Notes on the Prof.Girvin's Nobel Pizza Party Lecture: History of Superconducting Qubits

Jean

"Information is physical"

- Quantum information is stored in the states of qubits and can be represented as a superposition of any two (usually the lowest two) energy levels of any quantum system.

- It is important that the energy spacing between the different energy levels are different, so we can control the superposition state of the lowest two levels.

"Engineering is optimizing under constraints"

- The construction of qubits is subject to severe constraints

- (a) We want qubits with long coherence time, but that requires the qubit to be completely isolated from the external environment and remain unobserved.

    - Coherence time is the lifespan of a qubit's quantum state.
    - Longer coherence times allow for more complex quantum calculations before errors occur.
    - Isolating the qubit from the external environment extends coherence time because it blocks external noise.

- (b) We want to be able to change the states of qubits rapidly and read out their values accurately, but that requires the qubit to strongly couple with the environment.

    - Strong coupling with the environment means that the environment can affect the qubit easily.
    - We want this to happen so we can better control the state of the qubit
        - We control the qubit by applying control signals.
        - A strongly coupled qubit responds better to control signals
    - We also want this to happen so we can better read out the qubit's state
        - We need the qubit's state to leave an imprint on something classical.
        - Stronger coupling means larger measurement signal and faster read out.

- The story of qubits is a story of struggle between these two constraints.

"We have a choice between natural atoms & ions vs. synthetic atoms (superconducting qubits)"

- Qubits made with natural atoms & ions include:

    - Neutral atom qubits: individual atoms (typically Rubidium) trapped by laser light
    - Trapped ion qubits: ions held in electromagnetic traps

- Other types of natural qubits:

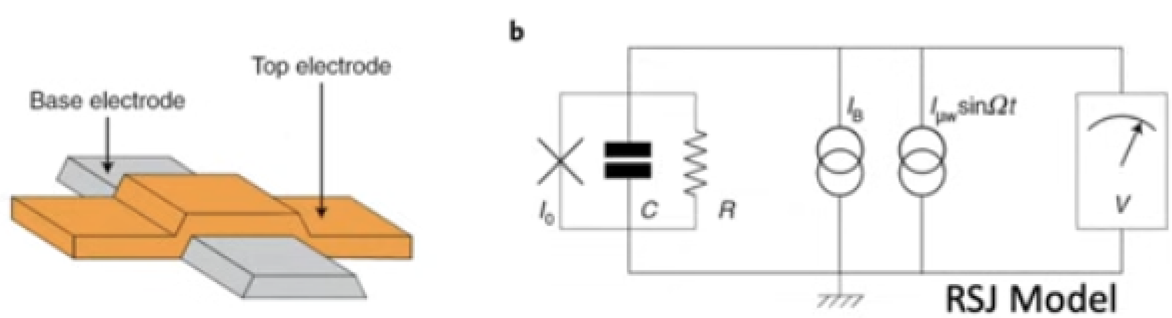
    - Nuclear spin qubits: encoded in the nuclear spin of atoms/molecules
    - Electron spin qubits: utilize the spin-½ of an electron
    - Photonic qubits: encoded in single photons (utilize Polarization/ Path/ Time-bin/ Orbital angular momentum)
    - Etc.

- Superconducting qubits

    - Good things about them:
        - Gate operations can be faster for neighboring qubits (while atoms have to be slowly moved around to perform gates with atoms that are originally far apart)
        - natural to electric circuits
        - strong coupling to electromagnetic fields

    - Bad things about them:
        - work best near absolute zero (have to utilize expensive cooling devices)
        - short coherence times compared to atoms
            - superconducting qubits have 100 microseconds -1 millisecond coherence time, while atoms have 1 second coherence times
            - work best near absolute zero (have to utilize expensive cooling devices)

To understand superconducting qubits we first have to understand the Josephson junction



- A Josephson junction is a device that sandwiches a piece of insulator between two pieces of superconductors.

- You can see it as an “artificial atom” with nonlinear energy levels, i.e., the spacing between its different energy levels is different, which allows us to control its different states.

- Oftentimes a current, called bias current (I_b), is run through the Josephson junction, to control the spacing between its energy levels. The larger the bias current, the smaller the spacing between its different energy levels.

