QC — How to build a Quantum Computer with Superconducting Circuit?

Jonathan Hui
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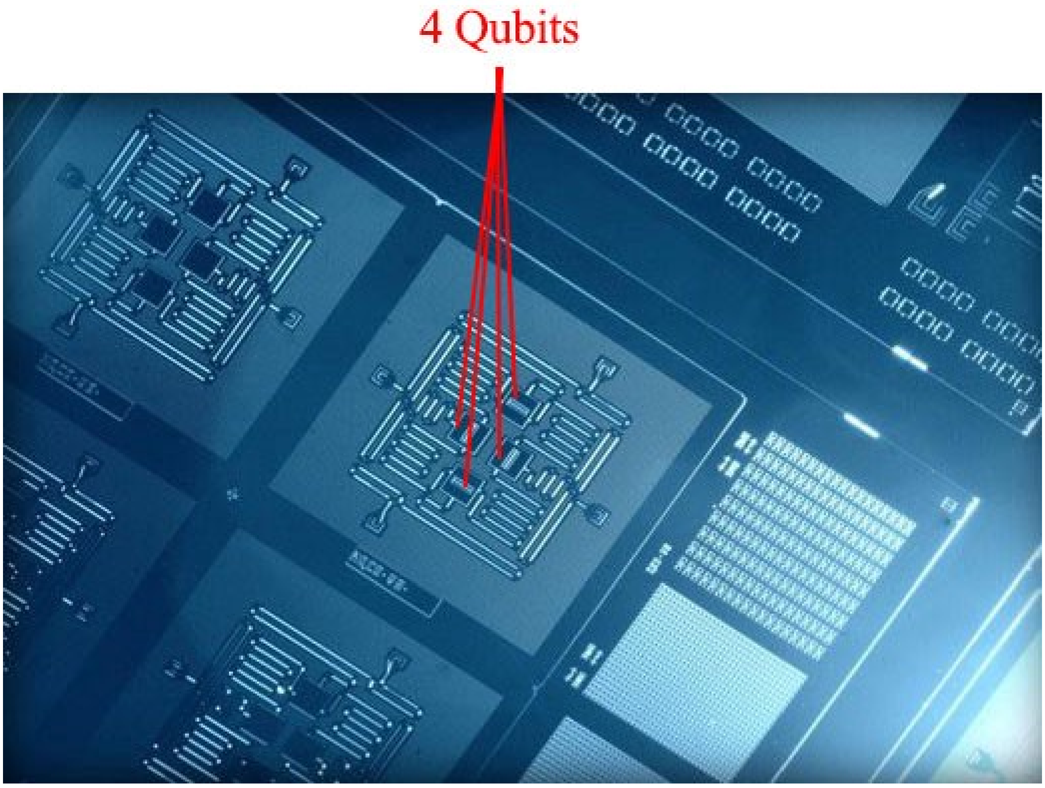
In quantum computers, many university research groups bet on trapped ions. But the industrial giants do not necessarily agree with that. Indeed, the superconducting circuit seems to be their top choice. Ironically, some of those decisions are not completely based on technical merit. Many universities have strong expertise in Atomic Physics and have the know-how on manipulate quantum information at the atomic level. But scaling up the solution is not necessarily their strength. On the other hand, many industrial corporations acquire semiconductor experts with years of experience in scaling systems. Instead of using atoms to store quantum information, engineers print artificial "quantum system" in a circuit for the qubits (where quantum computers store information- please spend some time on qubit if you are not familiar with it). Therefore, different organizations may adopt different approaches depending on their expertise. In this article, we will focus on the superconducting circuit and reserve another article for the trapped ion quantum computer. But we will have a high-level overview for some of the most promising approaches at the end of the article. Nobel prizes were given (including Superconducting, Josephson Junction) for theories mentioned in this article. So feel free to skip some details if it is not explained thoroughly.

Quantum Processors

We have many ways to implement qubits. We can explore the quantum property of atoms, or we can build an artificial quantum system. A trapped ions quantum computer uses lasers to change the energy level of laser-cooled ions trapped in an electric field. On the other hand, IBM Q quantum computer holds superconducting circuits to create a quantum system.

In a superconducting circuit computer, the quantum processor is the soul of the computer. The square block below holds four qubits.



Modified from IBM source

This processor is host at the bottom of a cylinder below.

