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Artificial Atom Circuit

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Introduction

Atoms are very small to work with, moreover they are very fragile and complex, so one has to look for an alternative means which could replace them. It is hard to mimic properties of natural atoms with ease, but, through in depth research and hard work, Scientists have started to crack the code. Many ways have been deduced to tackle such problems, which lead to realisation of artificial atoms.

Various Physics concepts such as Oscillators, Superconductivity, Electrodynamics etc. have been employed to make an artificial atom or a circuit capable enough to mimic the properties of an atom.

Physics of Artificial Atom

A quantum bit or qubit has two bits in superposition, namely |0> and |1> bits. These could also be referred to as the 'ground' state and 'excited' state. In any real/natural atom, these states have fixed energy associated with them. When they move between ground and excited states an electromagnetic wave of a particular frequency is either emitted or absorbed depending on transition direction, wherein the associated energy of the wave equals the energy difference between those ground and excited states. Atoms being the entities of the microscopic domain, on the other hand in the macroscopic world, an Inductor-Capacitor circuit (or an LC circuit) displays a similar phenomenon of transitions between the distinct energy states, and further could exist in superposition of those states. The oscillation of electric dipoles with periodic change in electric and magnetic fields leads to the formation of Electromagnetic waves of a particular frequency. However, there is one major difference, in an atom, the difference between the energy of two consecutive orbits decreases as we move to higher energy levels, whereas the energy gap throughout all the states is constant in LC circuits. The varying energy gaps are vital for uniquely identifying two states of particular energy separation in an atom for realisation of qubits with no leakage of information to other states. Therefore, to accurately mimic an atom, it must induce non-uniformity in the energy gaps between the states *i.e.*, "non-linearity" in an LC oscillator. To perform this task, one could replace the Inductor in LC circuit with the Josephson Junction that acts like an inductor. Josephson Junctions are made up of sandwiching a thin layer of insulators between two superconductors, wherein the superconductivity is exhibited with the transition of paired electrons called as Cooper pairs from one semiconductor to other via insulator. The superconductivity occurs at much lower temperatures about -273°C, which also assists in reducing errors due to heat. Having created an "Artificial" atom based on superconductivity, one could proceed to turn it into a qubit known as Transmon that could be further used to undertake Quantum Computing. The circuit-like structure of Transmon allows it to integrate with other qubits to create a multi-qubit quantum computer. Obtaining quantum behaviour using superconducting circuits is the only method, as artificial atoms could also be realised by various other means, for example using particles of a semiconductor that have a diameter of about a few nanometers.

Superconducting Qubit

Let's recall that, the ground state of an atom is being referred to as 0 ket (denoted as |0>) while the first excited state is 1 ket (denoted as |1>). The change of electron's state within an atom is achieved by supply of suitable external energy, which is possible with an excitation, *i.e.*, by providing energy E=hv, whereas the de-excitation also leads to change in state by releasing the energy. In practicality, this transition of electrons from one energy state to another is accompanied by the absorption or dissipation of energy.