- The physics of a Josephson junction is described by the following 4 equations:

$$\psi \equiv \psi_{top} - \psi_{base}$$

  - In a conventional superconductor, electrons form Cooper pairs, and these pairs condense into a single macroscopic quantum state that can be collectively described by a single quantum wavefunction. This quantum wavefunction has a phase.

  - ψ_{top} is the phase in the top superconductor and ψ_{base} is the phase in the base superconductor.

  - It is the difference between the two phases, ψ, that is important to us, as we will see in the following equations.

$$I_b = I_0 \sin(\psi) + \frac{V}{R} + C\frac{dV}{dt}$$

  - The current of the Josephson junction is composed of 3 parts:

    - The Josephson Current ($I_0 \sin(\psi)$): this is the part of the current carried by Cooper pairs that move without resistance through the Josephson junction. It depends on the phase difference ψ.

    - The Resistive Current ($\frac{V}{R}$): this is the normal resistive current though the Josephson junction (the Josephson junction has resistance).

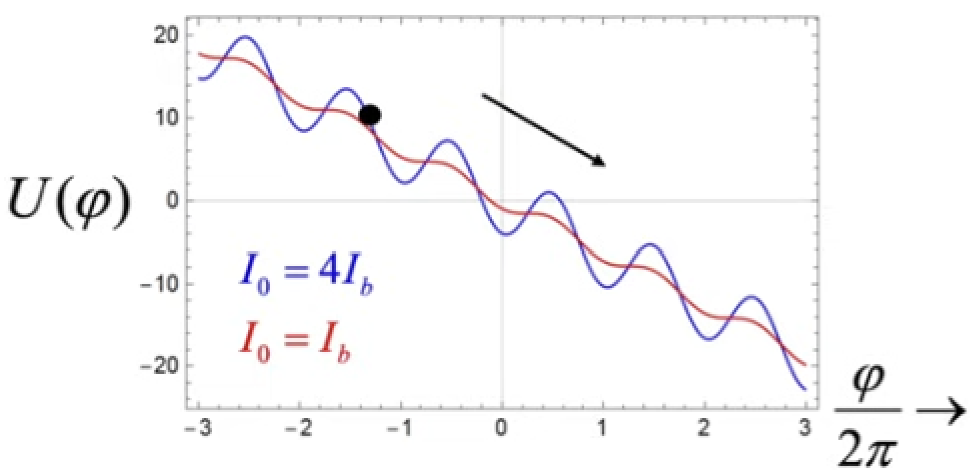
    - The Capacitive Current ($C\frac{dV}{dt}$): the Josephson junction can be seen as a capacitor (two conducting pieces that sandwich a dielectric), so it has a capacitive current (otherwise known as the displacement current, the current that flows through the wires as voltage changes)

$$\hbar\frac{d}{dt}(\psi) = (2e)V$$

- The change in phase difference creates a detectable voltage in the circuit.

$$C\ddot{\psi} = (\frac{2e}{\hbar})[I_b - I_0\sin(\psi)] - \frac{1}{R}\dot{\psi}$$

- It's been known since the 1960s that the phase variable ψ acts like the position of a particle that obeys Newton's equations of motion for classical particles $F = ma$.
    - $C\ddot{\psi}$ corresponds to ma, where C corresponds to mass.
    - $(\frac{2e}{\hbar})[I_b - I_0\sin(\psi)]$ corresponds to $-\frac{dU}{d\psi}$, which is the force due to a conservative potential $U(\psi)$.
    - $-\frac{1}{R}\dot{\psi}$ corresponds to viscous damping.



- The particle can be seen as trapped in a well of a "washboard potential" $U(\psi)$.
- If the particle escapes from the well and starts rolling downhill, it produces a detectable voltage.

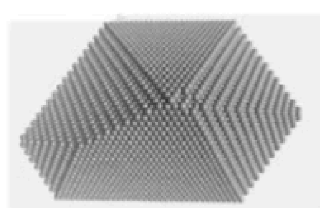
Tony Leggett's Question

- Tony Leggett asked: if ψ acts like the position of a classical particle that is bound by a potential well, is there any possibility that the particle could exhibit quantum behavior?
    - That is, its position is uncertain and described by a wavefunction.

- He also asked: how macroscopic could this particle be if it's quantum mechanical?
    - Michel Devoret's analogy:
        - Level 1: The phase of a superconducting condensate is a macroscopic, but classical manifestation of quantum order, just as the discrete facet angles of a crystal are macroscopic manifestations of the existence of quantum-ordered microscopic objects (the individual atoms).