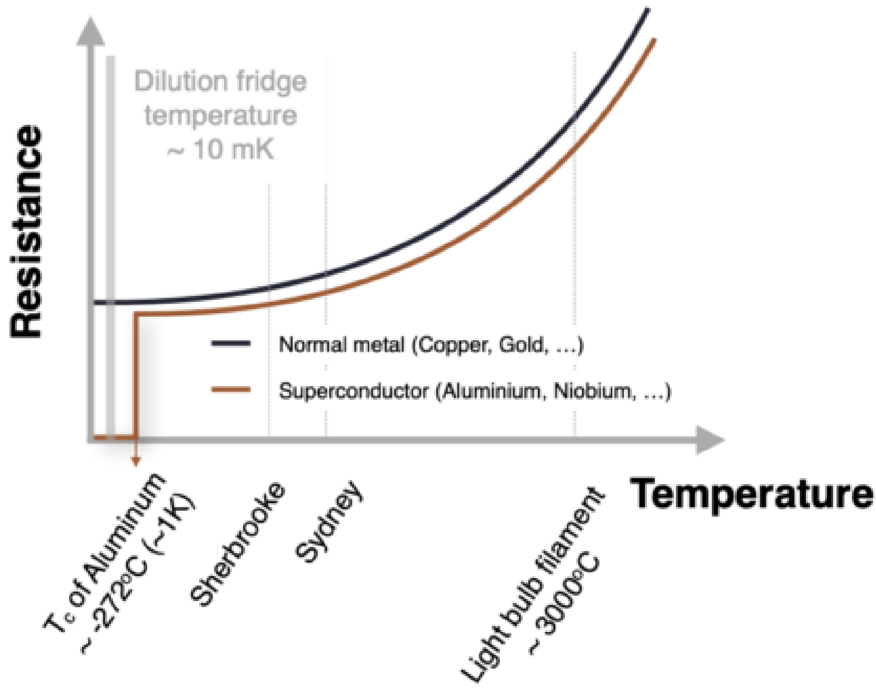
Left (Inside IBM 50 qubits quantum computer) Right (enclosing the quantum computer)

As often, to operate at the precision of the quantum scale, we need to go big. The IBM Q contains cables to send microwave pulses at different frequencies and durations to control and to measure the qubits. The qubit information is easily destroyed by thermal heats and other disturbance from the environment. To isolate the qubits, the computer contains a dilution refrigerator to cool down the quantum processor to 15 miliKelvin. In addition, the circuitry contains superconductor requiring an extremely low temperature to operate.

IBM Q (IBM Quantum computer)

Superconductor

We don't want our circuitry implementing the artificial quantum system to have resistance. Otherwise, it will dissipate energy and destroy the quantum information. So it is constructed with superconducting material which has zero resistance when cooled below a certain temperature (about 1K° for superconducting aluminum).



When the temperature drops below a critical value, two electrons form a weak bound and becomes a Cooper pair that experience no resistance when traveling through the metal. The pairing opens a gap in the energy state, which any excitation requires some minimum energy. This gap leads to superconductivity since not any random increase in energy is allowed. Many excitations such as scattering of electrons (resistance) that lead to an illegal energy state are not allowed (yet another non-intuitive behavior from quantum mechanics).

Source

Superconducting circuitry

We build semiconductor circuits for the qubits. Each qubit is actually an LC circuit, an inductor, and a capacitor. We manipulate its energy state to represent a superposition of $|0\rangle$ and $|1\rangle$.

Source

The energy level can be modeled as a quantum harmonic oscillator with quantized energy level.

Source

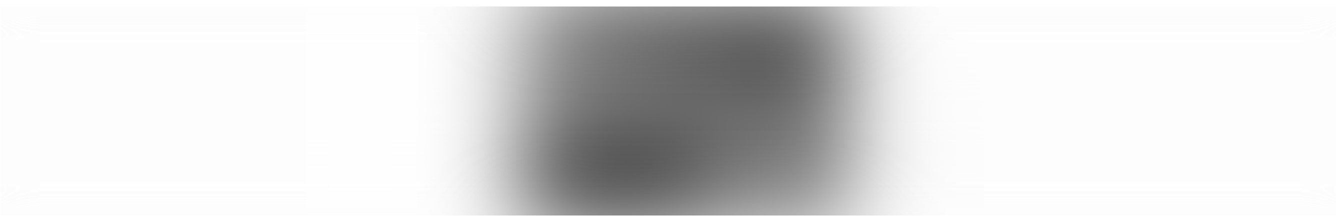
Our first challenge is the energy difference between levels is evenly spaced. As recalled in a trapped ions computer, its energy levels are uneven. The control signal that promoting quantum state |0⟩ to |1⟩ will not accidentally promote the quantum state to a higher level, the superposition will confine between |0⟩ and |1⟩.

