Leading Qubit Modalities

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1. Abstract

Qubits are mechanical systems that show two distinct states and can be coupled with other two-level quantum systems. Since the 1990s, many physical systems have been researched, prototyped and demonstrated as qubits. This report gives an overview of leading physical realizations of such qubits and compares them against specific benchmarks.

2. What makes a good qubit?

There are numerous examples of such quantum mechanical two-level systems in nature that can serve as qubits. For instance, the spin of an electron or the orbital state of an electron in an atom or ion etc. But what makes a good qubit? How do we assess these qubit modalities and compare them? How can we determine if a particular qubit implementation is well-suited for quantum computing?

We can answer this by asking the same questions about classical computing. What makes a good classical logic element? How did we end up with a transistor and not any other thing like, say vacuum tube? Suppose we want to build a computer large enough to perform complex operations. In that case, we should use the technology that scales well, where we know how to define and characterize the logic elements and where we can manufacture them in large numbers. These devices must also accurately represent and process classical information. We need to be able to provide input, i.e., we should be able to set the state of such classical logic element to provide input to the computer, and we need to be able to measure the results to get an answer. Lastly, these devices must be robust against failure in order to complete the computation and reliably obtain the answer. Clearly, transistors satisfy all these requirements very well, and that’s why today’s computers are built from transistors and not mechanical switches.

With this in mind, what makes a good qubit? Dr. David DiVincenzo articulated five necessary conditions that any qubit technology must possess if it is to be a suitable physical implementation for large-scale quantum computation., which are known as DiVincenzo Criteria today.

First, it should be a scalable physical system with well-defined and characterized qubits. Second, we must be able to set the input state and, third, measure the resulting output state. Fourth, we must be able to perform a universal set of gate operations and fifth, the qubits must robustly represent quantum information. In many ways, these requirements are similar to those for classical computers that we discussed in the second paragraph of this section of my report. In addition to these five, Dr. David also added two conditions related to the communication of quantum information between qubits. Number six is that the technology must support the interconversion of quantum information between a stationary qubit and a flying qubit, and seven, there must be a way to transfer flying qubits faithfully between two locations. Basically, these last two DiVincenzo criteria describe a quantum version of an interconnect – that is, the means to take the quantum information encoded in one qubit, convert it to an object that can move, like a photon, provide the means to guide that object without incurring any loss to another qubit at a distant location, and then hand back that quantum information. Again, this is analogous to requirements for routing signals within a classical computer.

So, these are the criteria which determine how good is a particular qubit physical implementation to perform quantum information and processing schemes.

Requirements for the physical implementation of Quantum Computing	
D1: Scalable Qubits	Scalable physical system of well-defined, characterized qubit
D2: Initialization	Prepare a simple, fiducial input state
D3: Measurement	Measure the qubit state
D4: Universal gate set	Perform a universal set of gate operations with high fidelity
D5: Coherence	Robustly represent quantum Information (long coherence time)
Requirements for routing Quantum Information	
D6: Interconversion	Ability to interconvert stationary and flying qubits
D7: Communication	Ability to transmit flying qubits between two locations

3. Benchmarking Qubits

There are two types of errors that can occur in qubits. One is energy relaxation, and the other is decoherence. Their corresponding characteristic lifetimes, T_1 and T_2, are commonly used to benchmark qubit implementation along with gate time and gate fidelity. This allows us to compare qubit modalities with one another.

3.1 Qubit Coherence (T_1 and T_2)

Qubit coherence time is the analogue of the mean time to failure for a transistor. Quantum Computers must be built from robust elements, and coherence time is one metric that quantifies the robustness of a quantum bit. Essentially, it's the amount of time, on average, that qubit's state is maintained before the quantum state is lost.

Consider a qubit that we set into a quantum state $|\psi\rangle$ and consider what happens to that qubit over time. At first, the state is well-defined. However, over time, the qubit begins interacting with its environment and experiences noise that alters the qubit state. Eventually, we can no longer recognize the state, and the quantum information is entirely lost. There are two fundamental ways in which a qubit loses quantum information.

The first is energy relaxation. If we put the qubit in its excited state, state $|1\rangle$, it probably won't stay there, due to noise; at some point, the qubit will lose its energy to the environment and return to the ground state $|0\rangle$. This energy loss is called energy relaxation; on average, it occurs after a time called T_1.