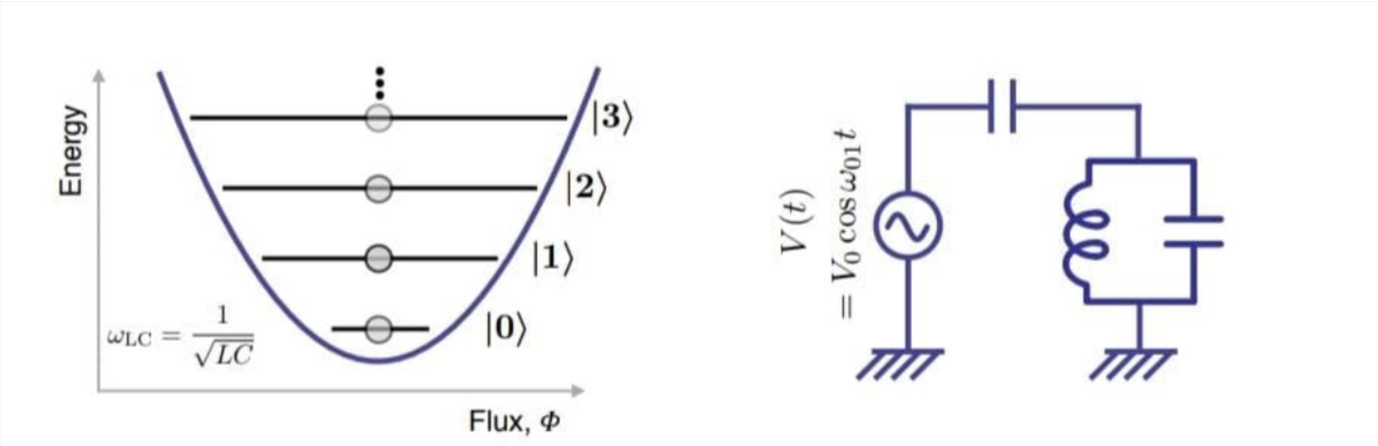
It is possible to have a superposition of ground and excited states by inducing oscillations of electrons between the atomic states called Rabi Oscillations. On the other hand Superconductivity being a quantum phenomenon and could only occur at minute length (or also called the quantum scale), could be a exploited to have a coexistence of two superconducting states, further system could undergo transitions among the states, in turn leading to superposition states just like qubits realised from natural atom's oscillation between ground and excited states.

In Classical Physics we come across various oscillations, *i.e.,* damped, periodic or harmonic etc. The real-life scenario of small oscillations is encountered through harmonic oscillations, wherein for example a particle oscillating performs a to and fro motion from the one extreme energy point to another, in a sinusoidal manner. This kind of oscillation could be even observed in an electronic circuit's charges too. In high School Physics, we have learned how oscillations of charge are formed through an LC-circuit. Here the charge passing through the inductor(L) and capacitor(C) performs a harmonic oscillation as a charge on capacitor given by: Q(t) = Q(0) cos(wt), where w = 1/Square-root(LC) angular frequency and Q(0) is the maximum charge accumulated on the capacitor. The total energy of such a system is equal to the sum of the potential energy and kinetic energy of an equivalent spring-mass system.

Here, the Potential energy(P.E) = 12k x2 where k=mw2equivalent to spring constant of spring-mass system, and the Kinetic energy(K.E) = 1/2 mp^2, where 'p' is the momentum of oscillating charge, hence the Total energy (E) = P.E + K.E = 1/2k x^2+ 1/2 mp^2

Similarly in Quantum Physics, the energy of any atomic system is defined as the Hamiltonian operator (H), which is expressed as by replacing momentum and position variables with their counterparts in the form of operator H= 1/2k x^2+ 1/2 mp^2

Using above Hamiltonian formalism, similarities between the harmonic oscillation among quantum states with the LC oscillations, wherein the oscillations occur among the various charge and discharge states of the capacitor contained in LC circuit. Therefore the Rabi oscillations could be mimicked by the circuit as shown below in the diagram.