Source

Josephson Junction

To overcome that, the superconducting circuit includes a Josephson Junction.

The junction behaves as a non-linear non-dissipating **inductor**. It contains two Aluminum superconducting electrodes which are weakly couple and is separated by a thin insulator about a thousandth of a hair thick.



It is non-linear such that the energy level is unevenly separated so we can use two lower states as the bases for our superpositions. In short, the junction provides the non-linearity such that we can control the states unambiguously.

Source

Qubit

This inductor is combined with a linear capacitor using Niobium superconductor to create an LC resonator.

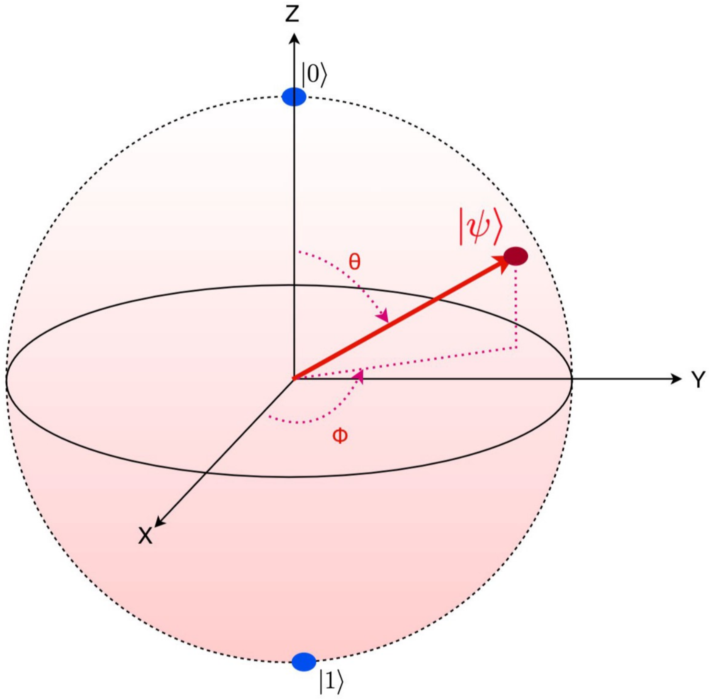
Modified from IBM source

With correct tuning, the circuit behaves like an atom with two quantum energy level, i.e. our qubit.

The qubit transition frequency depends on the capacitances and inductances in the circuit. Quantum operations are performed by sending electromagnetic impulses at microwave frequencies (around 4–6 KHz) to the resonator coupled to the qubit. This frequency resonates with the energy separation between the energy levels for $|0\rangle$ and $|1\rangle$.

Modified from IBM source

And the duration of the pulse controls the angle of rotation of the qubit state around a particular axis of the Bloch sphere.



Therefore, different pulses form different quantum gates.

Source: IBM

In Trapped ions computer, we use laser beams to control ions. To address two arbitrary ions in the string of trapped ions, it can be done with two laser beams (the red ones). This method can entangle two arbitrary qubits on the string of ions.

Source

In superconducting qubits, the coupling of two qubits is done by coupling them to a quantum bus. We print a superconducting circuit in a 2-D space (relatively speaking). To enable entanglement, a separate bus is used to couple two neighboring qubits. Connecting all two qubits together with a resonator is hard. Therefore, not all qubits are connected with each other.

For example, for the 5 qubits IBM Q, there are 20 possible combinations in pairing qubits, but only 6 of them are implemented. Here is the connection supported by the IBM Q20 (20-qubits).

IBM Q 20 Tokyo (20-qubits) — Modified from source

Measurement

To make a measurement, it sends a microwave tone to the resonator and analyzes the signal it reflects back. The amplitude and phase of the reflected signal depend on the qubit state. Once it is amplified, we know the energy level and therefore we can determine the state of the qubit.

Type of qubit

We need to map $|0\rangle$ and $|1\rangle$ to two different energy states of the physical system. There are three major ways to do it in a superconducting quantum computer: Charge Qubit, Flux Qubit & Phase Qubit. In the charge qubit, different energy levels correspond to an integer number of Cooper pairs on a superconducting island.

Wikipedia

This creates an artificial "quantized" system.

Source

The IBM Q computer is a Transmon qubit: an improved charge qubit in addressing the charging noise.

