bmatrix} C_{11} & C_{12} & C_{12} \\ C_{21} & C_{22} & C_{22} \\ C_{31} & C_{32} & C_{32} \end{bmatrix}$$

Transmon $\hat{H} = 4\boxed{E_C}(\hat{n} - \boxed{n_g})^2 - \boxed{E_J}\cos\hat{\varphi}$

Qubit + Resonator $H_{\text{JC}} = \underbrace{\omega_r\left(a^\dagger a + \frac{1}{2}\right)}_{\text{Resonator}} + \underbrace{\frac{\omega_q}{2}\sigma_z}_{\text{Qubit}} + \underbrace{\boxed{g}(\sigma_+ a + \sigma_- a^\dagger)}_{\text{Interaction}}$

EM Simulations

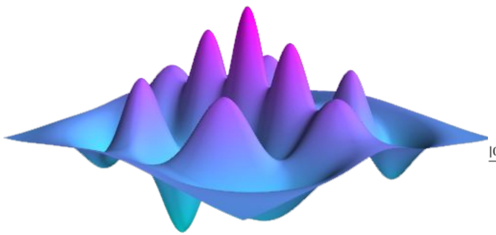
With EM simulations, we can extract all the quantum circuit parameters needed to analyze the Hamiltonian of a quantum system.

Transmon $$\hat{H} = 4\boxed{E_C}(\hat{n} - \boxed{n_g})^2 - \boxed{E_J}\cos\hat{\varphi}$$

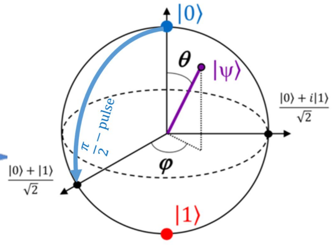
Qubit + Resonator $$H_{JC} = \underbrace{\boxed{\omega_r}\left(a^\dagger a + \frac{1}{2}\right)}_{\text{Resonator}} + \underbrace{\frac{\boxed{\omega_q}}{2}\sigma_z}_{\text{Qubit}} + \underbrace{\boxed{g}\,(\sigma_+ a + \sigma_- a^\dagger)}_{\text{Interaction}}$$

- Charging Energy E_C
- Josephson Energy E_J
- Offset Charge n_g
- Resonator frequency w_r
- Qubit frequency w_q
- Coupling coefficient g

Back to Quantum!



QuTIP

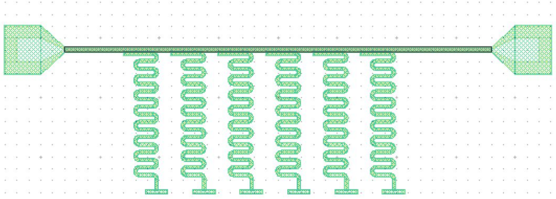


$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$

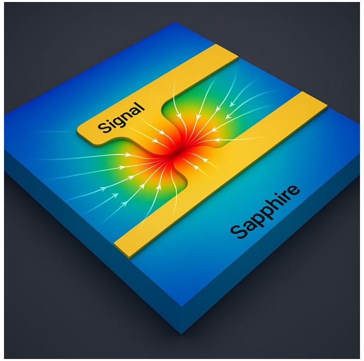
Testing Superconducting Circuits

Upcoming workshop focuses on these parts

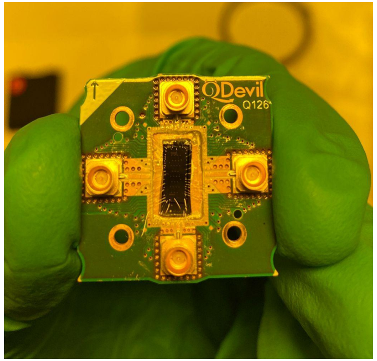
Design



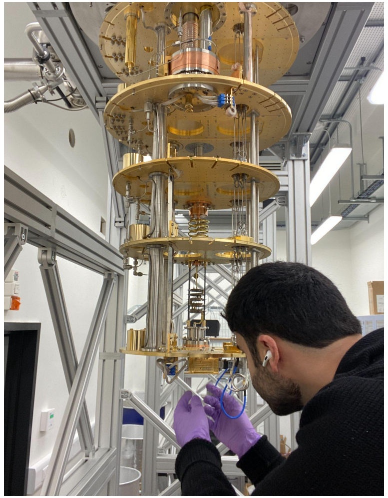
Simulation



Fabrication

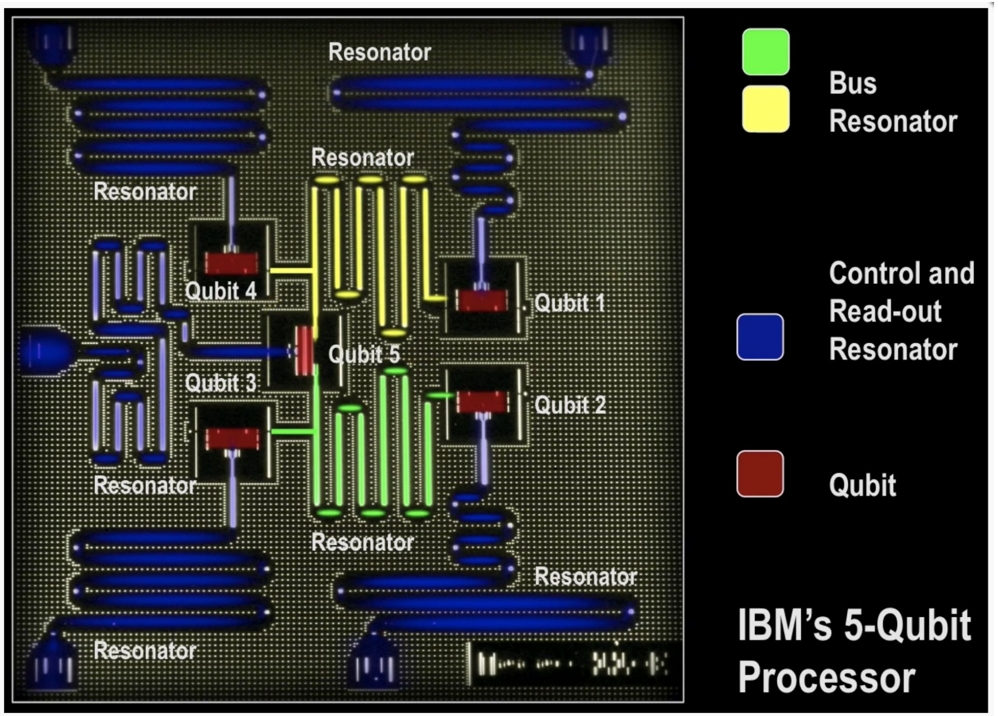


Measurement



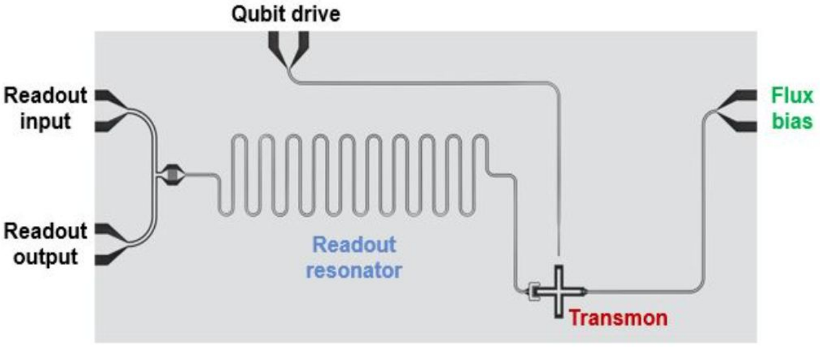
Superconducting Quantum Processors

Operating Frequency: 4 GHz - 7 GHz



https://www.researchgate.net/figure/An-image-of-IBMs-five-qubit-processor-with-its-main-elements-highlighted-including-the_fig4_358153899

