SUPERCONDUCTING QUANTUM COMPUTER DESIGN

A QHardware Tutorial Series

Part-4

TOPICS COVERED

- Superconducting Qubits- Transmon
- Circuit Quantum Electrodynamics (cQED) Architecture
- Qubit Manipulation and Measurement
- Qubit Characterization
- Quantum Circuits and Universal Gates

BASIC REQUIREMENTS TO BUILD QUANTUM PROCESSOR

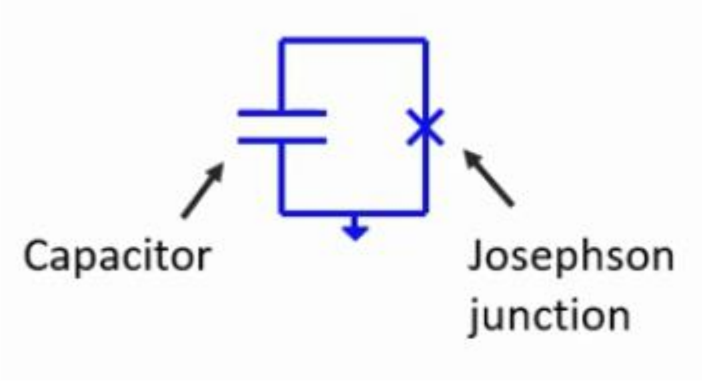
- Two level quantum systems
- Creating arbitrary states
- Measuring quantum states
- Couple multiple qubits
- Error correction (advanced feature)

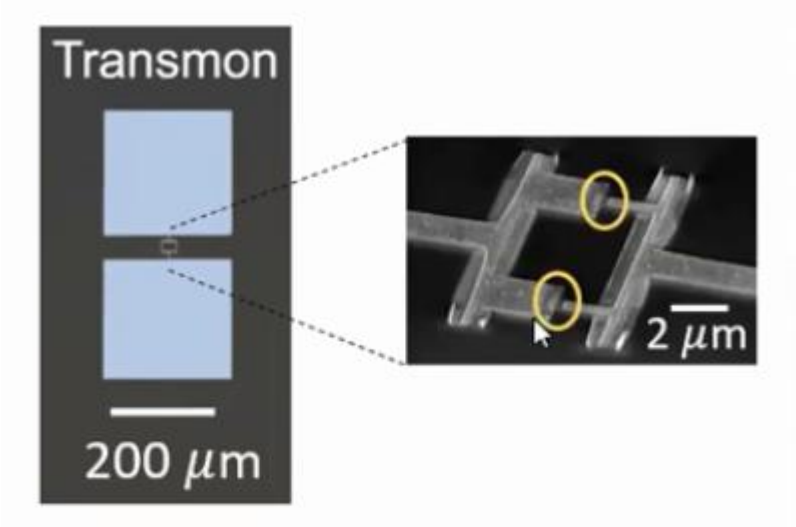
ADVANTAGE OF SUPERCONDUCTING QC

- Easy to manipulate
- Long lifetimes
- Strong couplings
- Scalability

TRANSMON QUBIT

- A transmon is a type of superconducting charge qubit that was designed to have reduced sensitivity to charge noise. The transmon is a Josephson junction and capacitor in parallel. Originally, transmons were differential circuits, i.e. two transmons on the same chip were not galvanically connected in any way.
- A Josephson junction is a quantum mechanical device which is made of two superconducting electrodes separated by a barrier (thin insulating tunnel barrier, normal metal, semiconductor, ferromagnet, etc.)



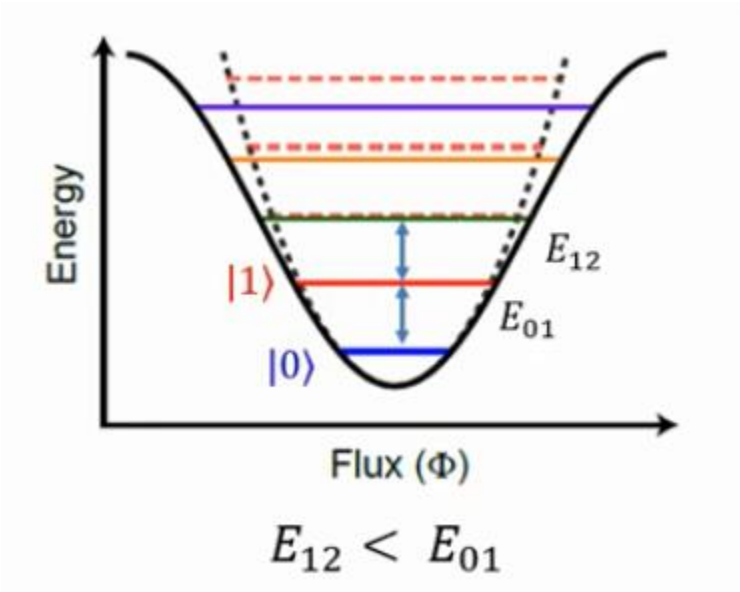


TRANSMON: ANHARMONIC OSCILLATOR

- Hamiltonian of a transmon circuit is defined as:

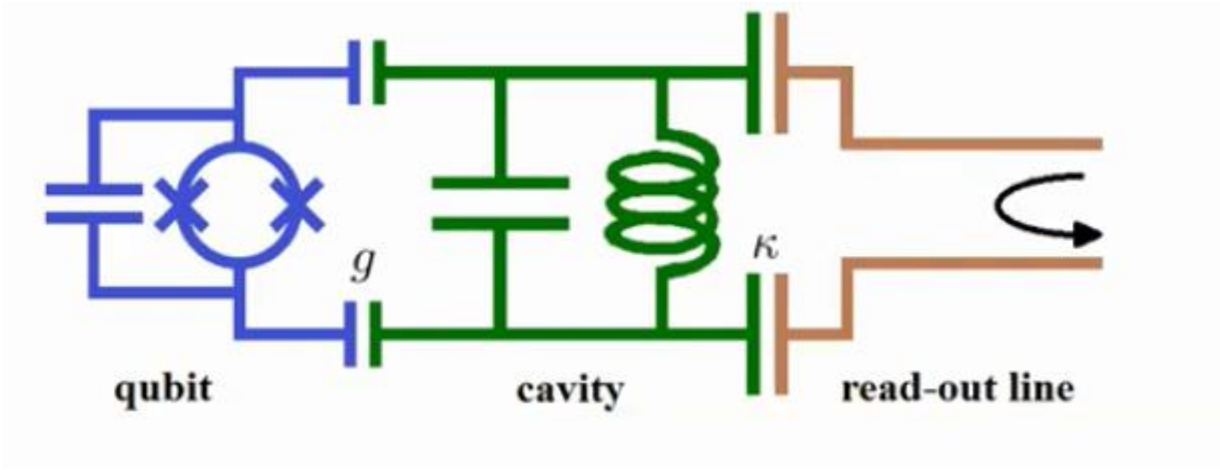
$$H_{\text{Transmon}} = \frac{\Phi^2}{2L_J(\varphi_{ext})} + \frac{Q^2}{2C} - \delta\Phi^4$$

- For quantum computation, we assume ground state as 0 and first state as 1.
- It's an effective two level system
- An oscillator that is not oscillating in harmonic motion is known as an anharmonic oscillator where the system can be approximated to a harmonic oscillator and the anharmonicity can be calculated using perturbation theory. If the anharmonicity is large, then other numerical techniques have to be used.



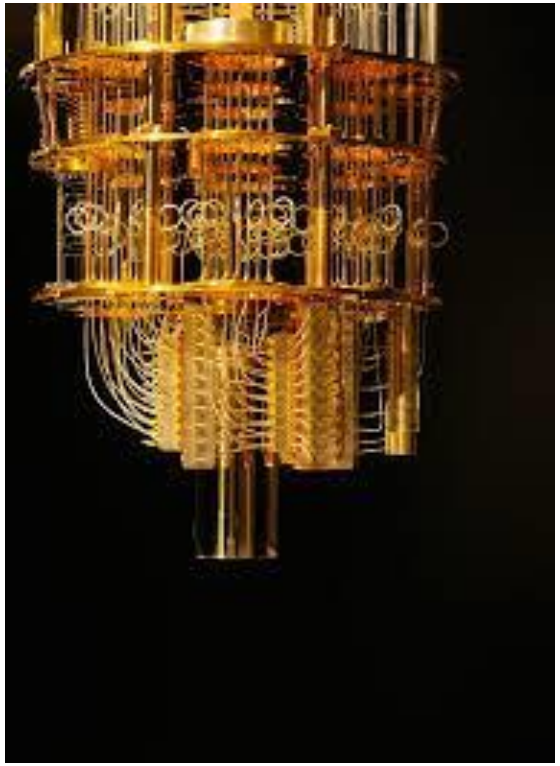
CIRCUIT QED ARCHITECTURE

- Circuit quantum electrodynamics (circuit QED) provides a means of studying the fundamental interaction between light and matter (quantum optics).



DILUTION REFRIGERATOR

- A $^3He/^4He$ dilution refrigerator is a cryogenic device that provides continuous cooling to temperatures as low as 2 mK, with no moving parts in the low-temperature region. The cooling power is provided by the heat of mixing of the Helium-3 and Helium-4 isotopes.

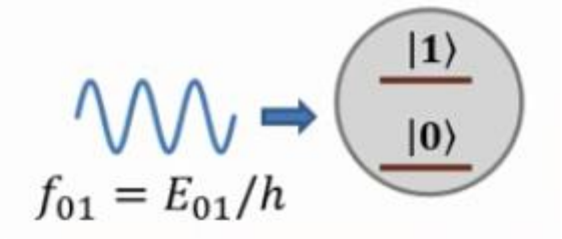


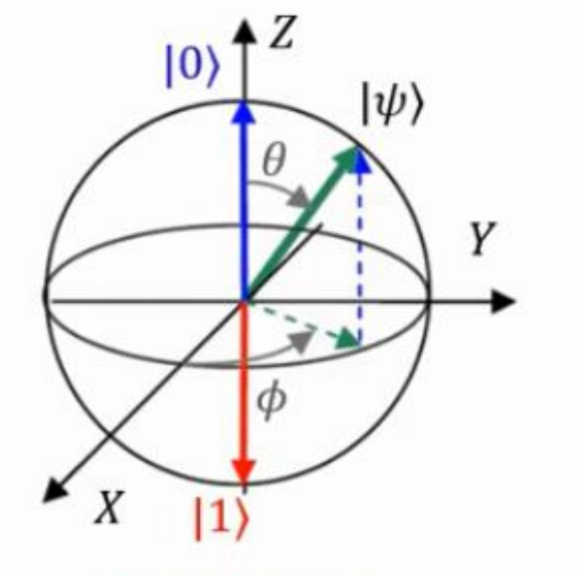
BLOCH SPHERE AND RABI OSCILLATION

- On the Bloch sphere, applying a light pulse to the qubit corresponds to a rotation around an axis in the equatorial plane. In quantum mechanics and computing, the Bloch sphere is a geometrical representation of the pure state space of a two-level quantum mechanical system (qubit).
- The Rabi oscillation in a coherent field with a finite photon number thus collapses after a time Tcollapse whose order of magnitude is the Rabi oscillation period in vacuum.

