This is CS4048!

GCR:wzj3vua

DiVincenzo's criteria

DiVincenzo's criteria

In the year 2000, David DiVincenzo proposed a wishlist for the experimental characteristics of a quantum computer. DiVincenzo's criteria have since become the main guideline for physicists and engineers building quantum computers.

DiVincenzo's criteria

1. Well-characterized and scalable qubits. Many of the quantum systems that we find in nature are not qubits, since we can't just isolate two specific quantum states and tarder them. We must find a way to make them behave as such. Moreover, we need to put many of these systems together.

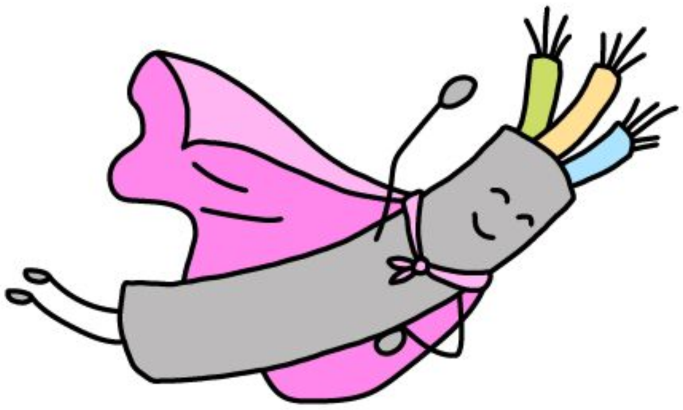
2. Qubit initialization. We must be able to prepare the same state repeatedly within an acceptable margin of error.

3. Long coherence times. Qubits will lose their quantum properties after interacting with their environment for a while. We need them to last long enough so that we can perform quantum operations.

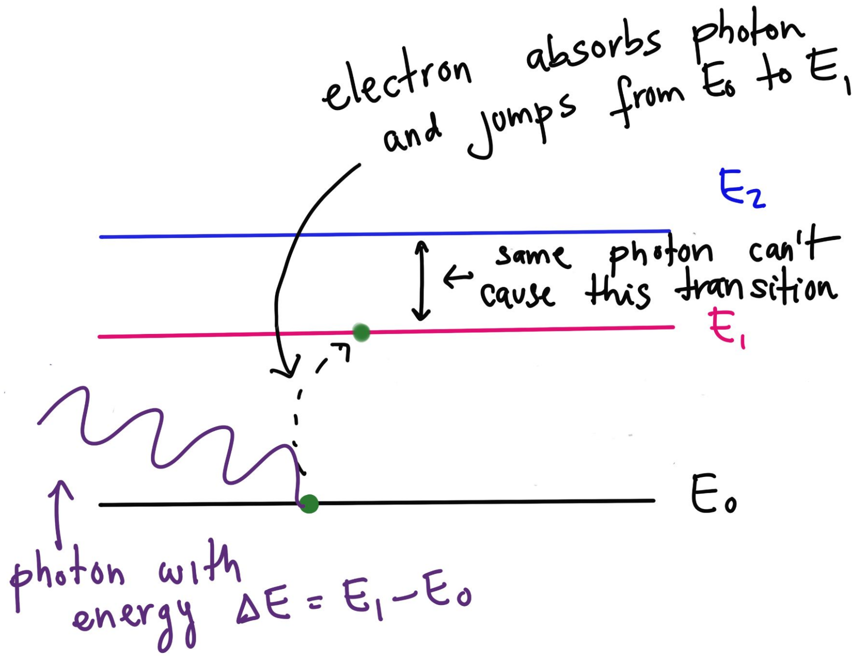
4. Universal set of gates. We need to perform arbitrary operations on the qubits. To do this, we require both single-qubit gates and two-qubit gates.

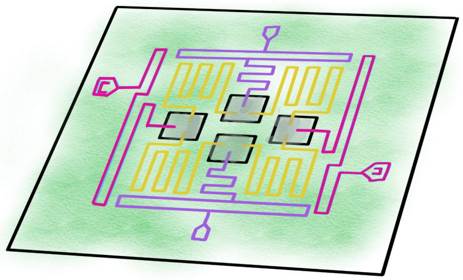
5. Measurement of individual qubits. To read the result of a quantum algorithm, we must accurately measure the final state of a pre-chosen set of qubits.