Recap



Jaynes-Cummings Hamiltonian (Light matter interaction)

$$H_{\rm JC} = \underbrace{\omega_r \left(a^\dagger a + \frac{1}{2}\right)}_{\text{Resonator}} + \underbrace{\frac{\omega_{\rm q}}{2}\sigma_z}_{\text{Qubit}} + \underbrace{g\left(\sigma_+ a + \sigma_- a^\dagger\right)}_{\text{Interaction}}$$

Dispersive limit: $\Delta = |\omega_{\rm q} - \omega_r| \gg g$

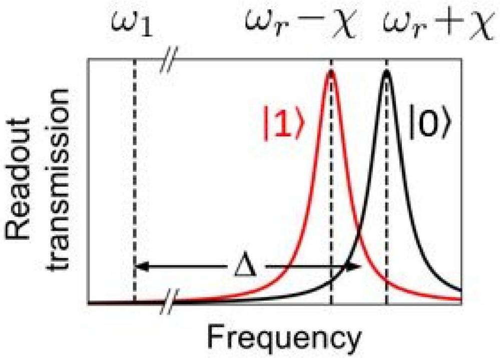
Resonator Frequency Shifts

$$H_{\rm disp} = \left(\omega_r + \chi\sigma_z\right)\left(a^\dagger a + \frac{1}{2}\right) + \frac{\widetilde{\omega}_{\rm q}}{2}\sigma_z$$

Dispersive shift

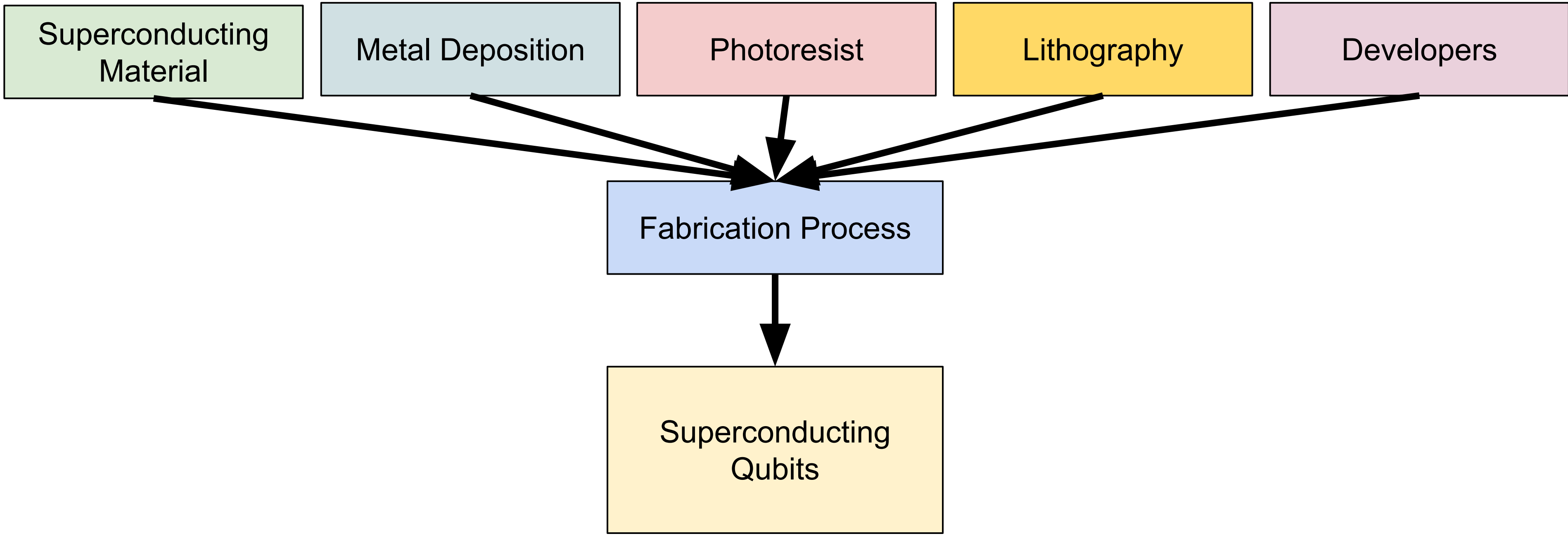
$$\chi = g^2/\Delta$$

Dispersive Readout



Thank you!