➢ Superposition: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



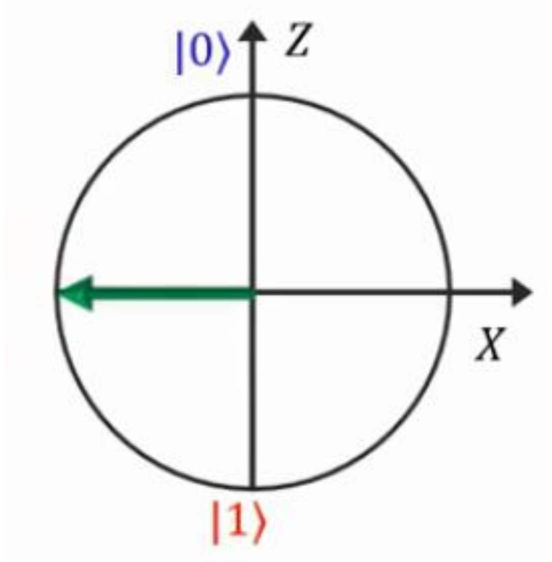


Bloch Sphere

SINGLE QUBIT GATE

- Single qubit gates correspond to rotations of a spin about some axis. The simplest gates are rotations about axes in the *xy*-plane, as these can be implemented using resonant RF pulses. The *flip angle* of the pulse (the angle through which the spin is rotated) depends on the length and the power of the RF pulse, while the *phase angle* of the pulse (and hence the azimuthal angle made by the rotation axis in the *xy*-plane) can be controlled by choosing the initial phase angle of the RF.
- For example, for pi/2 pulse, qubit angle rotation is happed

$$\pi/2 \text{ pulse:} \quad |0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$$
$$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$$

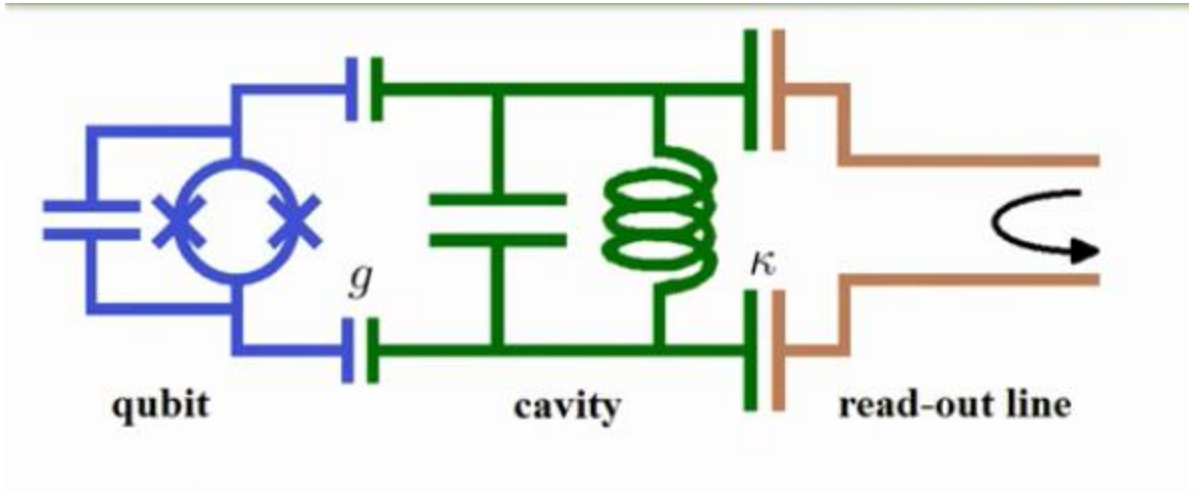


QUBIT MEASUREMENT

- The Jaynes–Cummings model (sometimes abbreviated JCM) is a theoretical model in quantum optics. It describes the system of a two-level atom interacting with a quantized mode of an optical cavity (or a bosonic field), with or without the presence of light (in the form of a bath of electromagnetic radiation that can cause spontaneous emission and absorption).

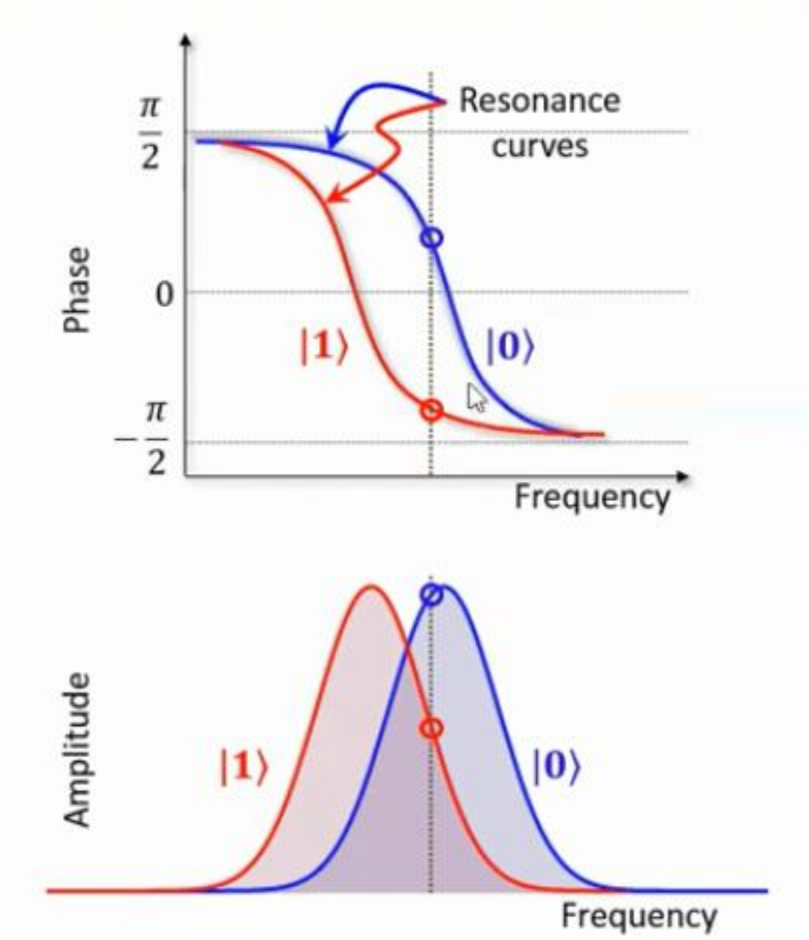
$$H_{JC} = -\frac{1}{2}\hbar\omega_q\sigma_z + \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) - \hbar\chi a^\dagger a\sigma_z$$

$$\boxed{H_{JC} = -\frac{1}{2}\hbar\omega_q\sigma_z + \hbar(\omega_r - \chi\sigma_z)a^\dagger a + \frac{\hbar\omega_r}{2}}$$