Level 1

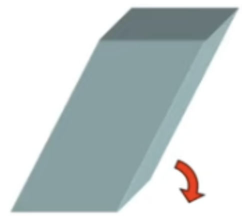
"Pyrite 60608" by Vassil



Arizona State University

        - Level 2: The orientation of the crystal in space depends on the collective center of mass motion of the entire crystal. Only in certain circumstances do quantum effects of this collective coordinate become visible.

Level 2

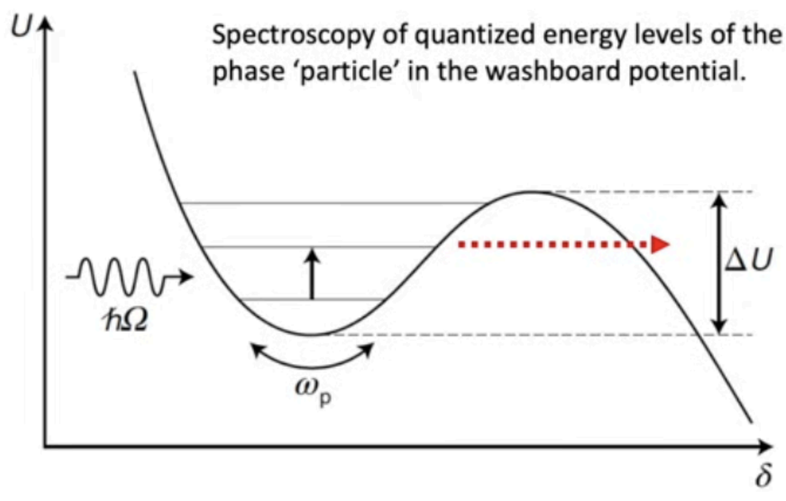


- To build a superconducting qubit, we need visible quantum effects of this collective coordinate.

2025 Nobel Prize in Physics

- The Nobel trio: Clarke, Devoret, and Martinis, showed the quantum effects of the collective coordinate ψ, demonstrating that it is possible to build a superconducting qubit.

- In their papers, they showed that the Josephson junction exhibits energy quantization, which is a quantum effect.

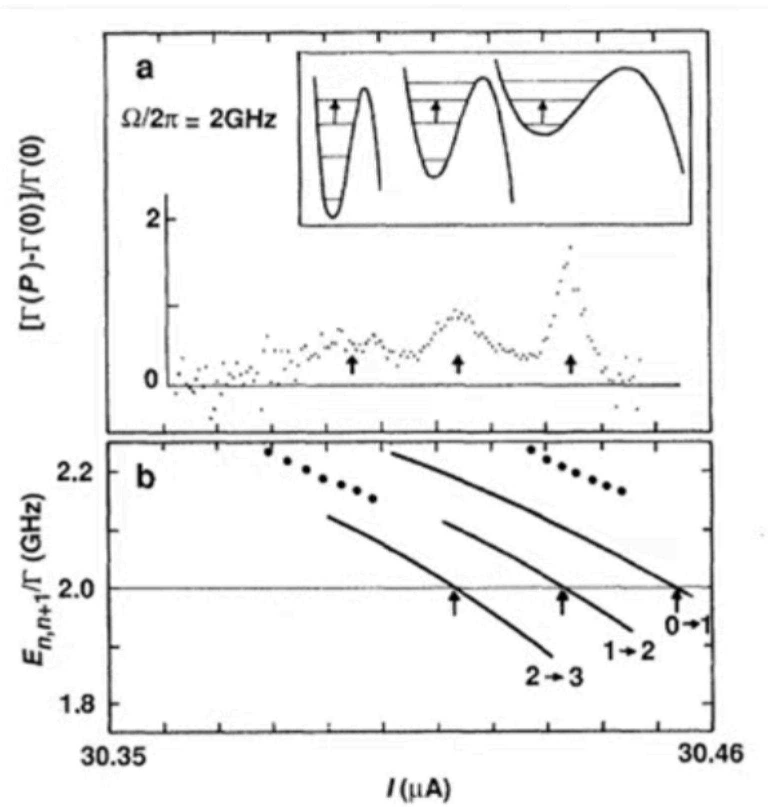


- The Josephson junction has discrete energy levels. When we shine a microwave pulse of appropriate wavelength at the junction, the phase particle absorbs the energy and jumps from the ground state to the excited state.