In-House Fabrication of Superconducting Circuits

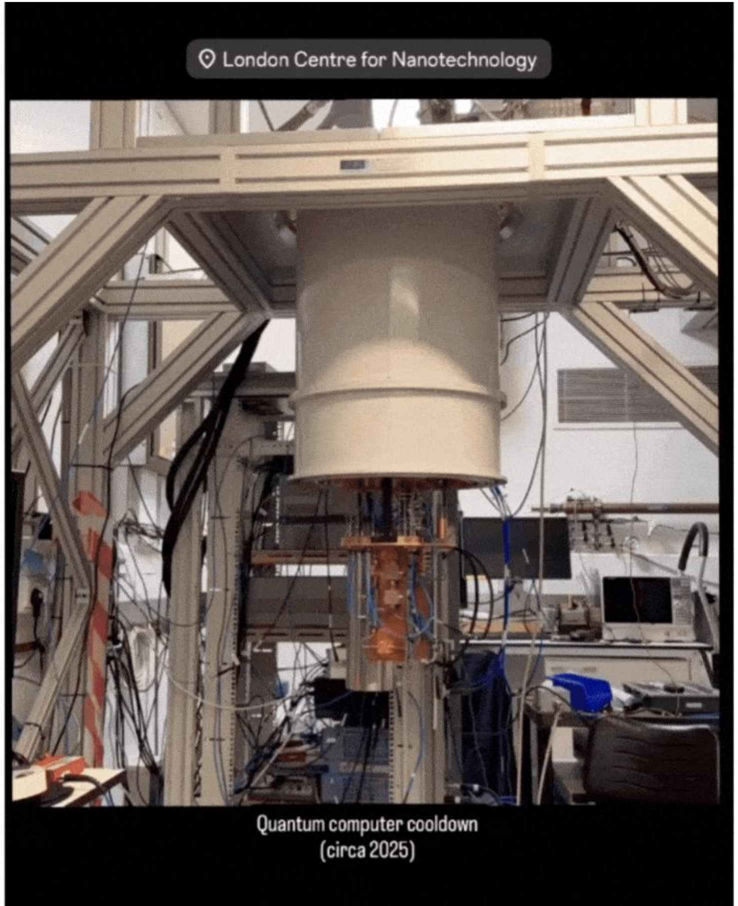


Preparing quantum chips/devices

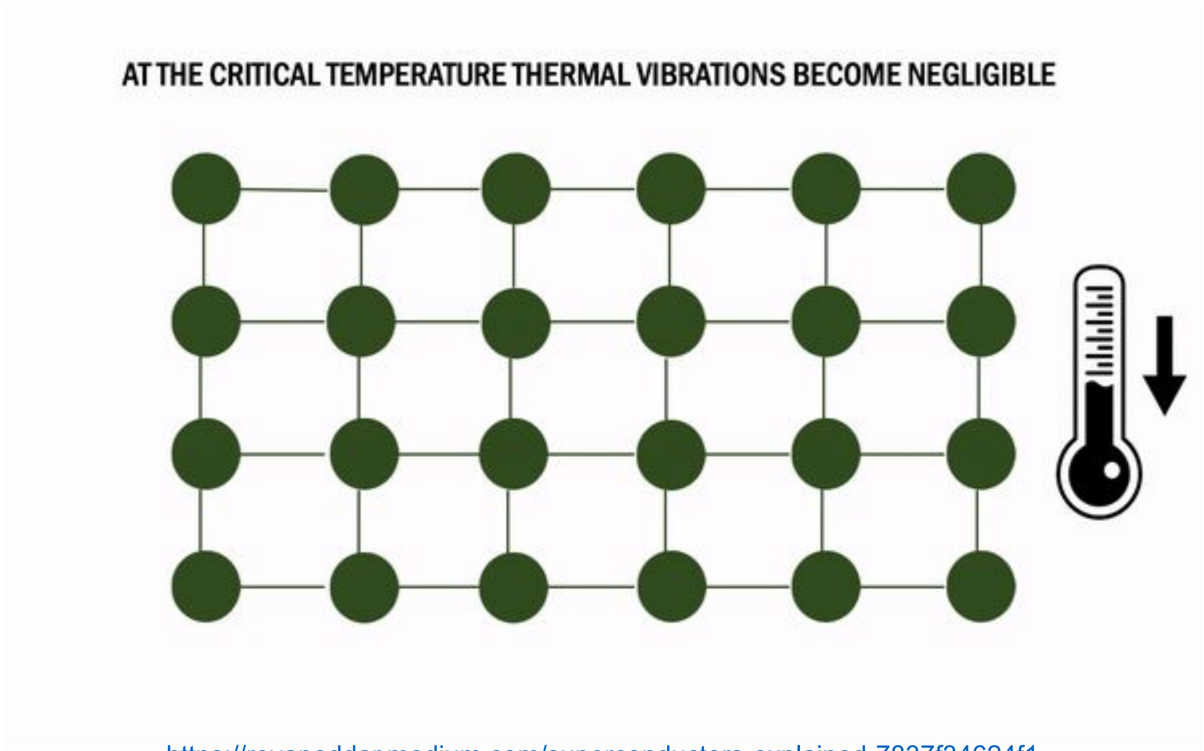
Expectation

Reality

Fridge Cooldown

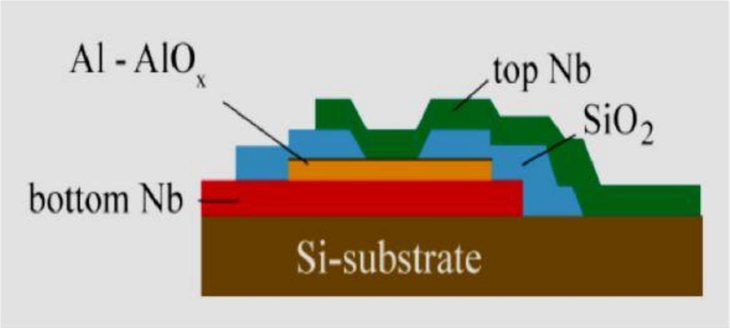


Supplementary Information

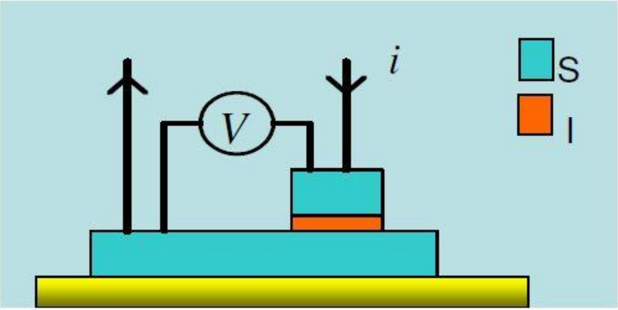


https://revapoddar.medium.com/superconductors-explained-7837f34624f1

Supplementary Information

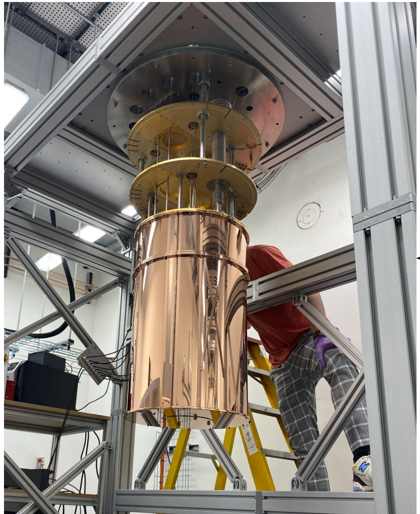


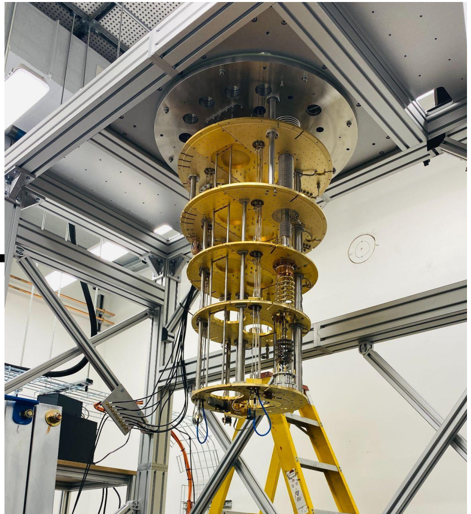
Typical junction cross-section



***I-V* Measurement Principle**

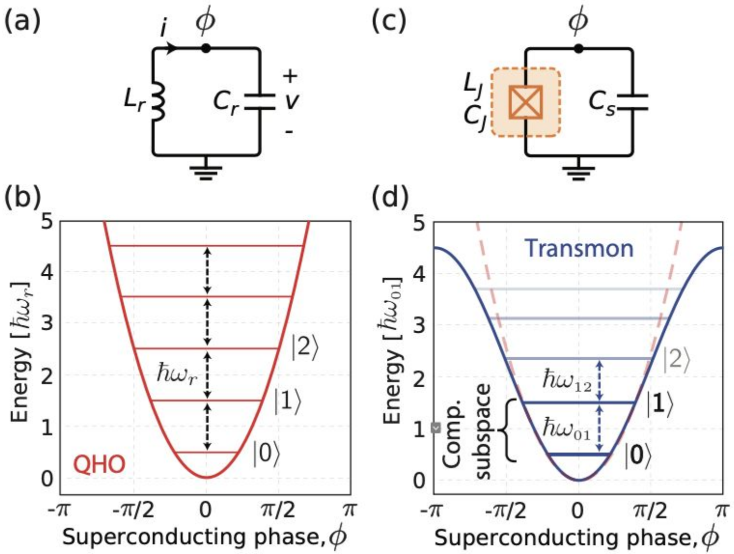
UCL





Transmon Qubit I

- Two level system with quantum mechanical properties (superposition, entanglement)
- Tunable qubit transition frequency via electromagnetic flux biasing
- Long coherence times (milliseconds)
- Qubit states being represented by the number of Cooper pairs on the island