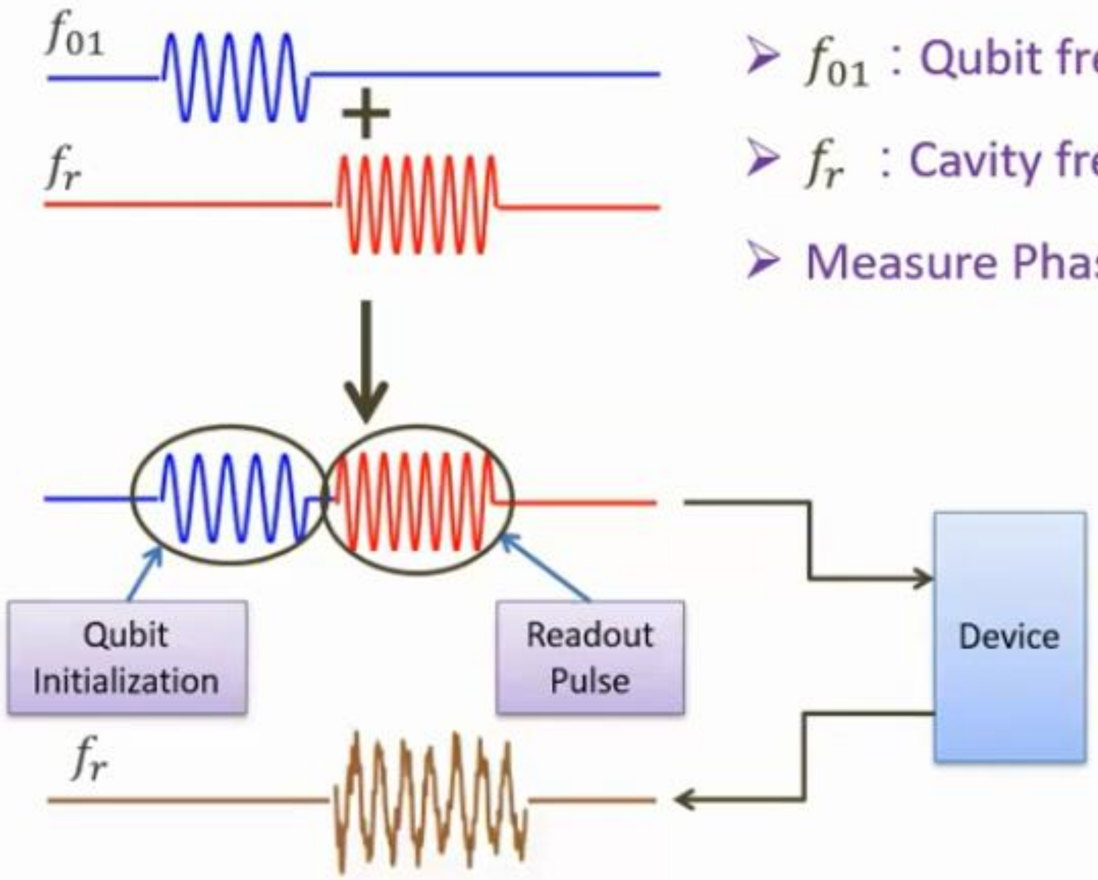


QUBIT MEASUREMENT

- To know the situation of qubit whether in ground state or excited state.