The second qubit loses its quantum information through phase coherence. Imagine that we set the qubit at one point on the equator on the Bloch sphere. It likely will not stay in that direction forever, and due to interactions with the environment, phase coherence is lost. Phase coherence itself can be lost in two ways. First, the qubit state may move around the equator on the Bloch sphere. The average time it takes to lose the phase information of a quantum state is called pure dephasing time, T_ϕ. The second way phase coherence is via energy relaxation. As we know, on the equator, the qubit is in a superposition of $|0\rangle$ and $|1\rangle$, with $|1\rangle$ being the excited state. If that component of the superposition loses its energy to the environment, then the $|1\rangle$ state flips to $|0\rangle$ and the superposition state is lost. Energy relaxation is also a phase-breaking process.

The average amount of time that a qubit remains coherent is related to both dephasing time (T_ϕ) and the energy relaxation time (T_1), which together give a time T_2 over which phase coherence is lost.

3.2 Gate time

One of the essential metrics for quantum computers is the clock speed, the time required to perform a quantum operation. This is called as gate time, and it generally differs for single and two-qubit gates. Typically, the slowest gate time is used to define the clock speed with which we can operate the quantum computer.

3.3 Gate Fidelity

One of the key benchmarks is the number of gates one can perform within the qubit lifetime. The more gates one can implement before an error occurs, the larger an algorithm we can run. However, this average number of gates one can perform only accounts for error due to qubit decoherence. Still, some qubit modalities are limited by some other sources of errors like control errors and imperfection in the pulses. For these qubits, even if their coherence times were infinite, their gates would still be subject to control errors.

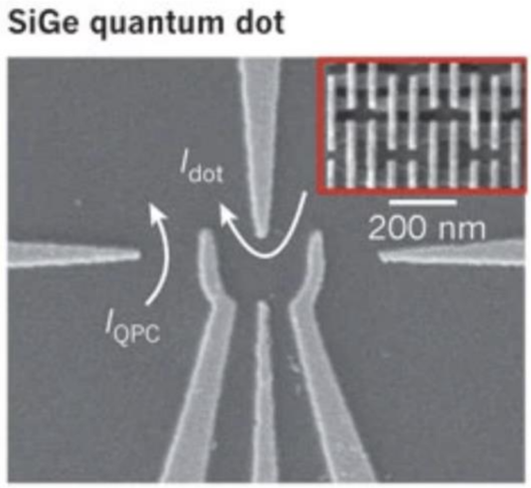
Therefore, to more rigorously characterize the robustness of a gate operation, we use a metric which is sensitive to a broad set of error sources, and that is known as gate fidelity. Essentially, it's a measure of how closely our actual gate operation matches, on average, a theoretically ideal version of that operation.

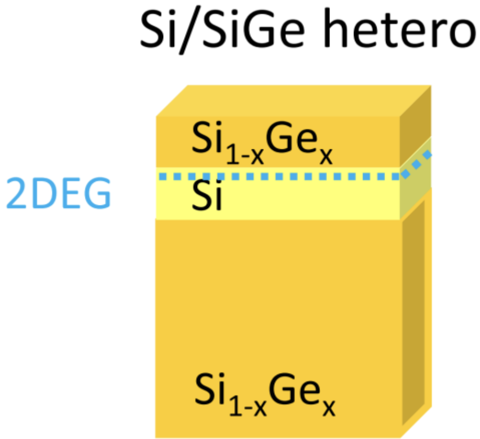
4. Qubit Modalities

There are several physical manifestations so of qubits. In this section of my report, we will take a look at several such qubit implementations.

4.1 Electron Spin – SiGe Quantum Dots

We know an electron has two spin states, spin up and spin down. It is a fermion with spin ½. But how do we actually isolate a single electron?