$$H = Q\dot{\Phi} - \mathcal{L} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} \equiv \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

$$H = 4E_C n^2 - E_J \cos(\phi)$$

$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right)$$

[1] P. Krantz, M. Kjaergaard, F. Yan (2021)
A Quantum Engineer's Guide to Superconducting Qubits

Transmon Qubit II

Transmon Hamiltonian

Excess number of cooper pairs on island

Reduced flux

$$H = 4E_C n^2 - E_J \cos(\phi)$$

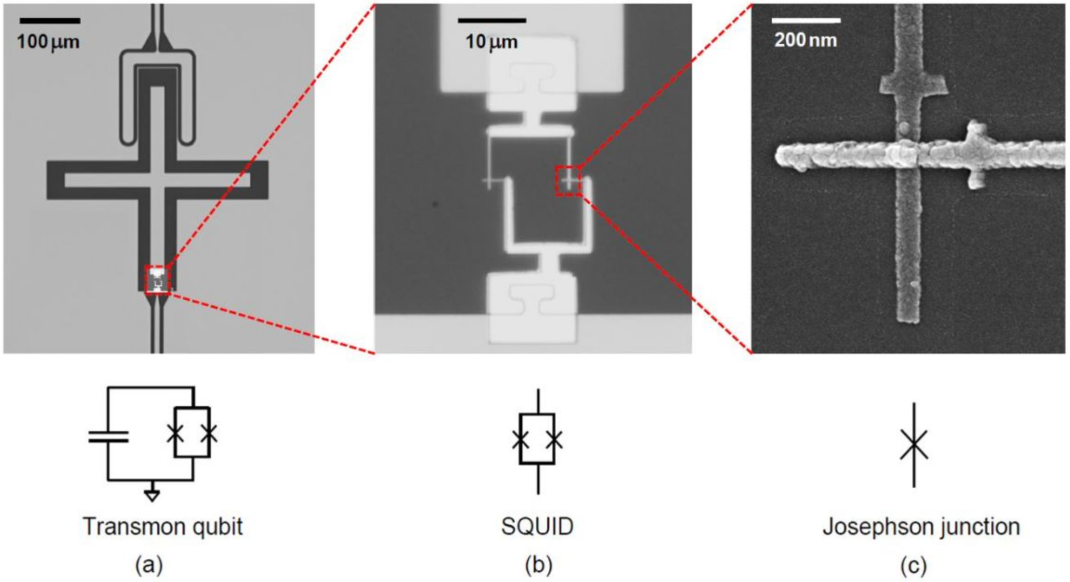
Energy required to add each electron of cooper-pair to island

Josephson energy

- Dynamics of quantum system are governed by E_J/E_C ratio
- E_C can be decreased by using shunt capacitor ($E_C \sim 1/C_{Total}$)
- In $E_J >> E_C$ regime, system is less sensitive to noise

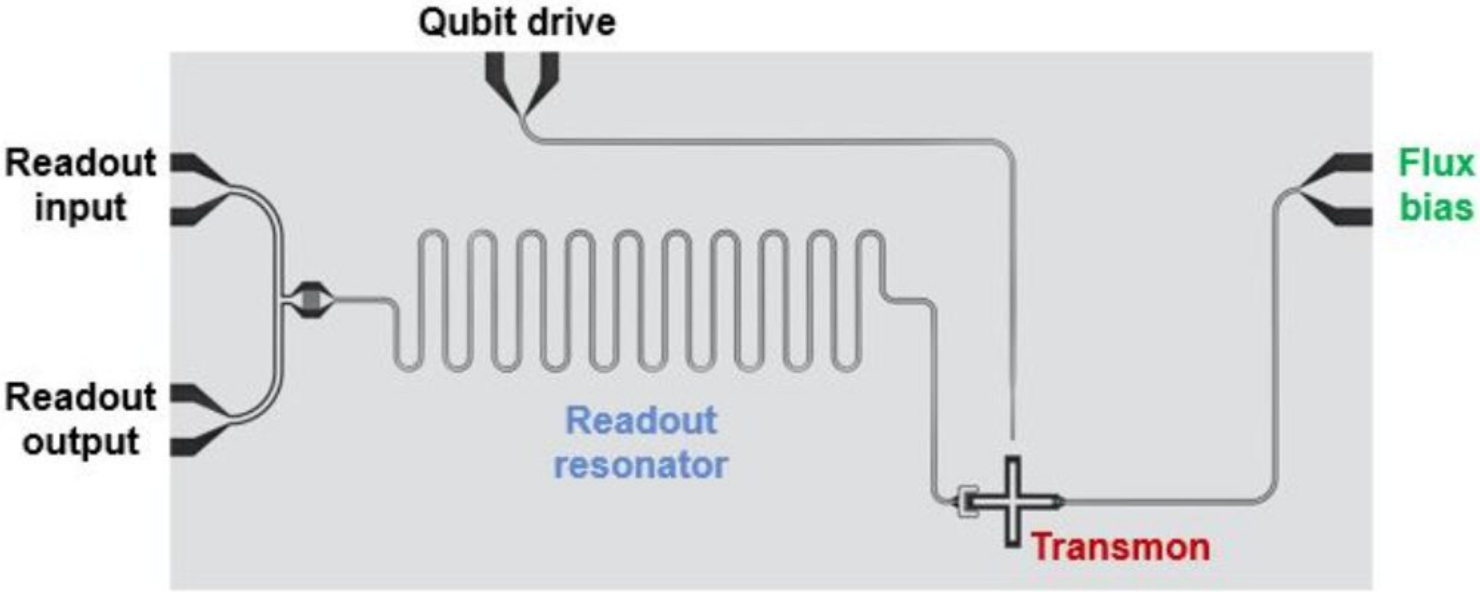
[1] P. Krantz, M. Kjaergaard, F. Yan (2021)
A Quantum Engineer’s Guide to Superconducting Qubits