- As we can see from the diagram above, excited states see a thinner potential barrier than the ground state, so when the system is in the excited state, the rate of quantum tunneling increases.

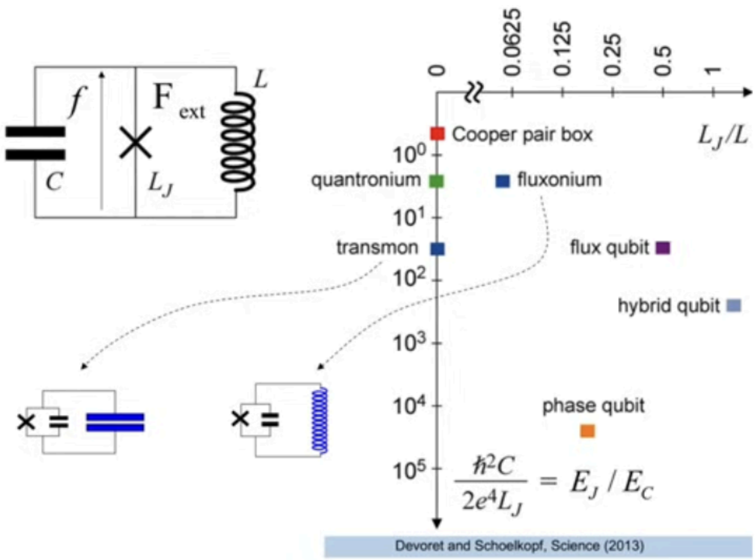
- Since energy levels are discrete, we should observe discrete spikes in the rate of quantum tunneling.

- And this is exactly what the trio observed.



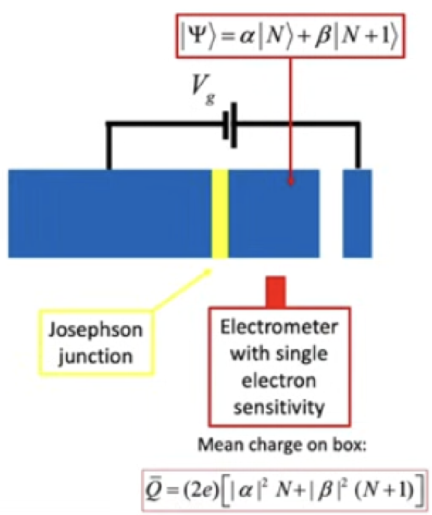
“A Periodic Table of Qubits”

- This discovery led to a periodic table of superconducting qubits.



- All of which consists of 3 basic elements: a capacitor, an inductor, and a Josephson junction.

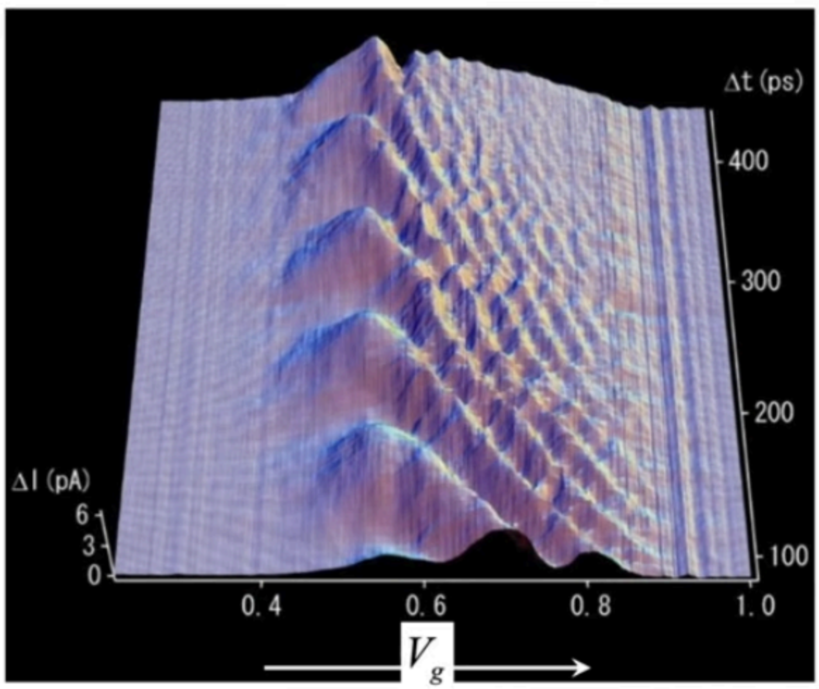
- The earliest qubit is the Cooper pair box, where the number of Cooper pairs on the island correspond to different quantum states. A bias voltage acts as the control knob, allowing the island to have two distinct charge states (N or N+1 Cooper pairs).



