Different types of hardware of quantum computer

At the moment you start using your laptop, multiple processes and computations are performed in order to make this possible. Bits, registers, and logic gates are the most common types of hardware used in a typical computer to do these tasks. Quantum computers, on the other hand, work with a distinct type of technology. Qubits, quantum registers and logic gates are the building blocks of these quantum computers. While most of the names sound similar there working is worlds apart.

We're not attempting to construct a Quantum "Computer," but rather a Quantum "Processor" that can be controlled using a regular interface similar to that found on our laptops. These Quantum Processors are made up of qubits.The hardware system must fulfil a number of requirements.

The first property which must be fulfilled is the *ability to hold the initial state*. We must be able to put our system into a starting point from where it will be able to follow different properties of quantum computing. Superposition or entanglement of two quantum states, for example.This beginning point is usually the ground state, where the system's energy is at its lowest.

The second property is *performing a universal family of unitary transformations* on one or more qubits.This is how quantum gates are applied to qubits, which are crucial for the implementation of these systems. Larger algorithms are decomposed into gates, which are then implemented one at a time.

The third property is that the system must be *able to withstand measurement*. This is akin to the famous Schrodinger's cat, where the cat is either dead or alive when you open the box. Similarly, when we measure the quantum state, it collapses into one of two possible states.

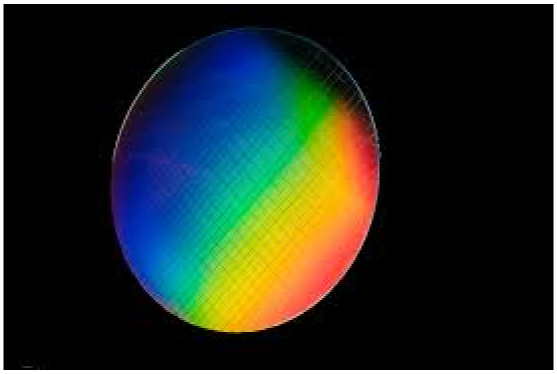
If a system possesses the three features listed above, it can function as a quantum processor. Let's have a look at some of the systems that are currently being investigated as potential quantum processors.

Spin Qubits

Using electron spin as Qubits will appear intuitive to people who have attended a Quantum Mechanics course. Because electrons have all of the traits listed above, their spin can only be in one of two states: up or down.

These electrons can be isolated using Quantum Dots, which are extremely small semiconducting materials that allow electrons to behave independently of other subatomic particles in their environment. Alternating Magnetic Fields may be used to control the quantum state of the electrons in these nanoparticles, and measurement can be done using a magnetic field perpendicular to the one used to manipulate the state of our system.Multi Qubit gates can be implemented by decreasing the potential barrier between any two qubits.

Spin Qubits can operate at temperatures of 1-4K, which is a significant advantage over other systems. However, because to the presence of additional electrons and nuclei (essentially any subatomic particle) in the Quantum Dot, they confront a greater problem: excessive noise.



Intel has been developing spin qubit systems(source)

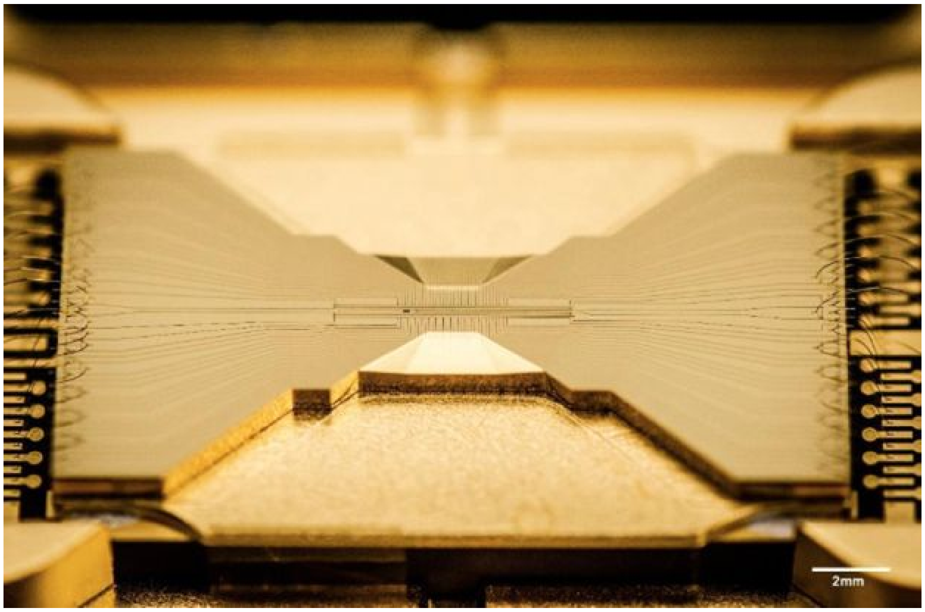
Ion Trapped Qubits

Instead of using the spin states as the basis for computation, Ion trapped qubits use Ions which are trapped in space using electromagnetic fields. The Ion trap used by quantum computers was designed in the 1950s by Wolfgang Paul, one of the leading pioneers of Quantum Mechanics. He used an oscillating electric field at radio frequency to create potential in the form of a saddle; the ions are trapped in the centre of the saddle point.