SEM Images of Transmon



Roth, Thomas E. and Ma, Ruichao and Chew, Weng C. An Introduction to the Transmon Qubit for Electromagnetic Engineers (2021)

Resonator + Qubit



Roth, Thomas E. and Ma, Ruichao and Chew, Weng C. An Introduction to the Transmon Qubit for Electromagnetic Engineers (2021)

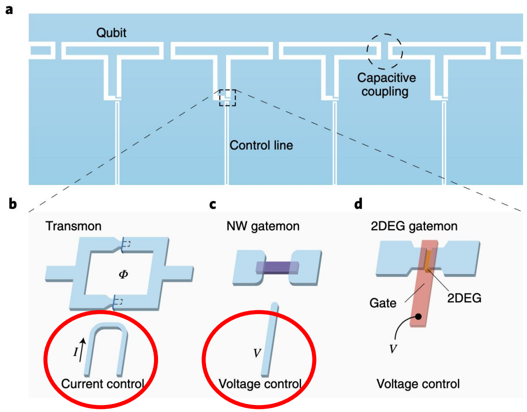
Gatemon Qubit

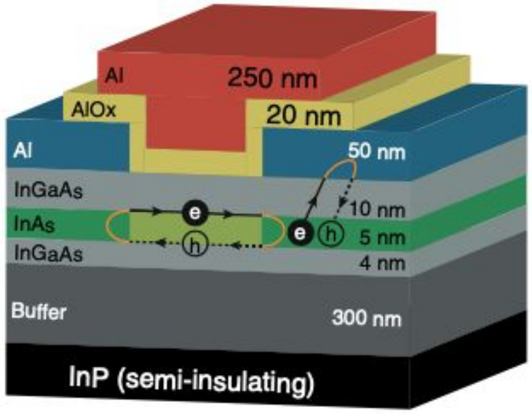
- Derived from Transmons, Superconducting gate tunable qubits based on Josephson Junction

- High fidelity two qubit measurements rely on qubit frequency

- Unlike flux inducing current reliance of transmon, gatemon relies on V_g to tune qubit

- Eliminates <u>heating</u> through wires caused by current as well as <u>crosstalk</u>





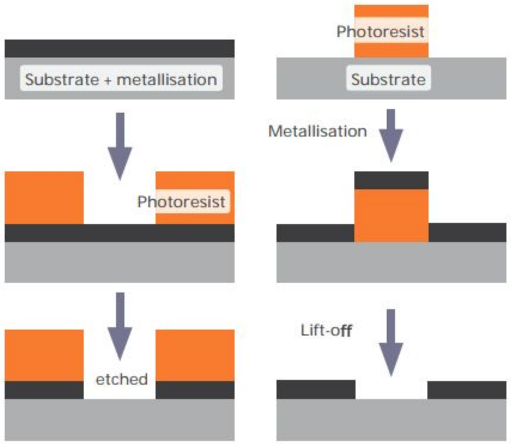
[1] Weber, S.J. Gatemons get serious. *Nature Nanotech* 13, 877–878 (2018).
[2] P. Krantz and M. Kjaergaard and F. Yan and T. P. Orlando and S. Gustavsson and W. D. Oliver. A quantum engineer's guide to superconducting qubits (2019)
[3]Casparis, L., Connolly, M.R., Kjaergaard, M. *et al.* Superconducting gatemon qubit based on a proximitized two-dimensional electron gas.(2018)

Photolithography

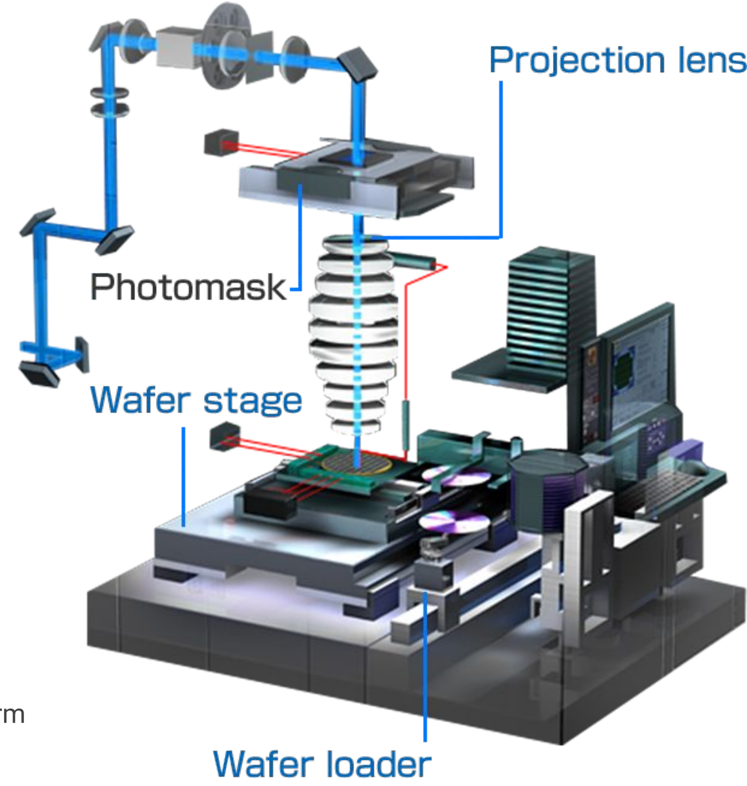
Parameters:

- Intensity of light [%]
- Laser Power [mW]

Etching vs Lift-off

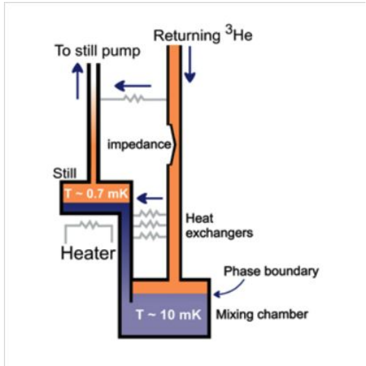


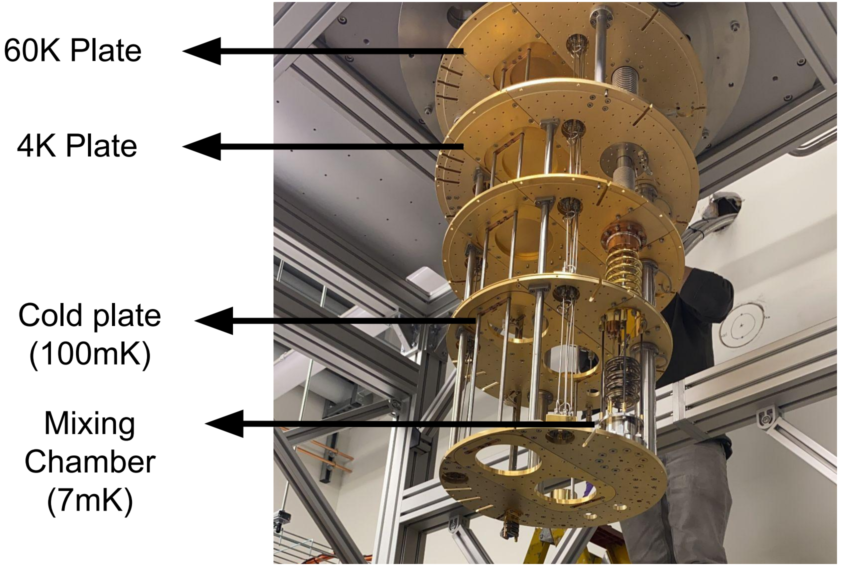
https://www.microchemicals.com/technical_information/lift_off_photoresist.pdf