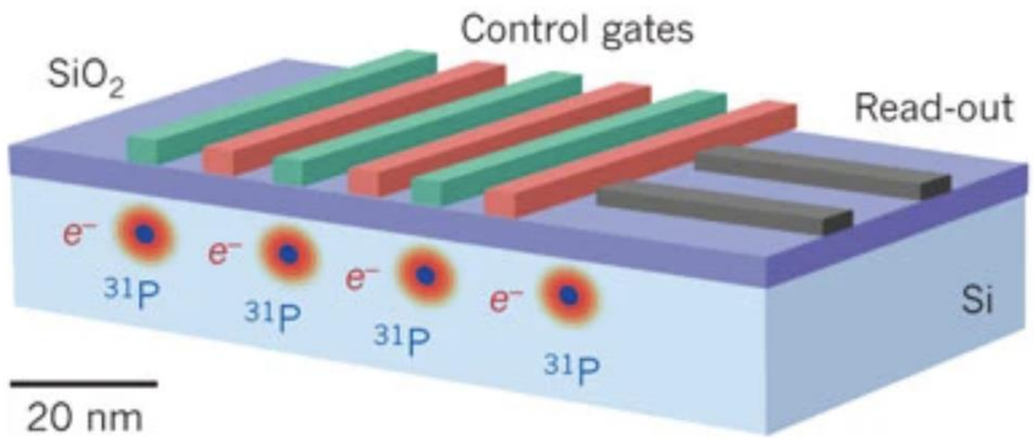


In our first qubit implementation, the electron spin is trapped in a quantum dot – A small region of semiconductor material where a single electron can be trapped. We start with a 2-Dimensional sheet of electrons called a 2-Dimensional electron gas, 2DEG for short, which can be created at the interface of a silicon slab and a silicon germanium slab. Metallic gates are defined on the surface of the device to electrostatically define the quantum dot region, and by applying appropriate gate voltages, a single electron can be trapped there. Combinations of microwaves and baseband pulses are then used to implement quantum gates.

The main advantage of quantum dots is that they leverage silicon fabrication technology, which is already quite developed, and we have a high level of precision in manufacturing at the nanoscale. Second, they are relatively small in area, so in principle, can be integrated to large numbers. And lastly, they are controlled using gate voltages. The main challenge is that multiple gates are required to define a single qubit, so 3D integration techniques will be required to realize large-scale circuits.

4.2 Electron Spin – Phosphorous-doped silicon

Another example of an electron spin qubit is in phosphorus-doped silicon. Here, phosphorus atoms are implanted in the Silicon substrate and the spin of its outermost electron servers as a qubit.

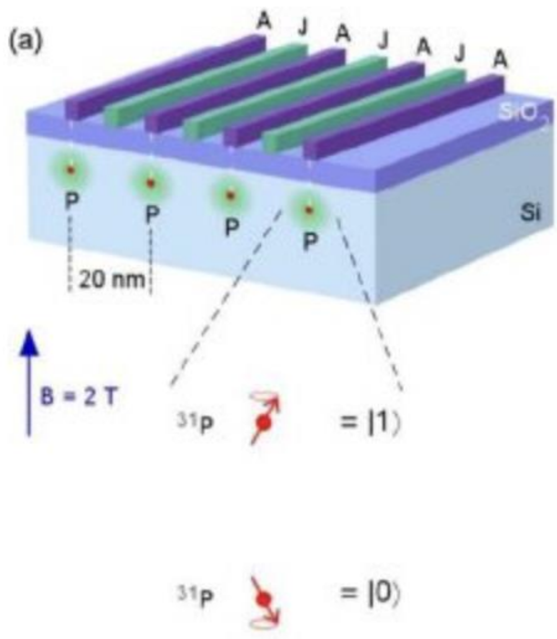


Just like quantum dots, electrostatic gates are used to control the qubit by utilizing a combination of baseband, radio and microwave pulses.

The main advantage of phosphorus-doped silicon is that it also leverages silicon fabrication technology and electron spin qubits have very long coherence times. A primary challenge is that the dopants must be in very close proximity to one another, around 10-20nm, in order to have sufficiently large two-qubit coupling to implement two-qubit gates. This makes it challenging to place the gates and route the wires required to control the qubits. It also means that crosstalk between control lines and qubits might be significant. Again, 3D integration technique will be necessary. Also, implanting dopants with high precision is also a challenge.