Dilution refrigerator

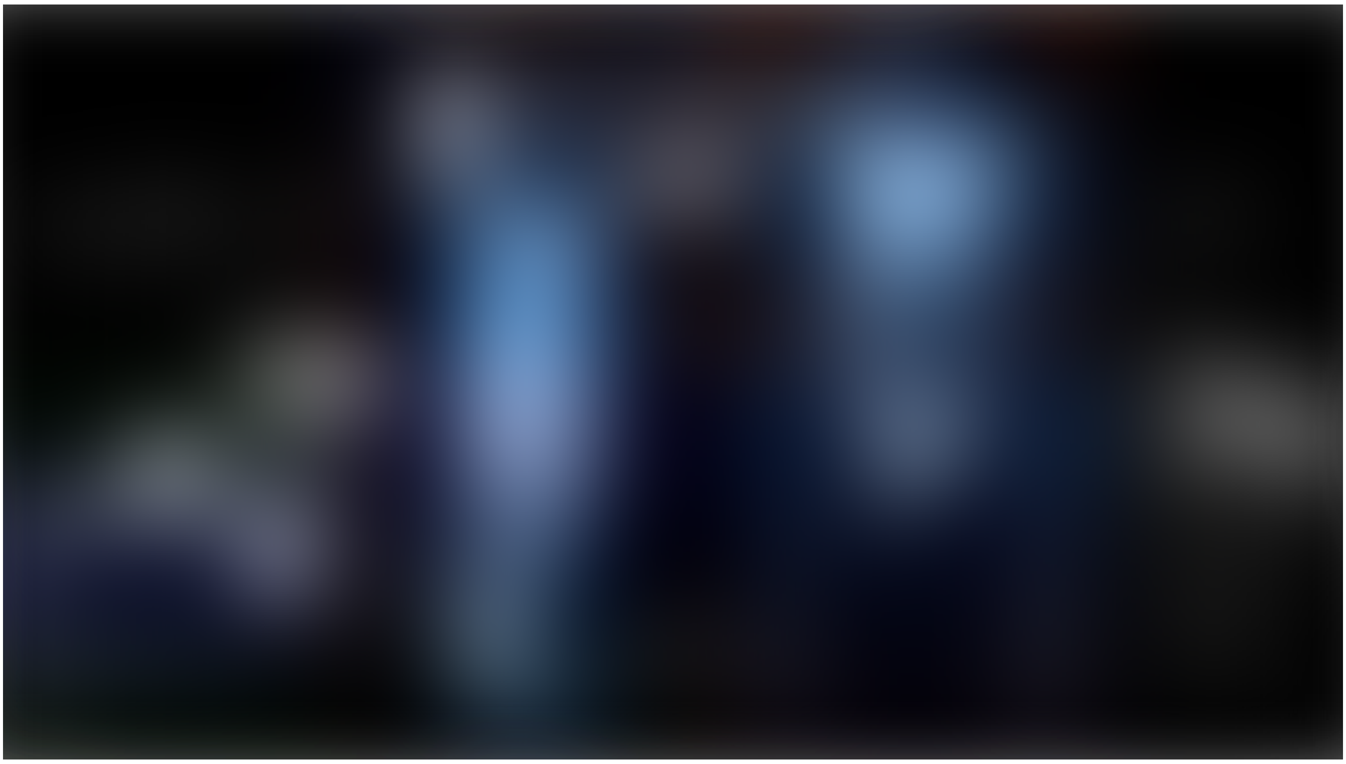
Maintain an extremely low temperature is important in a superconducting quantum computer. This dilution refrigerator has a system of pipes that contain a mixture of two helium isotopes (isotope ③ and ④). As the lighter isotope ③ is **diluted** into the heavier isotopes ④ inside the mixing chamber below, it absorbs heat as the entropy increases — a mixed solution is more disorder and has higher entropy. So the temperature surrounding the mixing chamber will drop. The mixing chamber is connected to the upper distilling chamber. Since isotopes ③ has a higher boiling point, it will vaporize. This reduces the concentration of isotopes ③ and draws more isotopes ③ to be diluted into the mixture in the other end, i.e. inside the mixing chamber. So the cooling process creates a cycling circle.

Modified from source

The diagram below shows how the IBM Q's dilution refrigerator cools temperature from 4° Kelvin to 15 Millilevins at the Cryoperm shield (lower right). This shield hosts the quantum processor. This diagram also shows the cables used to send microwave pulses down to the processor and how it readouts measurements using the amplifier on the left.