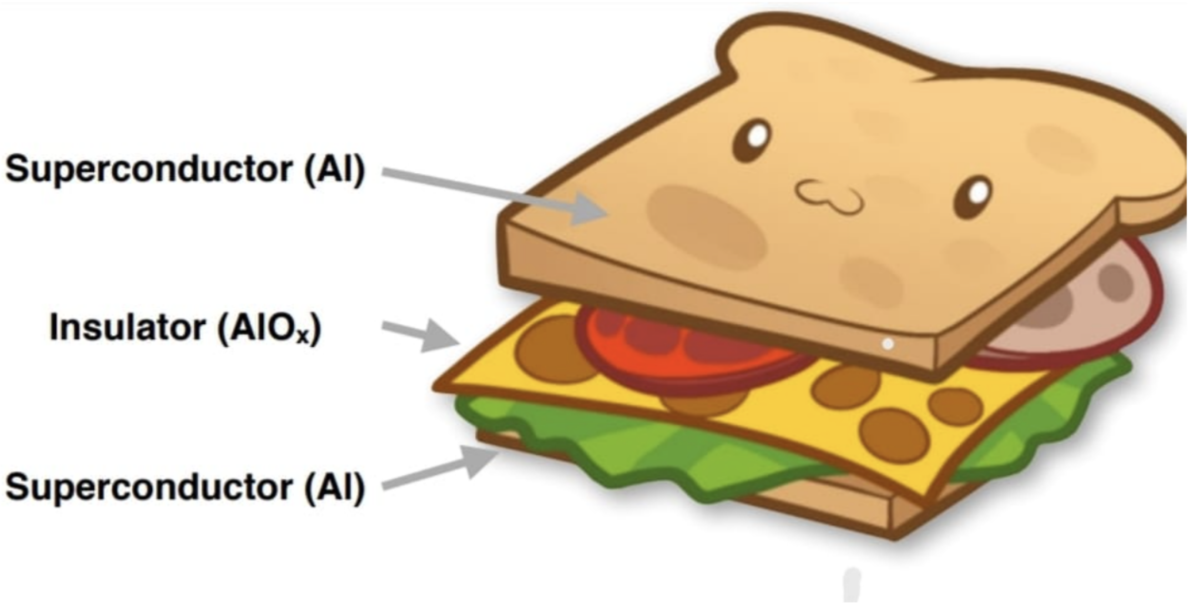


As one could see, the possible Rabi oscillations among the various energy states realized using the LC circuit could be controlled by some external voltage V(t) obtained from a microwave source. However, as there exists equal energy separation among the LC circuit states, yet this LC circuit based superposition could not be contained between any specific pair states.

Even the room temperature is enough to drive the system out of the specific superposition as the room temperature could supply thermal energy more than energy gaps of the states.