4.3 Nuclear Spin – Phosphorous-doped silicon

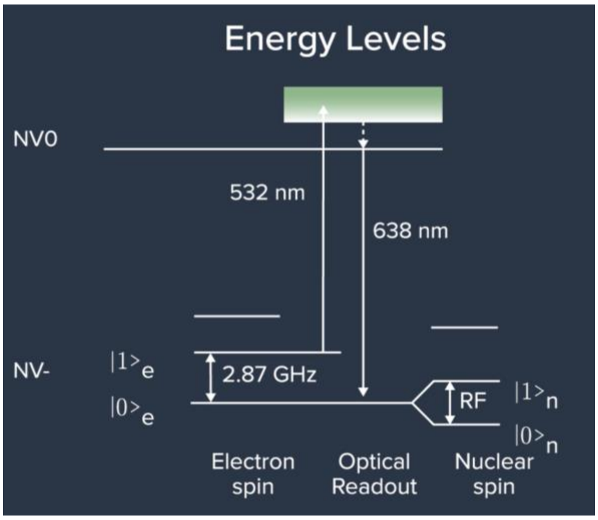
Phosphorus dopants also have a nuclear spin that can be used as a qubit which is controlled using radio frequency pulses.

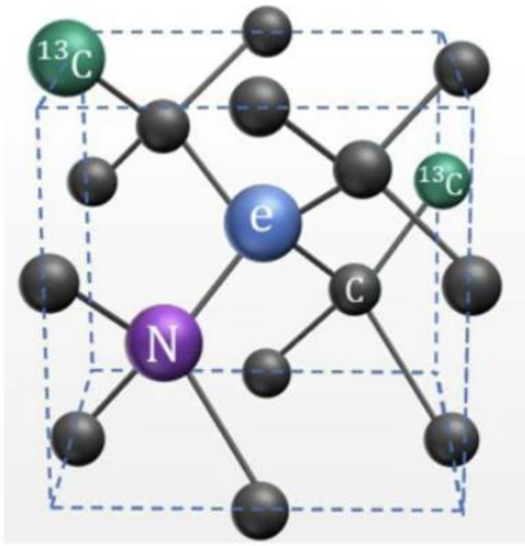


The main advantage of nuclear spin qubits is their extremely long coherence times which arises because spins are largely decoupled from their environment. The tradeoff is that gate times are much slower.

4.4 Electron &Nuclear Spins – Nitrogen Vacancies

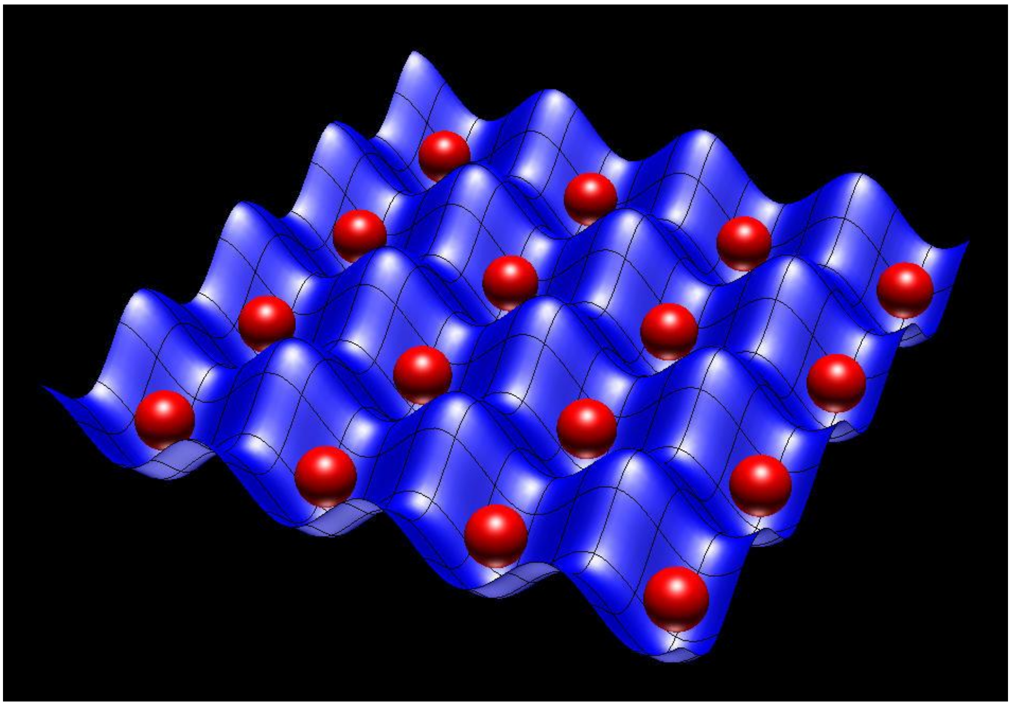
Another system which has both, electron and nuclear spin is the nitrogen-vacancy centre in diamond. Diamond is formed from a tetrahedral lattice of carbon atoms. Sometimes a defect interrupts this uniform lattice. One example of such deformation is a Nitrogen vacancy, in which a nitrogen atom is injected into the lattice, which causes the carbon vacancy to form. This results in extra electrons, which can be used as a qubit. Alternatively, the nuclear spin of the nitrogen atom or of the surrounding carbon atoms may also be used as the qubit. The electron spin is addressed by a combination of microwave pulses to implement qubit control, and lasers are used to initialize and measure the qubit. Nuclear spin is addressed using radio frequencies.