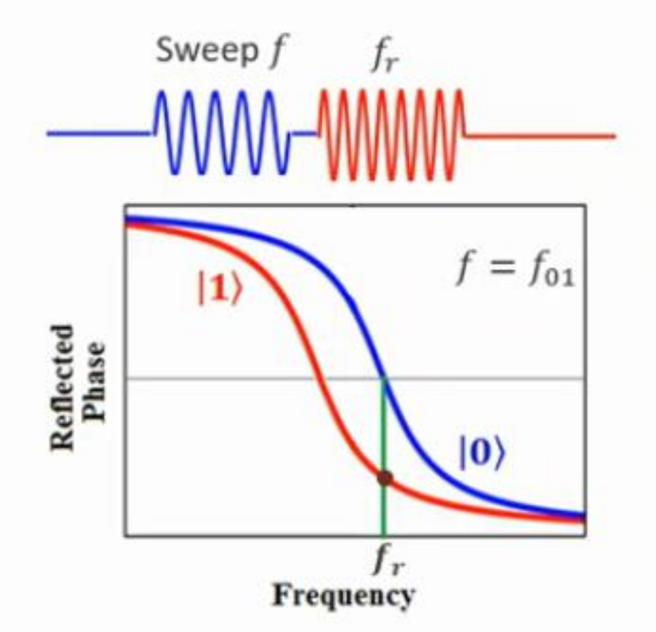
QUBIT MEASUREMENT PROTOCOL

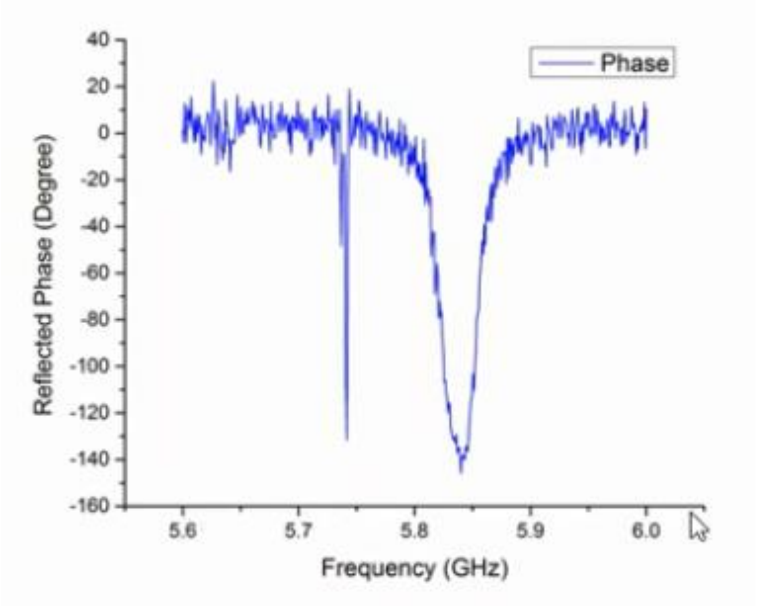


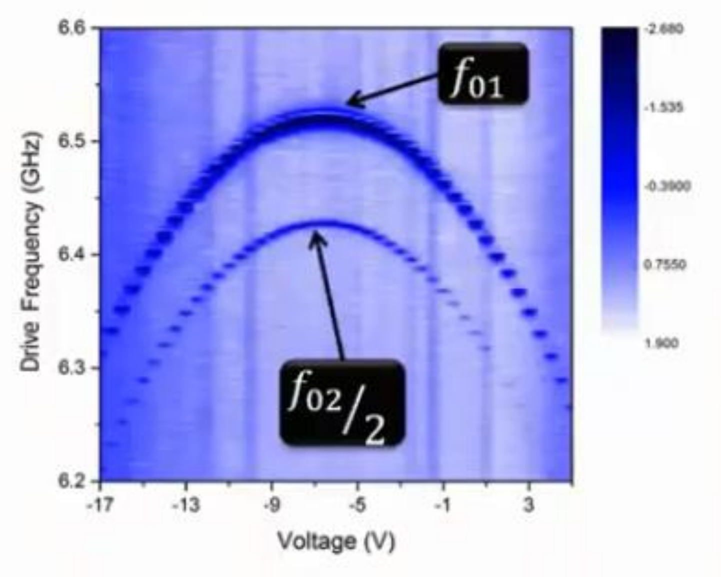
- f_{01} : Qubit frequency
- f_r : Cavity frequency
- Measure Phase / amplitude at f_r

QUBIT SPECTROSCOPY

- Tow tones: one at cavity resonance while sweeping another
- Measure phase of the reflected signal at readout frequency
- Change bias flux and repeat