SUPERCONDUCTING QUBITS

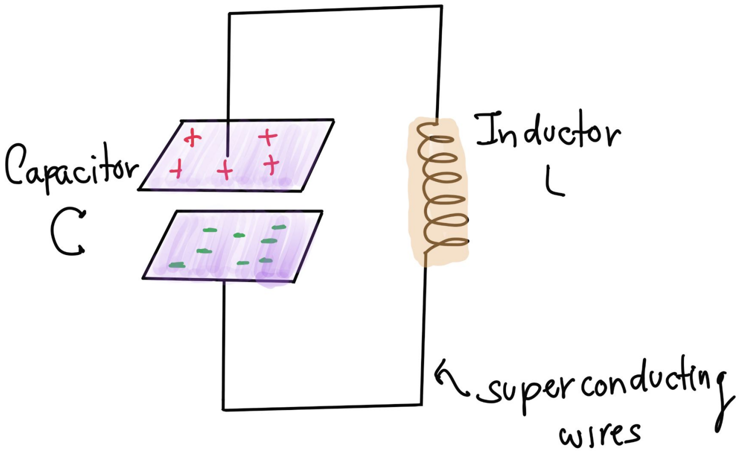


Superconducting Qubits



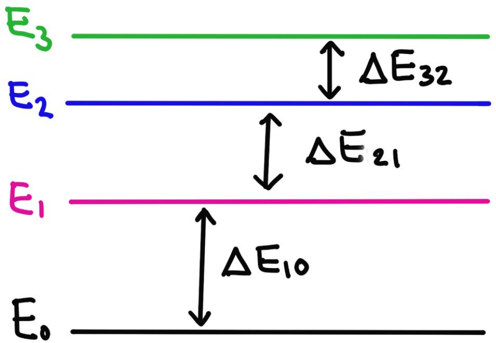


Superconducting Qubits



Superconducting Qubits

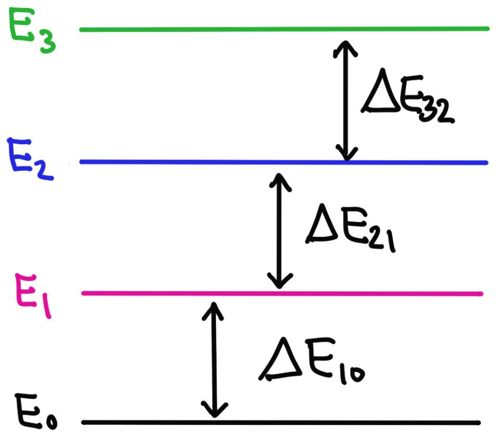
Atomic energy levels



$$\Delta E_{10} \neq \Delta E_{21} \neq \Delta E_{32}$$

(non-uniform)