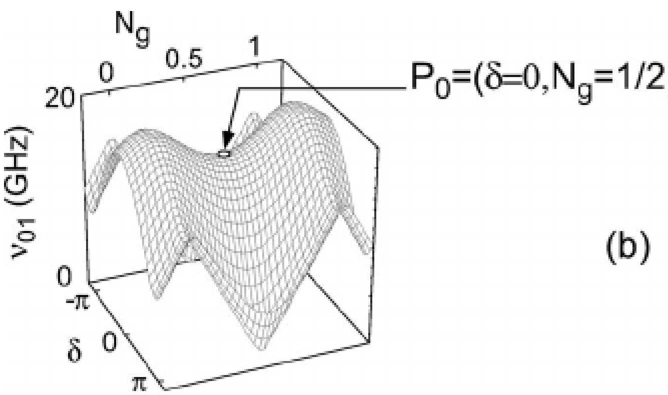
- In 1999, Nakamura and collaborators showed that macroscopic quantum states in a Cooper pair box could be coherently controlled.

- From this graph, we can observe that, if we fix a particular voltage, ΔI moves up and down as time progresses. Since ΔI is proportional to the charge on the island, a periodic oscillation in ΔI indicates that charge tunnels to and from the island periodically. In other words, the island switches between the N-Cooper pair and N+1 Cooper pair state periodically. This periodic switching between the two states indicates that the N and N+1 states are in superposition.

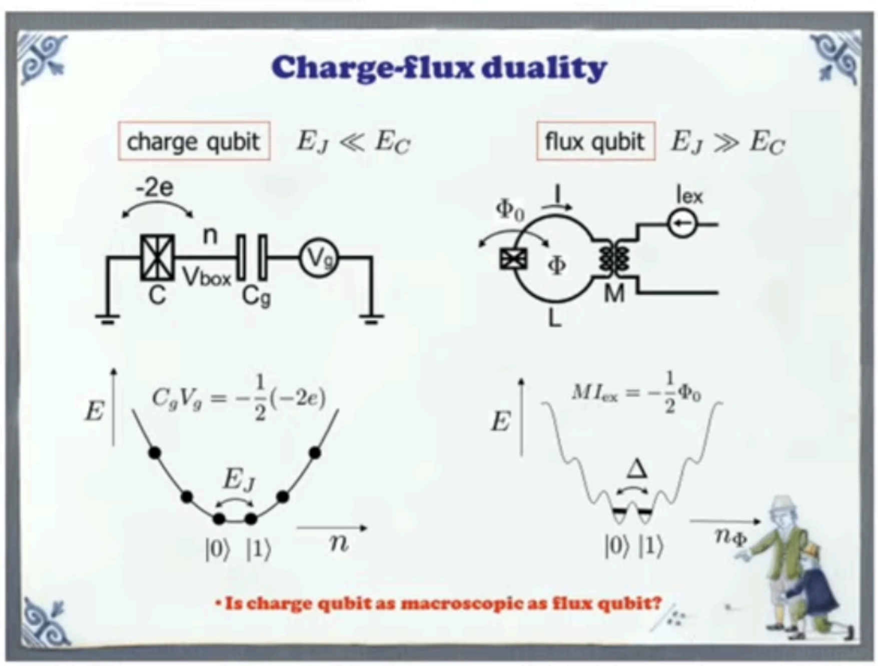
- This confirms that it is feasible to make a qubit with superconducting "artificial atoms."



- In 2001, the Sacaly group invented the quantronium, which improved coherence from the picosecond to the nanosecond timescale. The quantronium also has the property of being insensitive to accidental noise in a certain regime of gate voltage and magnetic field.



- Hans Mooij and collaborators invented the flux qubit, a superconducting loop with Josephson junctions whose two quantum states correspond to clockwise and counterclockwise persistent currents, which are coherently coupled by quantum tunneling.