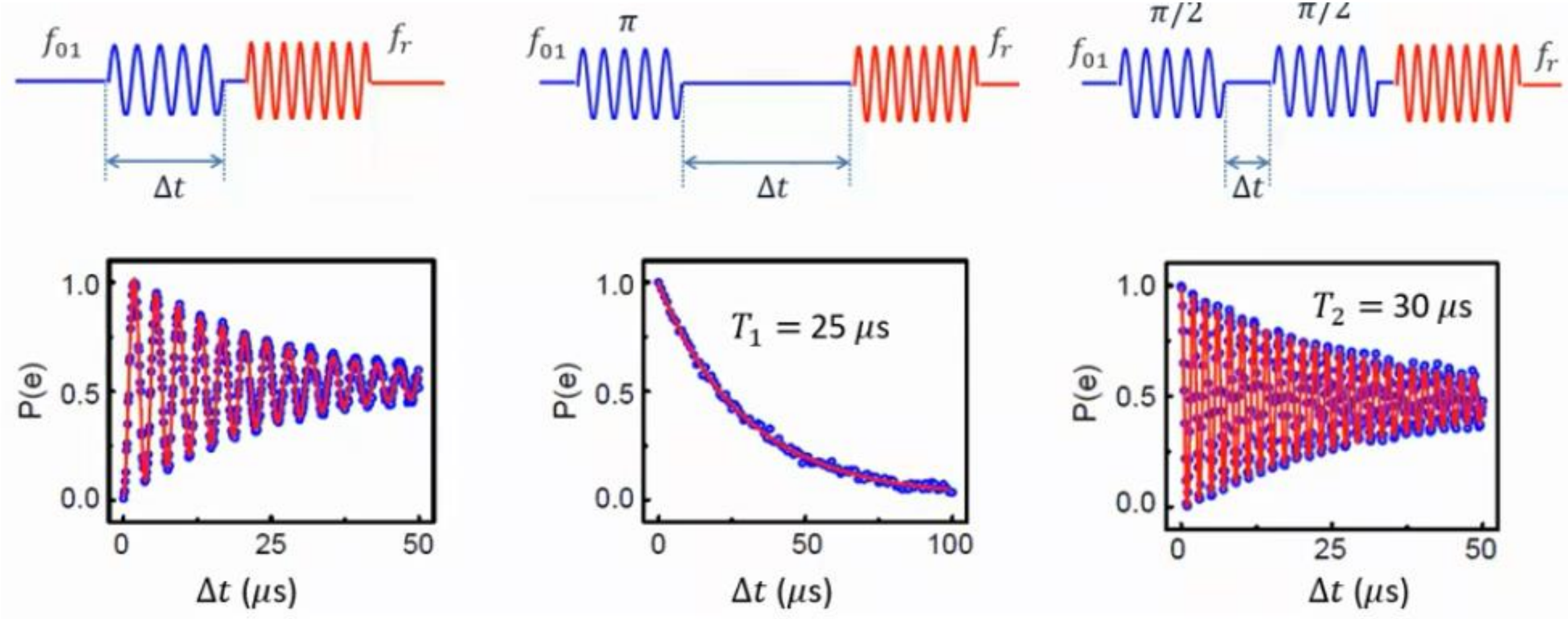


QUBIT CHARACTERIZATION

Rabi oscillation

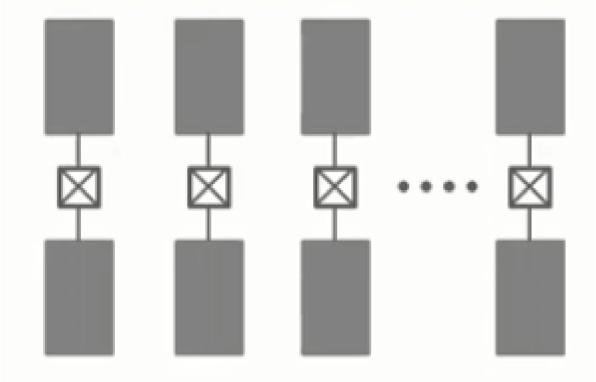
Qubit relaxation

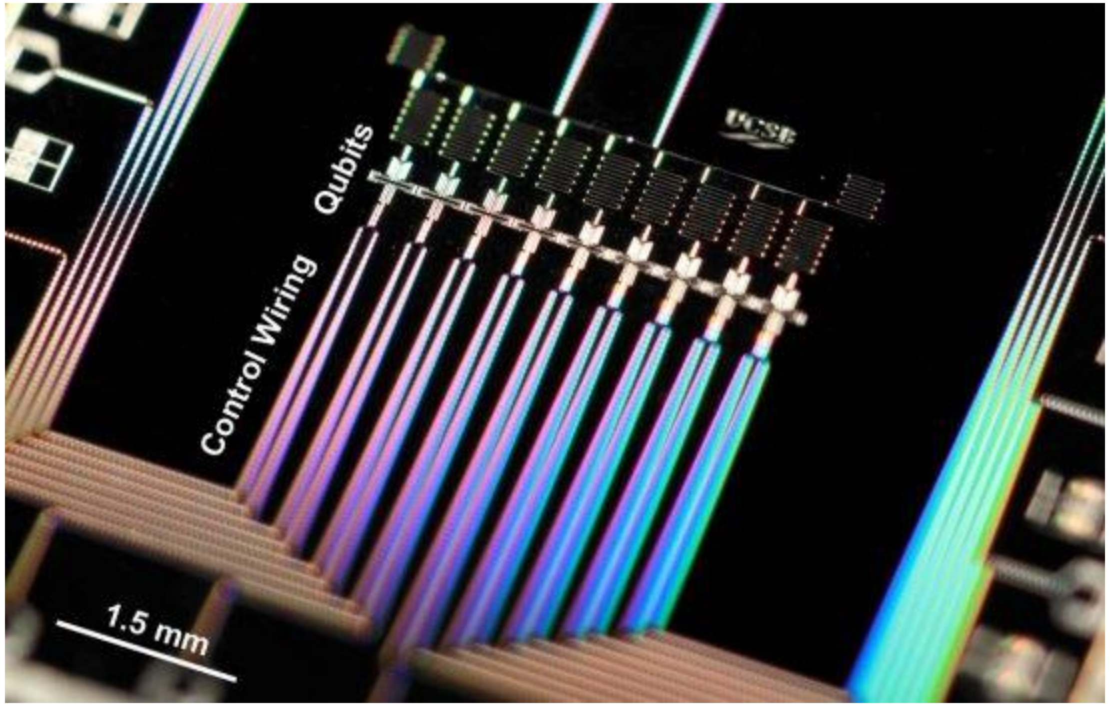
Qubit dephasing



MULTI QUBIT SYSTEM

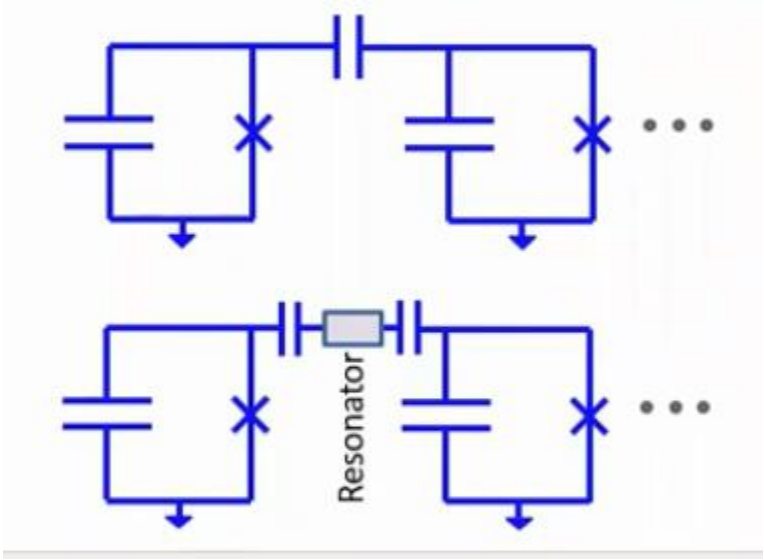
- Two types of multi-qubit architectures are used
- Google 9-qubit chip architecture