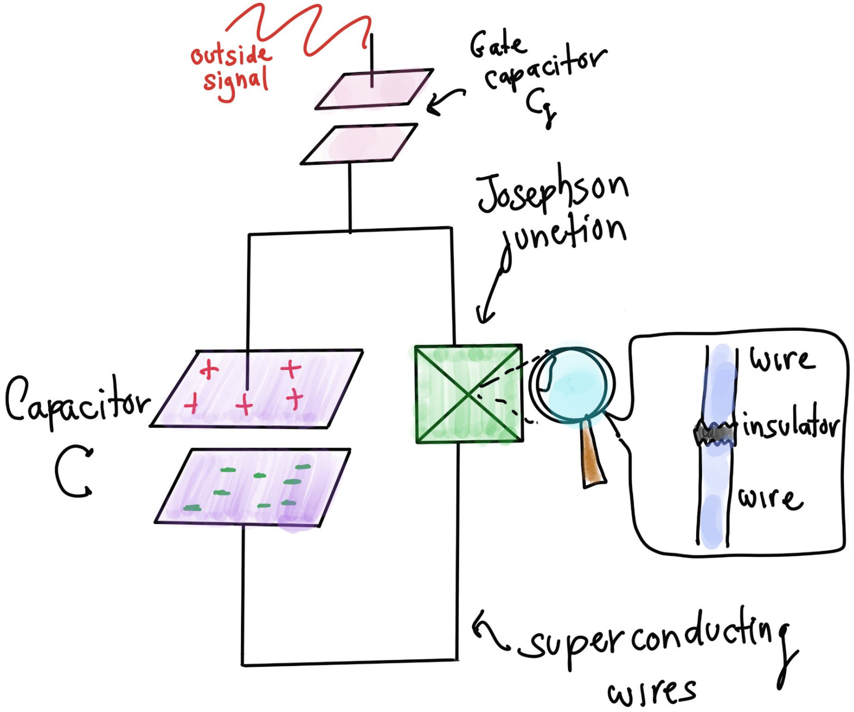
LC circuit energy levels



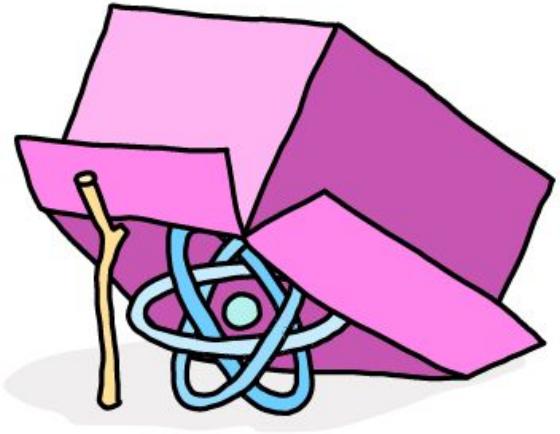
$$\Delta E_{10} = \Delta E_{21} = \Delta E_{32}$$

(uniform)

Superconducting Qubits



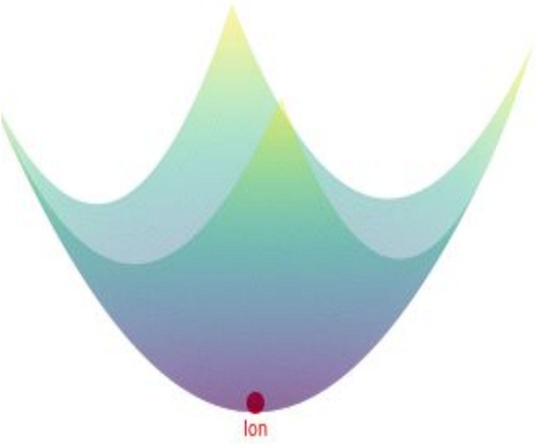
Trapped ion Qubit



Trapped Ion

Why do we use ions, i.e., charged atoms, as qubits? The main reason is that they can be contained (that is, trapped) in one precise location using electric fields.

It is not easy to create electric fields that contain the ion in a tiny region of space. The ideal configuration of an electric field —also known as a potential— would look like this



Trapped Ion

Calcium (Ca) and Strontium (Sr) enable scalable ion-trapped quantum computing.

- Vacuum Chamber: Steel chamber with electrodes at 5.37 K.
- Ionization: Lasers convert Ca and Sr atoms into ions.
- Trapping: Electric fields hold ions 50 µm above the chip, cooled by lasers.

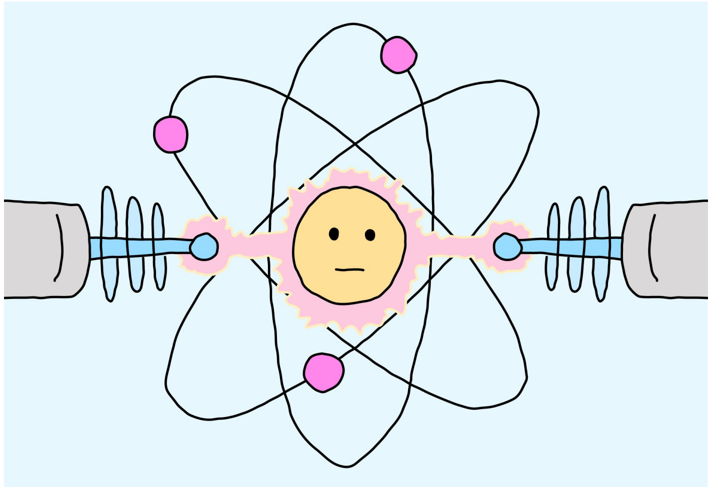
Sr+ Ions: Qubits storing quantum information.