These qubits can be created in one of two ways: using two ground state hyperfine levels or using one ground state and one excited state. The first is referred to as a hyperfine qubit, while the second is referred to as optical qubits.

The first requirement is initialization of the quantum state is done by using optical pumping. The excited ion is generated by a laser, and subsequently decays to a state that is not in resonance with the laser, which can be utilized as your ground state. This ground state can be further manipulated into other states by changing the electromagnetic field which has been applied for creating the trap . The final procedure we want is measurement, this is also performed using a laser which is only coupled to one of the states, causing a photon to be created when the qubit collapses in this state, which is then detected.

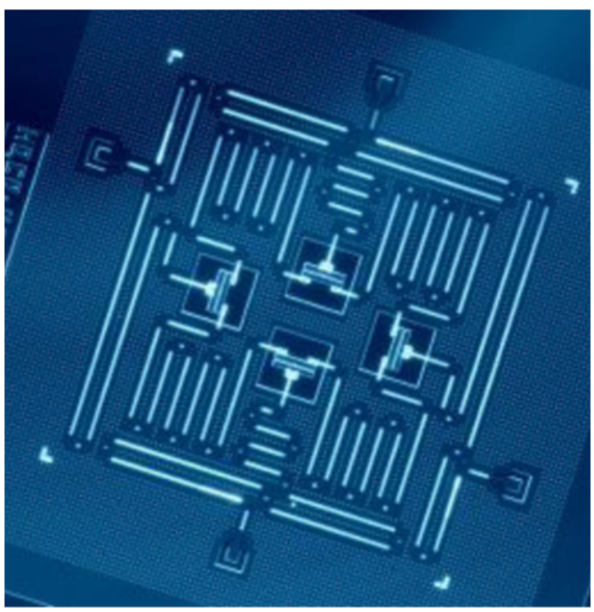
Ion trapped qubits have shown promising results and IonQ has been able to build a 32 qubit record breaking quantum computer using trapped ion qubits.



IonQ 32-qubit trapped ion qubit chip(source)

Superconducting qubits

Both spin and ion trapped qubits have exploited naturally occurring atoms in their construction. On the other hand, superconducting qubits are entirely man-made. This offers us an advantage because we can control all of our system's parameters.
The Transmon qubit is basically an LC oscillator with a non-linear inductor, a Superconducting Josephson Junction, in place of the linear inductor. While a linear LC oscillator acts like a harmonic quantum system with equispaced energy levels, a non-linear one acts like an anharmonic oscillator. We leverage this anharmonicity and use this to isolate the ground and the first excited state.



4 qubit device using Transmon Qubit by IBM(source)

The state of our qubit system can be controlled by a drive line via capacitive coupling. The drive line delivers an Electric field at microwave range which evolves the Hamiltonian of the system and state of the qubit oscillates between the ground and the excited state. Measurement is performed via another coupled LC oscillator. This is fed a pulse that is reflected by the state of the qubit; the reflected pulse can then be analysed to obtain the measurement.
Superconducting Qubits are widely acknowledged for usage in quantum computers, and companies like IBM and Google have employed them to create their own devices. One of the most interesting things you can do is experiment with these qubits yourself using QISKIT pulse, which is a part of IBM's Quantum Experience.

While most quantum enthusiasts have a lot of knowledge about the software and algorithms that we use on quantum computers, we lack the knowledge about what the hardware for these devices really looks like. My intention for this blog was to get you guys warmed up to the hardware side too, and for those of you who are more interested I strongly recommend QISKIT summer school lectures for a more indepth look into transmon qubits and this course on the Hardware of Quantum Computer on edX.

Resources

1.https://en.wikipedia.org/wiki/Trapped_ion_quantum_computer
2. https://en.wikipedia.org/wiki/Spin_qubit_quantum_computer
3. Nielsen, Michael A.; Chuang, Isaac L. (2010). Quantum Computation and Quantum Information (2nd ed.). Cambridge: Cambridge University Press
4. https://qiskit.org/textbook/ch-quantum-hardware/transmon-physics.html