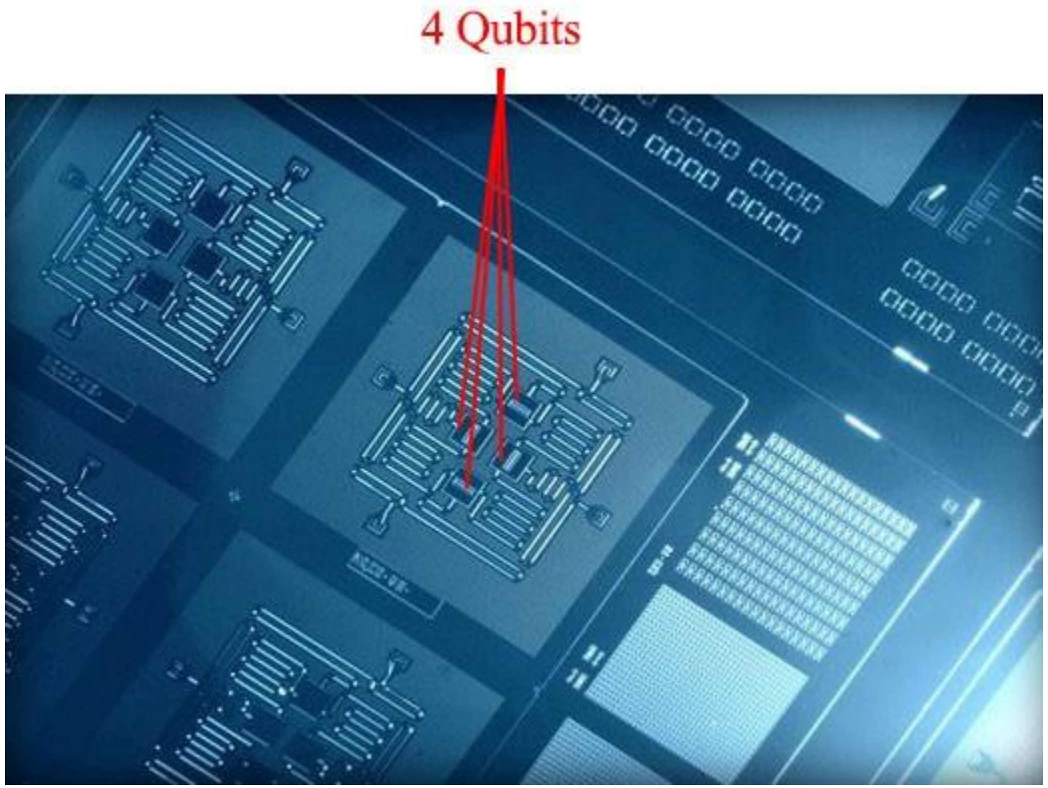




MULTI QUBIT

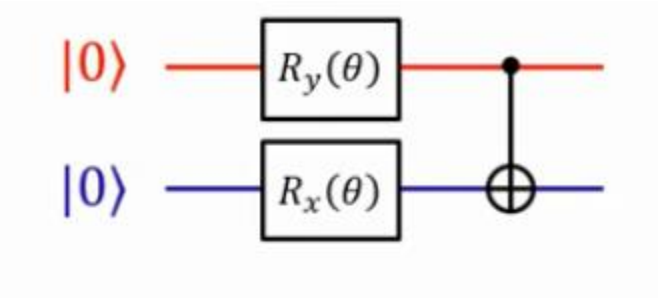
- IBM 4-qubit chip architecture





UNIVERSAL GATES AND QUANTUM CIRCUITS

- Single qubit rotation and CNOT gate from a universal set
- CNOT gate: flip qubit 2 only if qubit 1 is in | 1> state

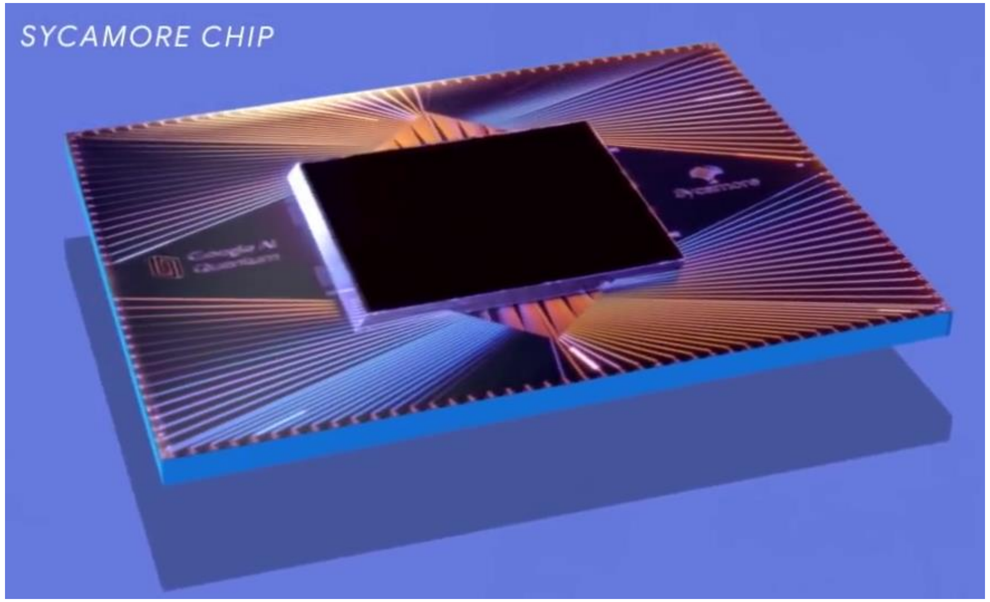


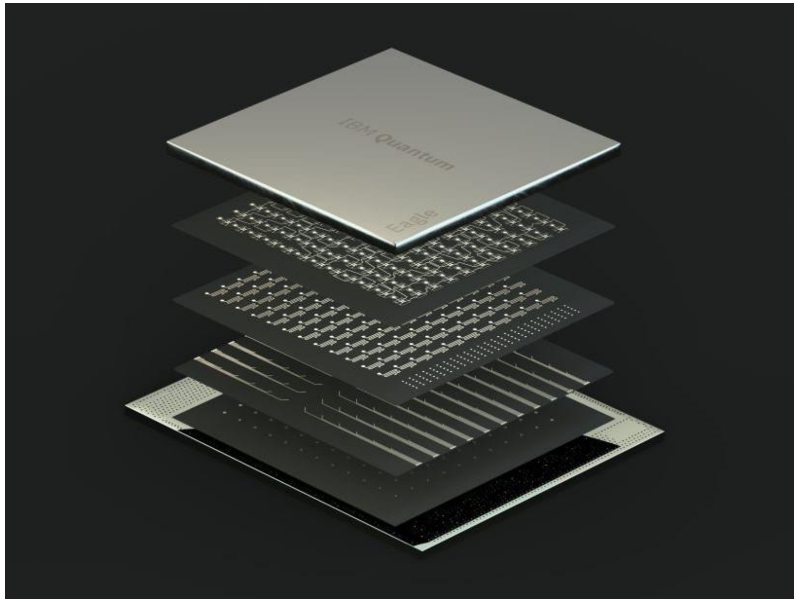
$$|10\rangle \rightarrow |11\rangle \qquad |00\rangle \rightarrow |00\rangle$$
$$|11\rangle \rightarrow |10\rangle \qquad |01\rangle \rightarrow |01\rangle$$