The problem that arises is that it is not still replicating an actual atom, rather it is still giving us the superposition of replicated energy levels, *i.e.*, the superposition of |0>, |1>, |2>, and so on. Hence the Hilbert space is not same as that of the atom, thus leaving in the leakage of qubits.

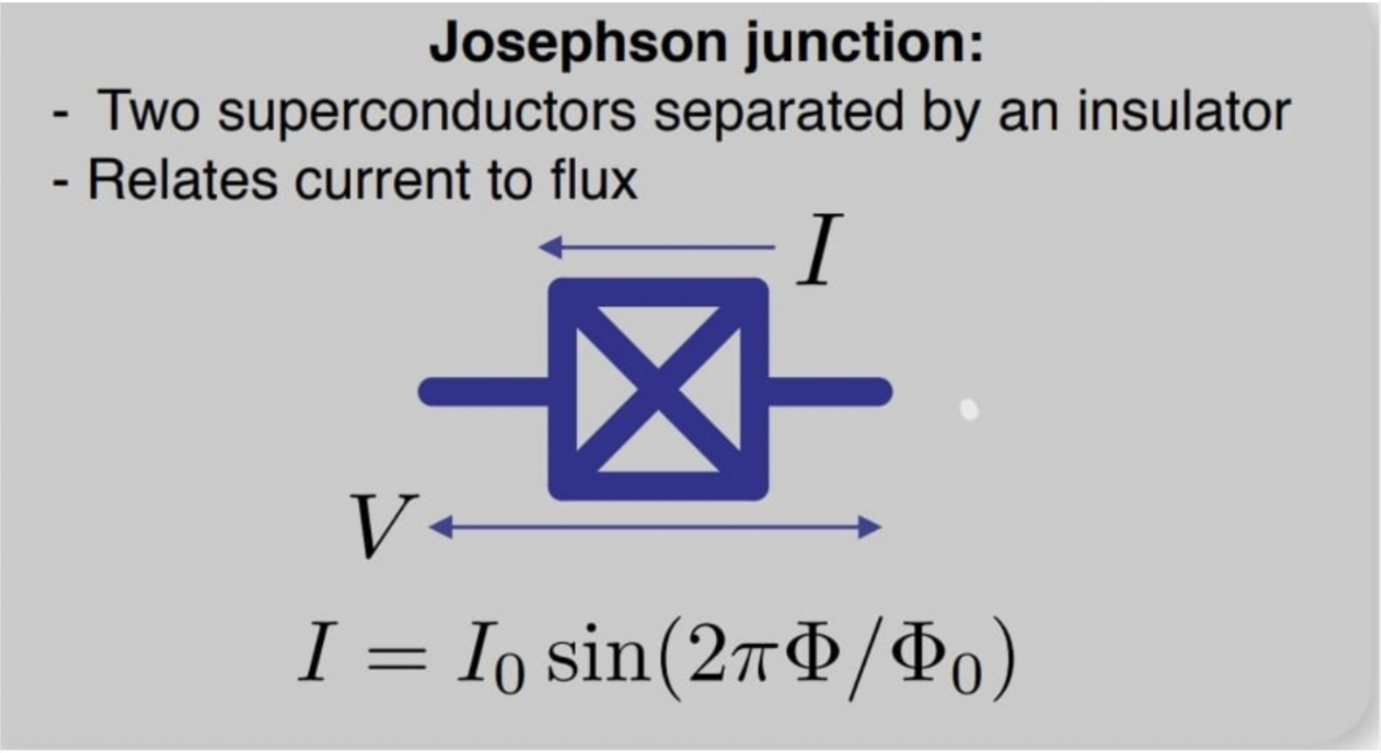
To overcome this problem, a Josephson junction invented by a British theoretical Physicist by name Brian David Josephson during his doctoral studies can be used instead. Josephson junction is constructed by sandwiching a thin layer of insulators between two superconductors, and this novel idea led to the Nobel prize in 1973.