Courtesy Y. Nakamura

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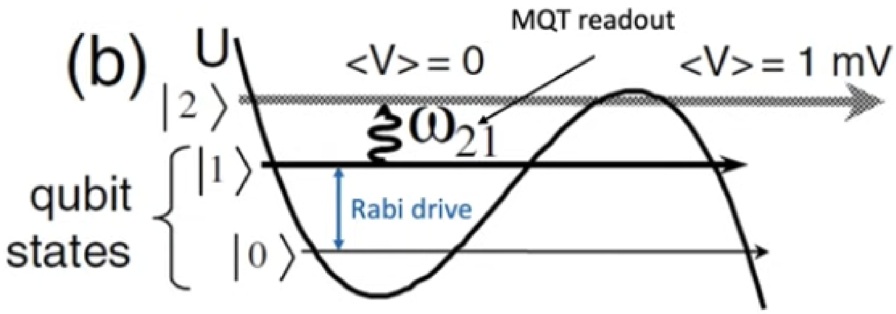
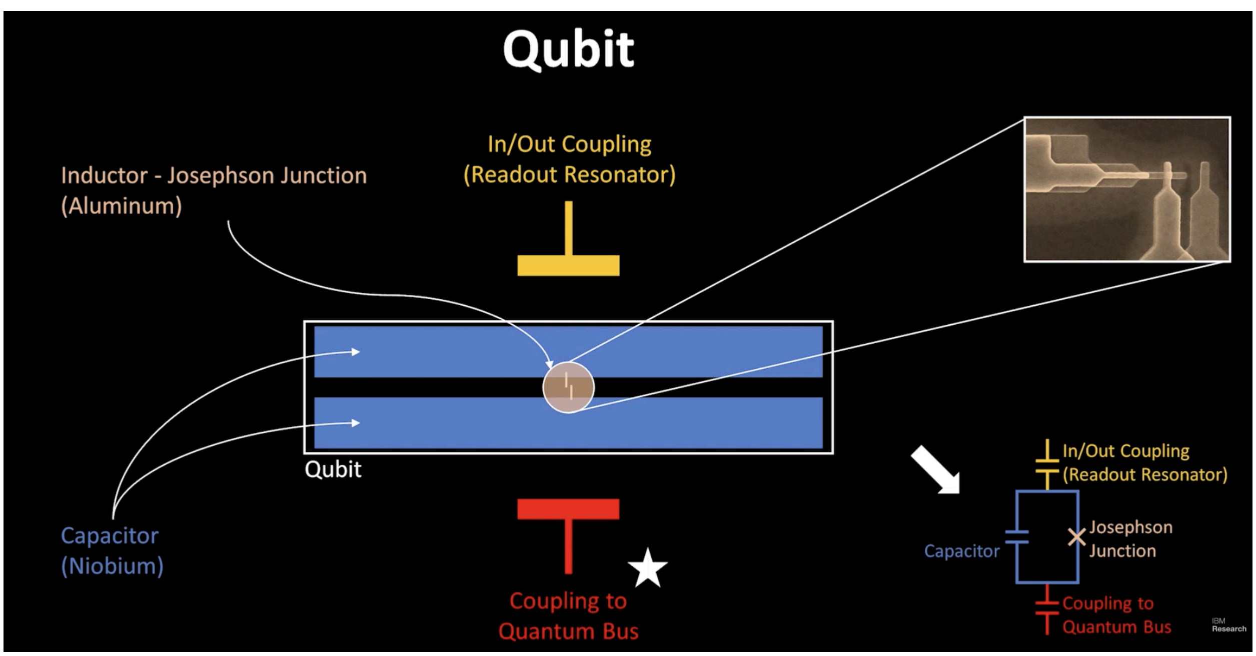
- John Martinis constructed the phase qubit, such that we can manipulate the lowest two states and read it out by applying a tone such that if it were in the excited state, it would jump to the next excited state, tunnel out, and produce a large voltage. This large voltage gives high read out fidelity, but the large voltage was later discovered to be destructive of the coherent states of nearby qubits.



- The qubit in widest use today is the transmon, which consists of two antennas connected by a Josephson junction.
  - Its very large antennas reduce the effect of stray low-frequency electric field noise that could disturb the energy difference between the ground and excited states, making the qubit more stable.
  - It also couples well with microwave signals, which makes the qubit easier to control.



“There’s been orders of magnitude progress in improving the qubit coherence lifetimes over the last 20 years”