Dilution Fridge I

- Dry dilution fridge using Pulse Tubes
- Uses mixture of He3 and He4
- Cooling power is generated by pumping heat out of the mixing chamber and into the surrounding stages
- Distilling He3 out of He4 is absorbing heat (Taking pure phase atoms into dilute phase, increasing entropy)

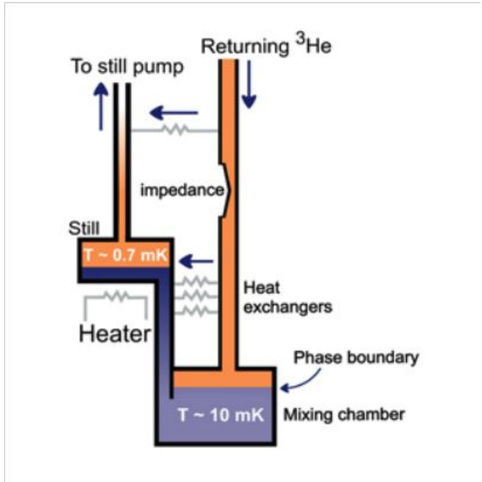


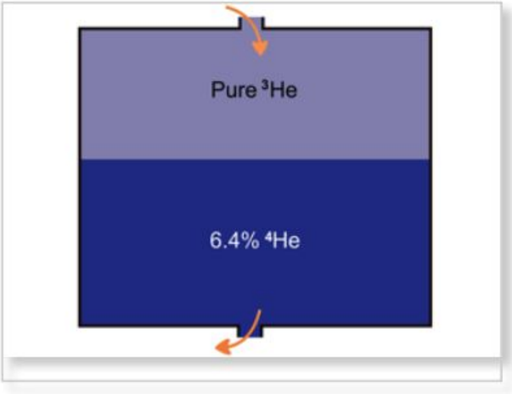


https://nanoscience.oxinst.com/assets/uploads/NanoScience/Brochures/Principles%20of%20dilution%20refrigeration_Sept15.pdf

Dilution Fridge II

- Pulse tubes offer low vibrations
- Copper braids are used to couple first two stages (avoids vibrations)
- He3 has lower latent heat of evaporation, higher vapour pressure
- He3 atom attracted to He4 due to Van der Waals
- Osmotic pressure pulls Helium up
- Pressure of chamber can be adjusted to change temperature





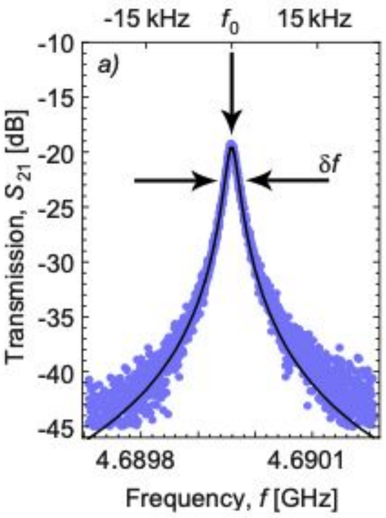
https://nanoscience.oxinst.com/assets/uploads/NanoScience/Brochures/Principles%20of%20dilution%20refrigeration_Sept15.pdf

UCL

QCoDeS

RF Measurements

Single Tone Frequency Sweep



M. Göppl and A. Fragner and M. Baur and R. Bianchetti and A. Wallraff. Coplanar waveguide resonators for circuit quantum electrodynamics (2008)

```
class singleToneFreqSweep(spectroscopyMeas):

    name = 'singleToneFreqSweep'

    def __init__(self, parent_dir, date, vna=None, vna_settings=None, fridge=None):
        super().__init__(parent_dir, date, vna, vna_settings, fridge)


## Retrieving data
    def get_mag(self, path=None, counter=None):
        return self.grab_file('mag.txt', path, counter)

    def get_phase(self, path=None, counter=None):
        return self.grab_file('phase.txt', path, counter)

    def get_freqs(self, path=None, counter=None):
        return self.grab_file('freqs.txt', path, counter)

    def meas(self, vna_settings=None, plot=True, save=True, reduce_bg=False, style=None):
        channel = self.vna.channels.S21
        self.write_vna_settings(vna_settings)

        self.prepare_meas()

        ## Start Measurement
        amp, phase = channel.trace_mag_phase()
        #mag = 10*np.log10(mag)
        mag = util.mag2dB(amp)

        if reduce_bg:
            channel.power(-80)
            mag_bg, phase_bg = channel.trace_mag_phase()
            mag = mag - util.mag2dB(mag_bg)
            phase = phase - phase_bg

        ## Plot and save data


        freqs = util.sweep(self.vna_settings['center'], self.vna_settings['span'], self.vna_settings['npts'])
        freqs = util.freq2GHz(freqs)
```

SGS

VNA

Noise & Dissipation

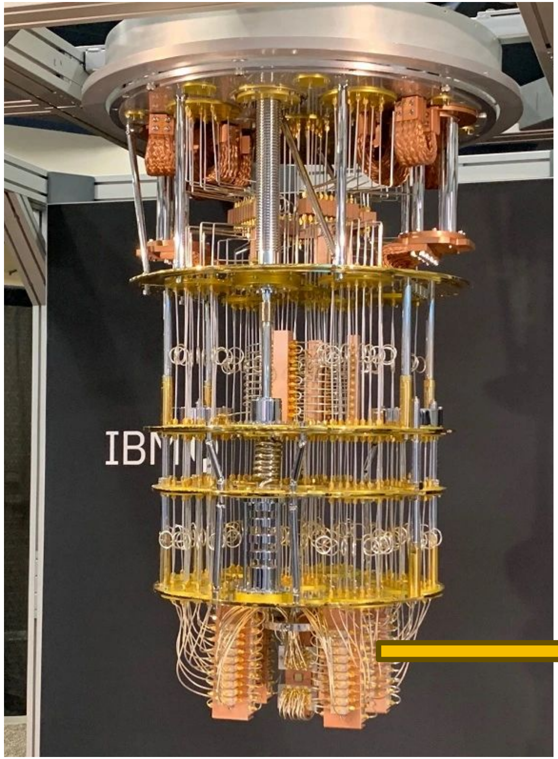
- Caused by fluctuations in the temperature of the environment, generating fluctuations in electrical properties of the quantum system.
- Electromagnetic interference (EMI): This is caused by electromagnetic fields (external sources, power cables, electrical devices, environment)
- Noise from electrical components and instruments
- Lossy Resonators lead to dissipation of energy