Ca+ Ions: Absorb energy to cool Sr+ ions.

Laser pulses entangle Sr+ and Ca+ ions to form quantum gates.

Entangled Sr+ ions transfer quantum information.

Neutral Atom Qubit



Neutral Atom

Neutral Atom Computing uses uncharged atoms (neutral atoms) as qubits, typically arranged in arrays using optical tweezers.

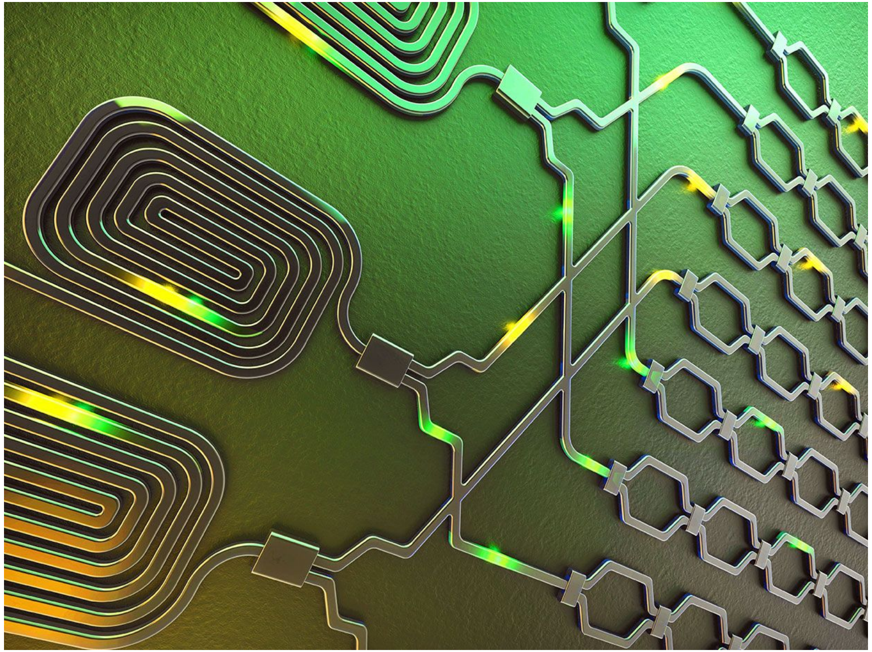
Atoms are manipulated and entangled via lasers or microwaves, with their internal states encoding quantum information.

Neutral atom systems offer scalability due to their compactness and the ability to create large arrays of qubits. They also benefit from long coherence times and flexible architectures for quantum operations.

Neutral Atom

1. Possible to work with a large number of qubits.
2. Fault-tolerant model and error correction are much more accessible.
3. Powerful computational problems can be solved using this platform.
4. Absolute temperature is required to carry out the computation.

Photonic Qubit



Photonics Qubit

Photonic qubits are quantum bits encoded in the properties of photons, such as polarization, phase, or photon number.

These qubits can exist in superpositions, allowing them to perform quantum computations.

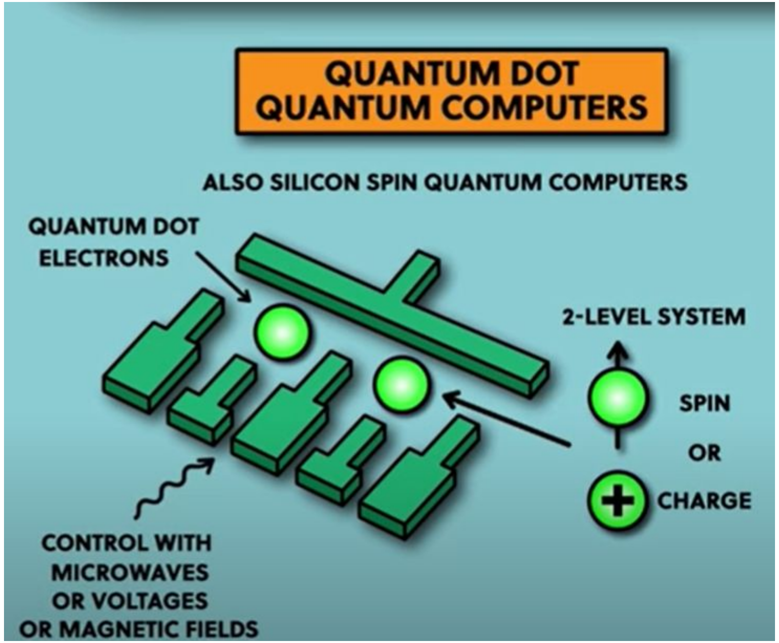
Photons are ideal for quantum communication due to their ability to travel long distances without significant loss.