CURRENT SUPERCONDUCTING QUANTUM PROCESSORS

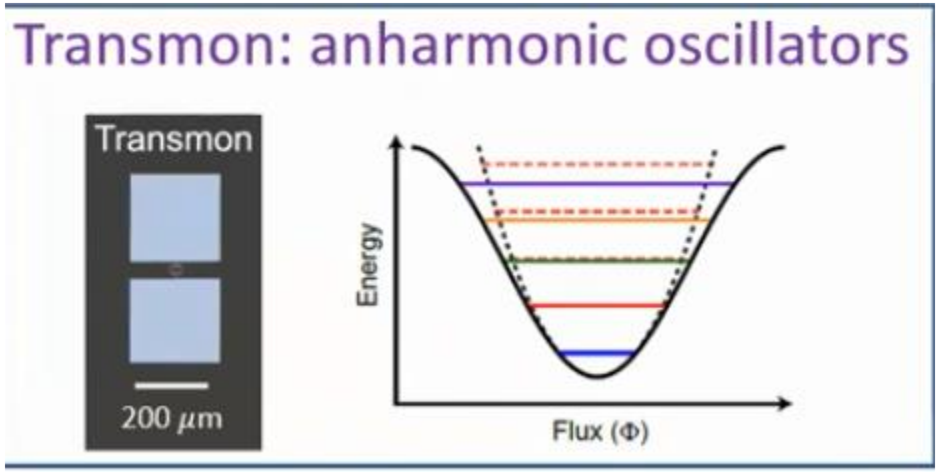
- **Sycamore** is a quantum processor created by Google's Artificial Intelligence division. It has 53 qubits.
- **IBM Eagle** is a 127-qubit quantum processor. IBM claims that it can not be simulated by any classical computer. It is two times bigger than China's Jiuzhang 2. It was revealed on the 16th of November 2021 and is claimed to be the most powerful quantum processor ever made.

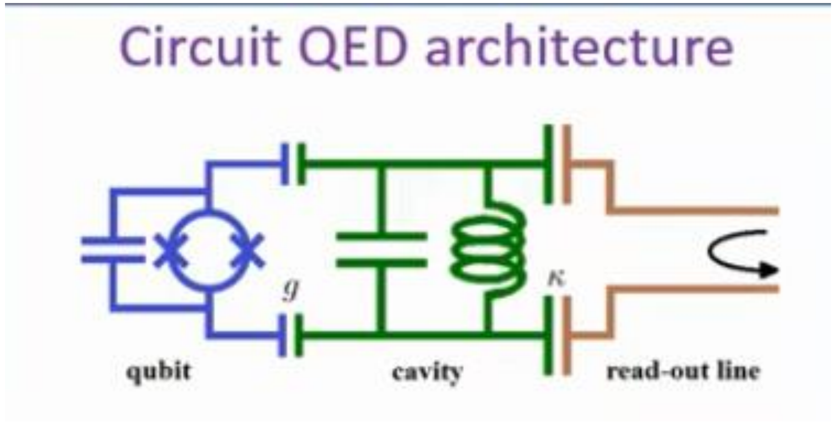
GOOGLE SYCAMORE AND IBM EAGLE PROCESSOR

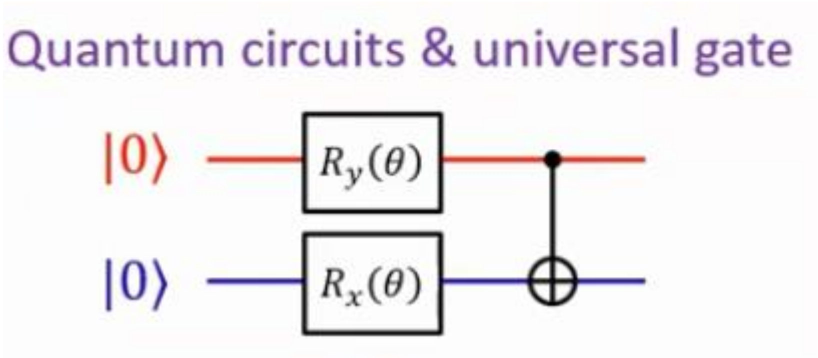


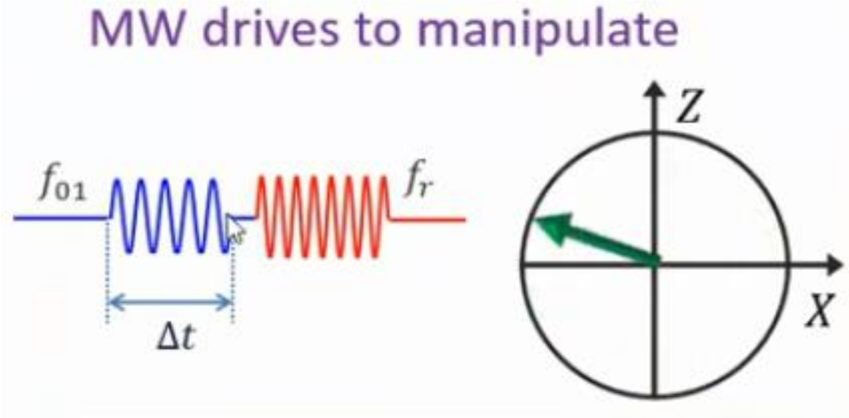


SUMMARY


Transmon: anharmonic oscillators
Transmon
200 μm
Energy
Flux (Φ)


Circuit QED architecture
g
κ
qubit
cavity
read-out line


Quantum circuits & universal gate
$|0\rangle$
$R_y(\theta)$
$|0\rangle$
$R_x(\theta)$


MW drives to manipulate
f_{01}
f_r
Δt
Z
X

REFERENCES

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- 4. Quantum Computation and Quantum Information by Michael A. Nielsen and Isaac Chuang
- 5. Principles of Superconducting Quantum Computers by Daniel D. Stancil and Gregory T. Byrd
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