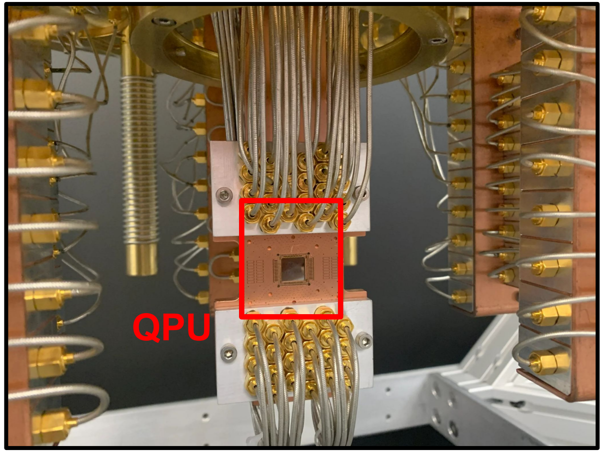
Various Quantum Computing Architectures

Qubit Type	Pros/Cons	Select Players
Superconducting	***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start. ***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.	rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum
Trapped Ions	***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent. ***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.	IONQ, AQT, QUANTINUUM, Universal Quantum, oxford ionics
Photonics	***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs. ***Cons***: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges.	PsiQuantum, XANADU, QUIX QUANTUM, ORCA Computing
Neutral Atoms	***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required. ***Cons***: Requires ultra-high vacuums. Laser scaling challenging.	ColdQuanta, QuEra Computing Inc., atom computing, PASQAL
Silicon Spin/Quantum Dots	***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds. ***Cons***: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges.	intel, Silicon Quantum Computing, diraq, QUANTUM MOTION, QUANTUM BRILLIANCE

https://quantumtech.blog/2022/10/20/quantum-computing-modalities-a-qubit-primer-revisited/

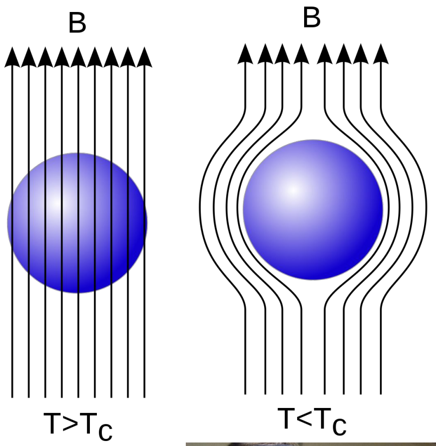
Superconducting Quantum Computers



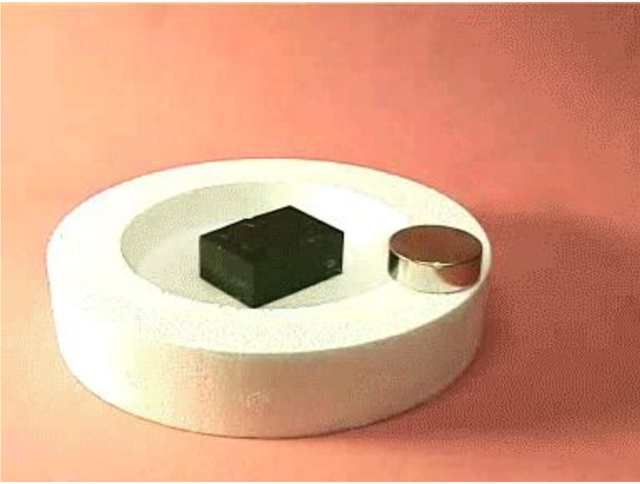


Superconductivity
Meissner effect

Meissner effect

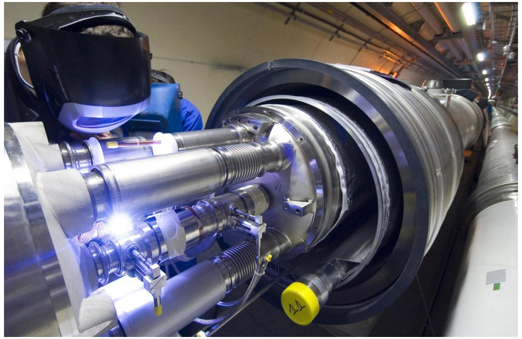


Expulsion of magnetic fields from the superconductor



https://www.pinterest.co.uk/pin/431571576761730279/

Magnetic field shielding used at CERN



https://home.cern/news/news/knowledge-sharing/exchanging-knowledge-industry-superconducting-tech

MRI

https://www.medimaging.net/mri/articles/294795607/use-of-high-temperature-superconductors-to-make-mr-imaging-more-affordable-accessible-and-sustainable.html

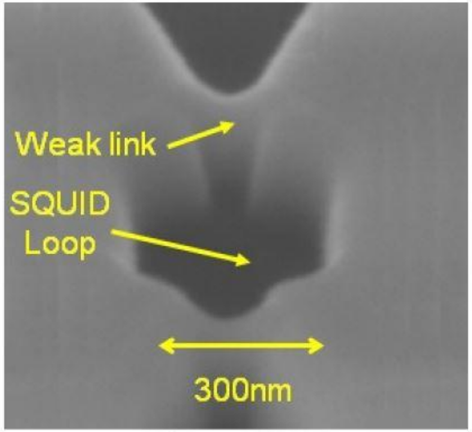
Superconductivity
Back to Quantum

Why are superconductors good for quantum?

- Ability to control quantum effects
- Advancements in Semiconductor industry are transferable to superconducting chips
- Minimal energy dissipation

SQUID
(Superconducting Quantum Interference Device)