Source: IBM

The quantum processor sits inside the Cryoperm shield, a light-tight and a magnetic-field shield, used to isolate the qubits from environmental disturbances. The following is an end-to-end flow on how microwave pulses are sent down to control the qubits and how the qubits are readout.



Source: IBM

Here is another view of the IBM Q machine and the quantum chip.

Source

Decoherence

Source: IBM

The quality of a quantum computer is often measured by its decoherence. T1 and T2 measures how fast the quantum information stored in the qubit may lose. As shown below, we make very good progress in the superconducting quantum computers over the years.

Source: IBM

Tapped ions & superconducting circuits

Trapped ions quantum computer is another popular realization of quantum computers. We trap ions (for example, positively charged Calcium ions) with an oscillating electrical field inside a high-vacuum chamber. We laser-cooled the ions so it is close to stationary. A string of ions is formed and float between electrodes. Scientists have studied Atomic Physics for a century. We know its different energy states and how to manipulate between them. i.e., we know how to use these ions to create qubits. To manipulate and to measure the qubits, we shine lasers of different frequency and duration to the ions.

Source: University of Innsbruck

The following is a recap on the superconducting and trapped ions quantum computer:

Source

Comparison

Trapped ions have longer coherence time compared to a superconducting circuit but the gate operation time is faster in the superconducting circuit. Google has built a 72-qubit superconducting quantum computer in March 2018. As we write this article (Dec. 2018), IonQ has just announced a 79-qubit quantum computer. The competition is fierce and in an early phase. It is hard to determine who is the winner for now. Trapped ions need a vacuum chamber while the superconducting needs a diluted refrigerator. Trapped ions are all "natural" and identical while the gate performance for each qubit in the superconducting computer is slightly different. Not all qubits in a superconducting computer are connected to form 2-qubit operations. But, as the number of trapped ions increases, trapped ions are suspectable to noises and the error rates become intolerable. Superconducting circuits work with microwaves while trapped ions system often involves lasers which are harder to integrate into the system.

Other technologies

There are over a dozen other technologies. Let's have a quick overview.

Source

Neutral Atoms

Neutral atoms quantum computers use neutral atom instead of charged ions in the trapped ions computer. Neutral atoms can be held in close confinement to create complex 2-D or 3-D qubit array. This helps to scale the number of qubits.

Source

In fact, we can construct complex 3-D structures which cannot be done with trapped ions due to strong interactions.

D. Barredo Et al/Nature 2018

Atoms do not interact with others so it can be a bad candidate for the purpose of building 2-qubit operations. But with timed laser pulses, the outermost electron can be excited. It inflates the atom to billion times and reaches the Rydberg state — which the electrons are excited to a high principal quantum number close to 100 and become sensitive to external influences including microwave radiation. i.e. it behaves more like an ion that can interact with neighboring atoms. This behavior will be exploited to create entanglement. Currently, researchers are still working on the gate fidelity (error rate).

Quantum dots quantum computer

A single electron trapped in a semiconductor structure can form the basic building block for a qubit. We use the microwave to control the spin of the elections to construct the silicon quantum dots.

Source: Matthieu Delbecq and Shinichi Amaha, RIKEN Center for Emergent Matter Science

Here is another view of the quantum dots:

Source

Nitrogen-vacancy (NV) centers in diamond

Source

Diamond is made up of carbon atoms. It has a type of impurity (defect) called a Nitrogen-vacancy (NV) center which a nitrogen atom replaces a carbon atom and a vacancy takes the place of a neighboring carbon.

Source

Isolated spins can be extremely stable and a good choice for the qubit. The NV center harbors a spin triplet electronic ground state that can be polarized, manipulated and optically detected.

Source

In quantum computing, we often look for energy states that have long coherence time with easy ways to initialize them and manipulate them.

Source

So similar to the trapped ion, once these transition rules are known and quantify, we can design a quantum computer from them. However, how to create entanglement (2-qubit operator) can be tricky for NV center quantum computers.

Source

Phosphorus atoms in silicon

For those that want to know the phosphorous implants. Here is a 7 minutes video for your reference. Basically, we use the spin of Phosphorus to create qubits. We put Phosphorus atoms into a silicon chip and reuse our expertise in transistors to perform the measurements.

Quick summary

Source

Thoughts

Now we have a nice picture of how quantum computers are built. Next, we will look into another popular approach, the trapped ions.

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Quantum information processing has been theorized since the 80s but it took a few more decades to develop the first…

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