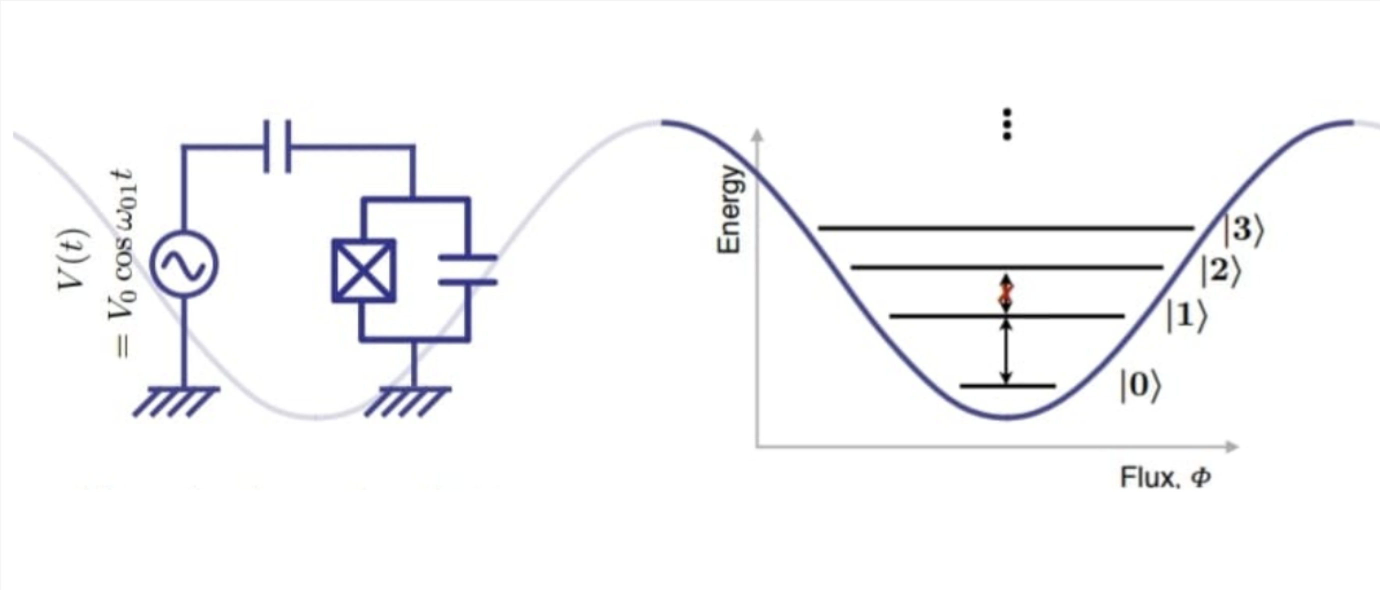
We know in the LC circuit that the inductor(L), there involves a linear relation between magnetic Flux (*Φ*) and the current as ***I = Φ/L***. The total energy in terms of Hamiltonian operator of the LC circuit would be the sum of energy stored in capacitor and inductor in the form of charge accumulation and magnetic field, respectively:

$$\hat{H}=\frac{1}{2}C\hat{V}^2+\frac{1}{2}L\hat{I}^2$$

wherein the terms are similar to classical harmonic oscillator potential and kinetic energies. Various possible energy states of the system would be represented by the ladder steps that exist within the parabolic potential dictated by the second term similar to potential energy of the classical oscillator. As long as current is a linear function of flux, the possible energy states are placed equally in the parabolic potential. This being the reason for the same level of harmonic oscillation and resulting in an equal spacing between the resulting energy levels. While on the other hand, the Josephson junction which acts like an inductor gives the current and flux relationship in a non-linear manner, as shown below.

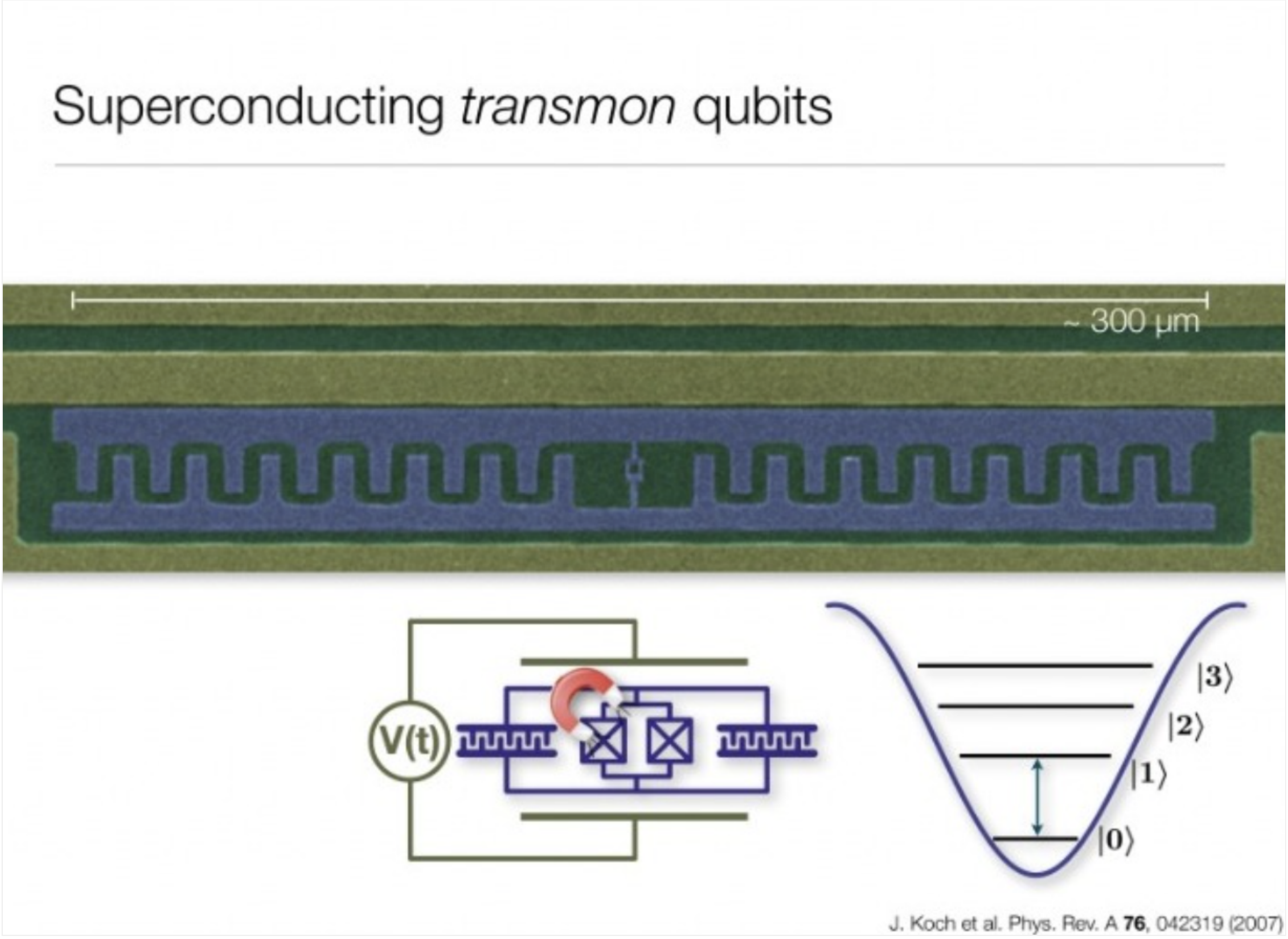


Inclusion of Josephson junction, alters the nature of potential energy from a simple parabolic to a conine function in magnetic flux . Once the potential curve gets converted to cosine function, all the equally spaced energy levels which were extended to infinity earlier, would gets squeezed to much smaller vertical domain, and that leads to unequal spacing between the energy levels, hence replicating an atomic levels to form an artificial atom which we wanted is shown below in the diagram.



Finally, we have arrived at a circuit that replicates an atom and hence is being used as a qubit.

Further advancements in the LC circuit with Jospheson junction lead to development of a “Transmon”, which is a unique type of superconducting charge qubit that was designed to have reduced sensitivity to charge noise. The transmon was developed by Robert J. Schoelkopf, Michel Devoret, Steven M. Girvin and their colleagues at Yale University in 2007. Its name is an abbreviation of the term ***transmission line shunted plasma oscillation qubit***; one which consists of a Cooper-pair box "where the two superconductors are also capacitively shunted in order to decrease the sensitivity to charge noise, while maintaining a sufficient anharmonicity for selective qubit control".



The transmon achieves its reduced sensitivity to charge noise by significantly increasing the ratio of the Josephson energy to the charging energy. This is accomplished through the use of a large shunting capacitor with more surface area of the capacitor plates having merged two comb structures. The result is energy level spacings that are approximately independent of offset charge. Planar on-chip transmon qubits have $T1$ coherence times ~ 30 µs to 40 µs. By replacing the superconducting transmission line cavity with a three-dimensional superconducting cavity, recent work on transmon qubits has shown significantly improved $T1$ times, as long as 95 µs. These results demonstrate that previous $T1$ times were not limited by Josephson junction losses. Understanding the fundamental limits on the coherence time in superconducting qubits such as the transmon is an active area of research.