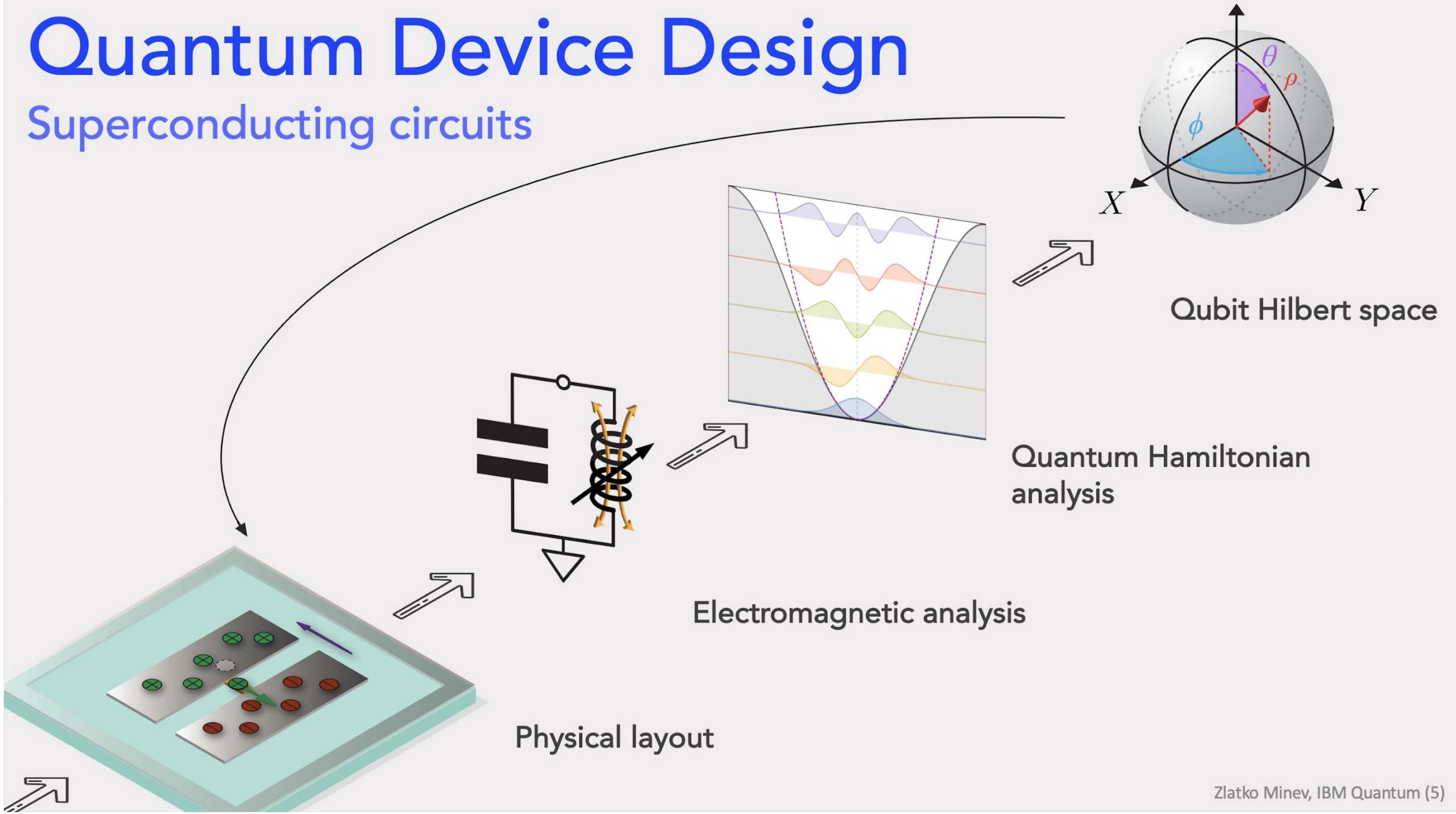
Giant SQUID



Nano SQUID

Quantum Device Design

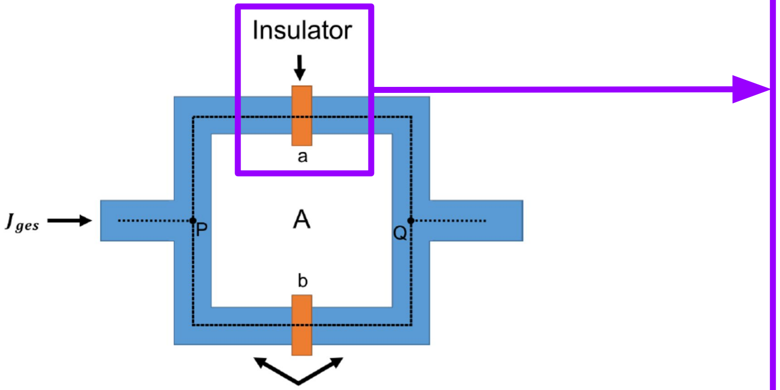
Superconducting circuits



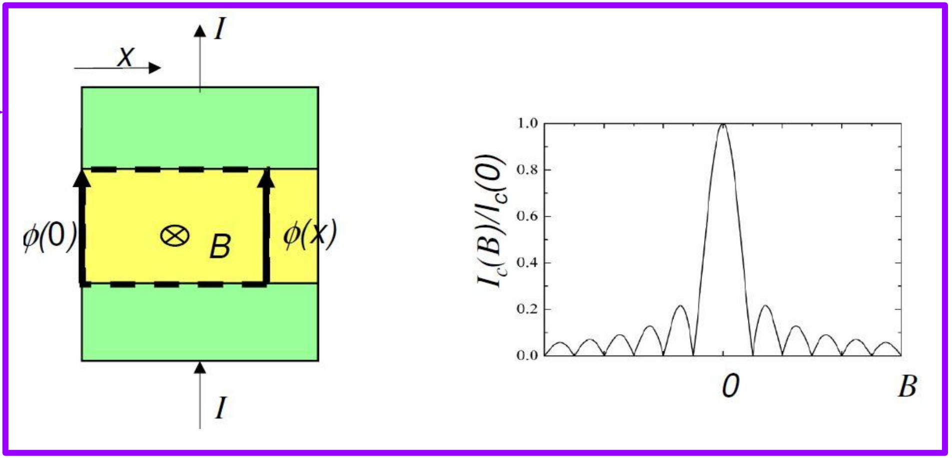
Zlatko Minev, IBM Quantum (5)

Superconducting Quantum Interference Device (SQUID)

SQUID diagram

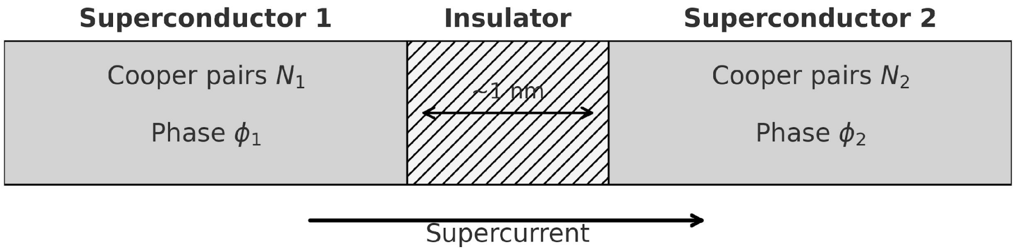


Macroscopic quantum interference



When a magnetic field is applied perpendicular to the junction, the critical current Ic changes in a way that resembles the diffraction intensity of light diffracted through a single slit (Fraunhofer Diffraction).

https://owlcation.com/stem/What-Are-Superconducting-Quantum-Interference-Devices-or-SQUIDs



Dynamical Variables: $n = N_1 - N_2, \quad \varphi = \phi_1 - \phi_2$

Josephson Relations

$$I_s = I_c \sin(\varphi)$$

$$\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$$

Differentiate I_s with respect to time:

$$\frac{dI_s}{dt} = I_c \cos(\varphi) \frac{d\varphi}{dt}$$

Substitute $\frac{d\varphi}{dt} = \frac{2e}{\hbar} V$:

$$\frac{dI_s}{dt} = I_c \cos(\varphi) \frac{2e}{\hbar} V$$

Compare to $V = L \frac{dI}{dt}$:

$$L_J(\varphi) = \frac{\Phi_0}{2\pi I_c \cos(\varphi)}$$

where $\Phi_0 = \frac{h}{2e}$ is the flux quantum