They are used in quantum systems for their high speed and low interference with the environment.

Photonics

1. Qubits in this technology are much more stable.
2. A large number of photons can be entangled.
3. Computation can be done at room temperature.
4. This technology has achieved quantum supremacy.
5. Less fault-tolerant and difficult to correct errors.

Quantum DOTs



Quantum Dots

Quantum dots are nanoscale semiconductor structures that confine electrons in three dimensions, creating quantized energy levels.

These confined electrons can be manipulated to represent qubits, where the electron's spin or charge state can encode quantum information.

Their small size and tunable properties make them promising candidates for scalable quantum computers and quantum communication systems.

Key Terms

Fidelity : refers to a measure of how accurately a quantum state or quantum operation matches its ideal or intended version. It is a critical metric used to evaluate the quality and reliability of quantum processes.

Modalities: refer to different physical implementations of qubits, such as trapped ions, superconducting circuits, photonic systems, or quantum dots. Each modality uses distinct technologies and principles to encode, manipulate, and measure quantum information.

Key Terms

Cryogenic: refers to extremely low temperatures, typically below −150°C, used to study or manipulate materials and systems. In quantum computing, cryogenic environments are essential for technologies like superconducting qubits to minimize thermal noise and maintain quantum coherence.

Coherence times: refer to the duration for which a quantum system, like a qubit, can maintain its quantum state (superposition or entanglement) before it is disrupted by noise or decoherence. Longer coherence times are crucial for performing reliable quantum computations and minimizing errors.

Qubit Type	Pros/Cons	Select Players
Superconducting	***Pros***: High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start. ***Cons***: Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.	rigetti, Google, IBM Q, QuTech, OQC, IQM, qci Quantum Circuits, Inc, 本源量子 Origin Quantum
Trapped Ions	***Pros***: Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent. ***Cons***: Slow gate times/ operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.	IONQ, AQT, QUANTINUUM, oxford ionics, Universal Quantum

Photonics	***Pros***: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs.	PsiQuantum; XANADU; QUIX QUANTUM; ORCA Computing
	Cons: Noise from photon loss; each program requires its own chip. Photons don't naturally interact so 2Q gate challenges.	
Neutral Atoms	***Pros***: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required.	ColdQuanta; |QuEra> COMPUTING INC.; atom computing; PASQAL
	Cons: Requires ultra-high vacuums. Laser scaling challenging.	

Silicon Spin/Quantum Dots	***Pros***: Leverages existing semiconductor technology. Strong gate fidelities and speeds.	intel Silicon Quantum Computing diraq QUANTUM MOTION QUANTUM BRILLIANCE
	Cons: Requires cryogenics. Only a few entangled gates to-date with low coherence times. Interference/cross-talk challenges.	

QC hardware

https://medium.com/quantum-untangled/quantum-hardware-in-a-nutshell-50cc70c1ffd4
https://pennylane.ai/qml/demos/tutorial_photonics
https://pennylane.ai/qml/demos/tutorial_sc_qubits

https://pennylane.ai/qml/demos/tutorial_neutral_atoms

Quantum Complexity Theory

Last Notes

You have probably encountered several fancy terms and technologies that you may have never heard about and have no idea their function.

Don’t be worried!.

Quantum hardware is a highly specialized field, and many things will not make sense the first time you read about them. These things require a lot of time to understand intuitively, but it is gratifying when you do so. My advice is to pick one technology that you found the most interesting and look for more resources about them. Read a lot, look at lectures, and do anything that works best for your learning. I hope this article has helped you find something you are interested in and given you a good introduction.