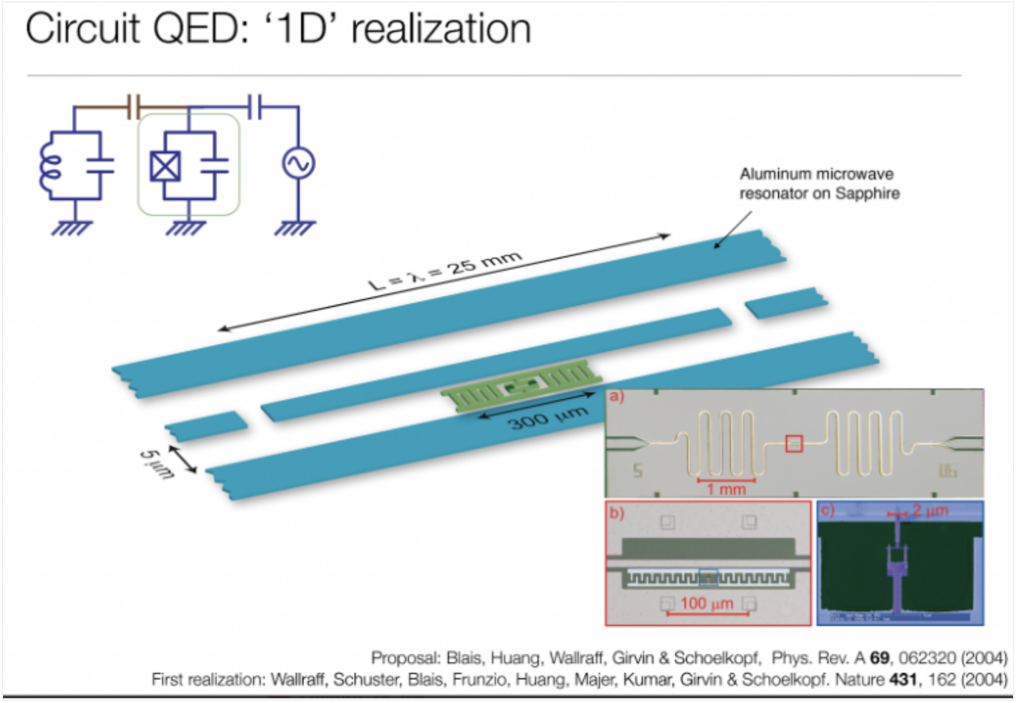
Circuit QED

Now we have seen how a qubit can be formed with the help of a Josephson junction, a capacitor and a controlled voltage source. Let's lookout for the circuit combination that can be formed, which will lay a foundation for the qubit architecture.

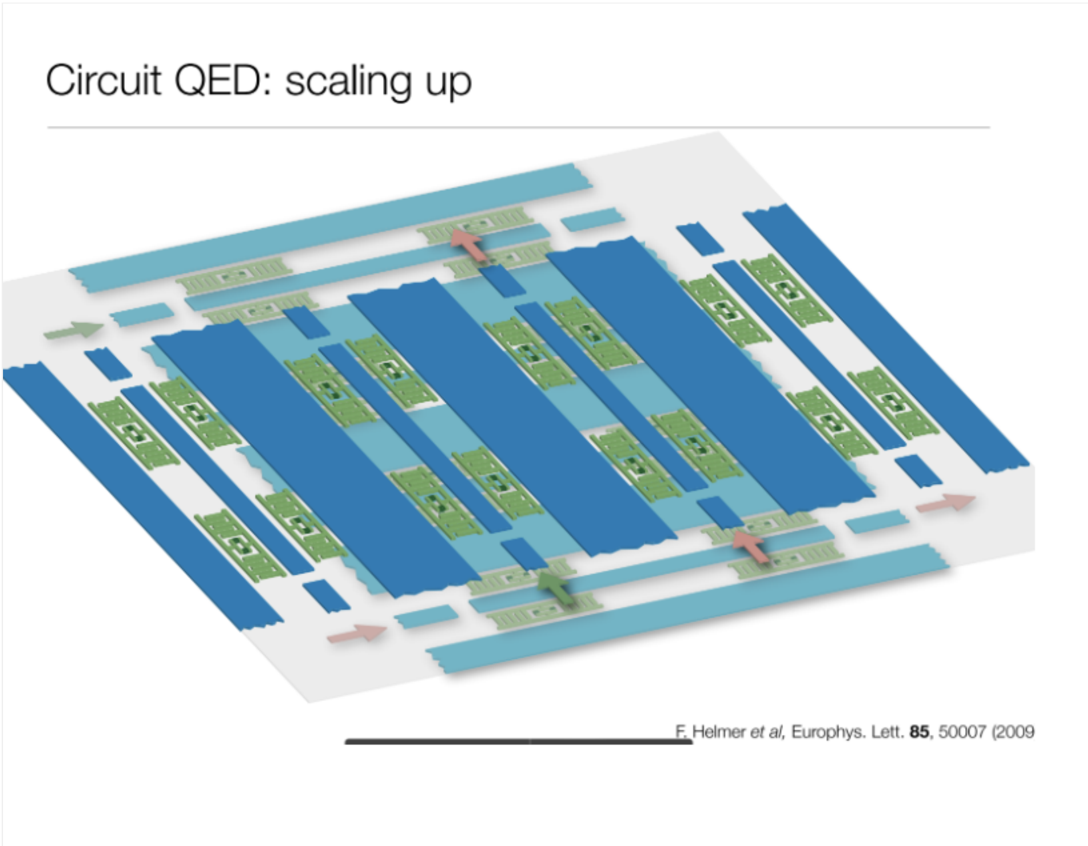
Like classical computing using transistors (MOSFETS circuits), this Josephans junction along with a capacitor forming a nonlinear LC circuit could be analogized as a transistor on the Quantum Computers.