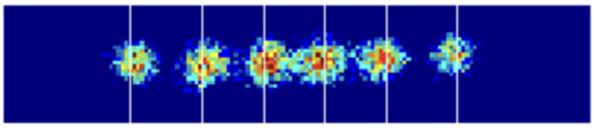
The advantage of NV Centers is that they are relatively well suited for interconversion and communication of quantum information. They have reasonably long coherence times. They can be operated even at room temperature (with slightly lower coherence). A primary challenge for NV centers is [Click6] their scalability. While few qubit clusters local to a single NV center have been demonstrated, it's very hard to place high-coherence nitrogen vacancies in precise locations to create large qubit arrays.

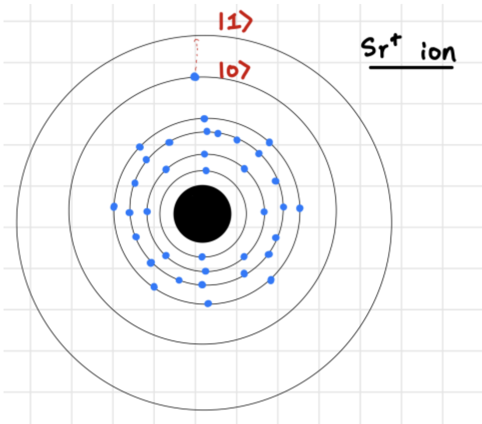
4.5 Neutral atoms in Optical Lattice



Another qubit technology is based on the internal states of an atom – a neutral atom. A neutral atom can be trapped by cross-propagating optical beams, which combine to form a wave-y egg-carton-like potential. The qubit states are hyperfine states resulting from an interaction between electron spin and nuclear spin. Such hyperfine transitions are very well-defined and controlled using microwave frequencies. These are highly stable qubits, and as such their coherence times are very long. Thus, the gate fidelity in neutral atoms is generally limited only by control errors. The main advantage of neutral atoms is their long coherence times and the ability to trap these atoms in 2-dimensional and even 3-dimensional arrays. Arrays of 100 qubits have been demonstrated. There are a few challenges, however. One is the immense laser power required to trap and control these neutral atoms. Another is that loading the trap is a stochastic process. Atom re-arrangement can later be made to fill in the gaps, but it requires extra steps. And third, neutral atoms will need integrated optics to ultimately be scalable.

4.6 Trapped ions



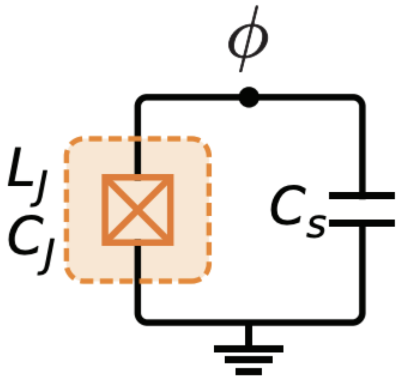


Our next example is trapped ions. Trapped ions have been used as atomic clocks for decades, and these systems are stable and well-characterized. Ion qubits generally start as atoms with two electrons in the outermost shell. Then the atom is ionized, removing one electron and leaving a single electron in the outermost orbit. The qubit is realized either as an optical transition between the orbital states of the outermost electron or a microwave transition between hyperfine states.