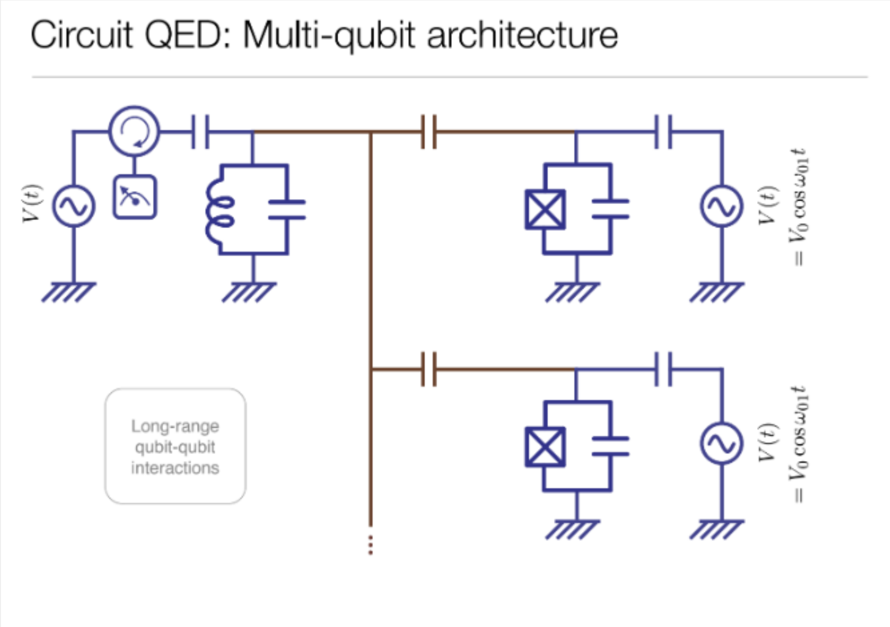
In classical computers the transistors are either being operated through current or voltage (in case of MOSFET). Here the single qubit is being manipulated/operated through microwaves (an electro-magnetic wave). These waves are the set of inputs given to the transmon. This set of input is circulated throughout the artificial atoms contained in the cavity. The cavity acts as a quantum bus, which helps in communication between qubits and forming multi-qubit architecture. The flow of signals are manipulated through different frequencies and use of different capacitors helps by activation of the qubit information at that instant.

The diagram below is the realiation of a single qubit in 1D.



Here, the cavity through which the microwave could travel and interact with the transmon to give a particular output as required. Now for various qubits to interact with each other one could scale up this qubit structure and form a multi-qubit structure by linking cavities of various transmons (*i.e.,* Quantum Bus) as shown below:





We can also realise the transmon circuit multi-qubit architecture in a classical manner as shown in the above figure.

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1. artificial atoms - Bing
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4. **Content** Reference

1 1

abhanaikim2604

Great article! Pretty interesting 🤔
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GaurangBelekar

Thank you ma'am!!
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A **AdhavRajesh**

I agree! it was very interesting!
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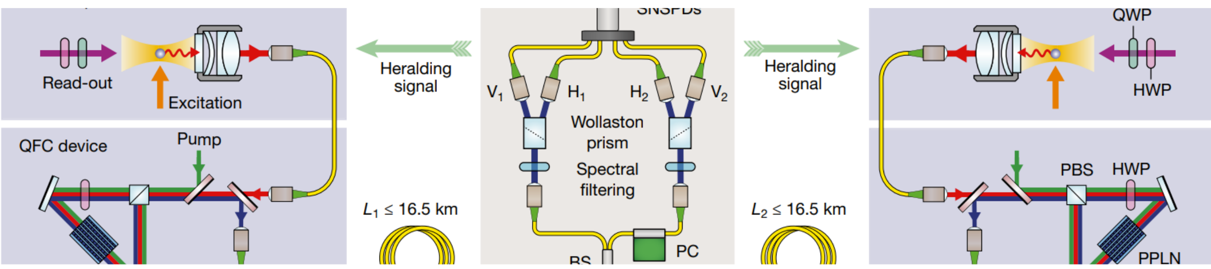

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