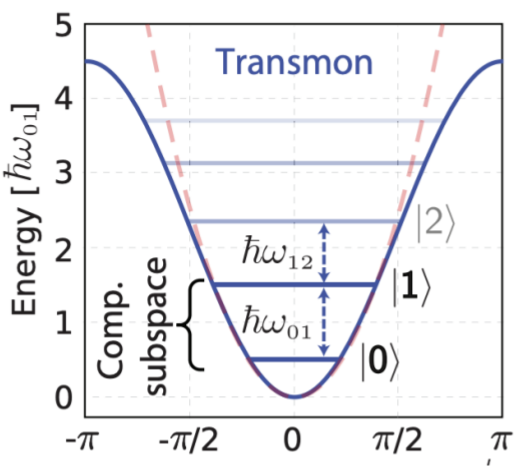
A primary advantage is that many of the DiVincenzo criteria are satisfied for trapped ion qubits. To date- arrays of 30 trapped ion qubits have been demonstrated, and surface traps in silicon are under development to both capture and control these ions in a scalable manner. The primary challenge is the 3D integration of optical and electrical technologies into the surface traps to make them scalable.

4.7 Superconducting Qubits

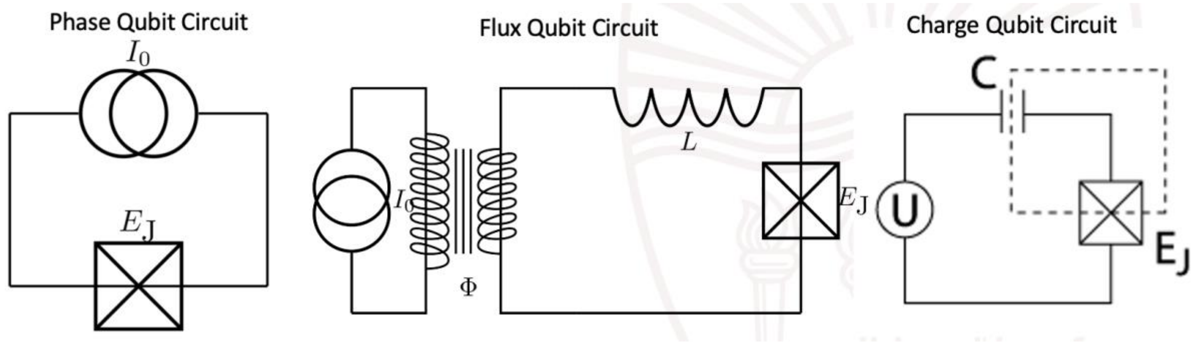
The next example, superconducting qubits, are manufactured artificial atoms. Unlike previous examples based on spins and naturally occurring atoms, superconducting qubits are electrical circuits that behave like atoms.



Essentially, superconducting qubits are non-linear oscillators built from inductors and capacitors. The inductor is realized by a Josephson junction, a nonlinear inductor that makes the resonator anharmonic. Anharmonic oscillators feature an addressable two-level system that we will call a qubit.



The qubit states can either be states of phase across the Josephson junction, Flux in a superconducting loop or even charge on the junction island.

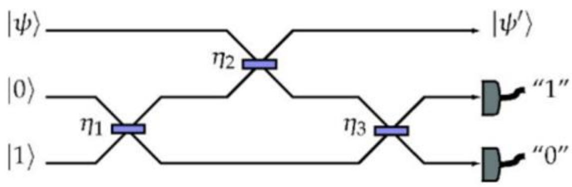


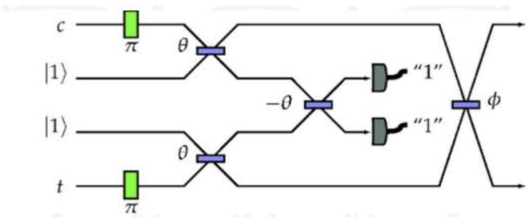
The main advantage of the superconducting qubit is that gates are fast compared with the other qubits, and they are manufactured on silicon wafers using materials and tools common to CMOS foundries. Recently IBM announced their 433-qubit chip. The main challenge is the integration of control and readout technologies that maintain qubit coherence, even at millikelvin temperatures.

4.8 Other Notable Qubit Candidates

There are several other qubit modalities being pursued that are at various stages of development.

4.8.1 Linear Optics Quantum Computing





In this, the presence or absence of a photon constitutes the qubit. Quantum information is processed using linear optical components like beam splitters, phase shifters, mirrors and interferometers, photon sources, photodetectors etc. The main challenge with linear optical quantum computing is that it is very hard to make two photons interreact with one another.

4.8.2 Quantum Emulator using Rydberg atoms

Another type of quantum computer based on neutral atoms is a quantum emulator. An emulator uses Rydberg atoms or Bose-Einstein condensates to emulate a condensed matter or atomic system through the use of tailored atomic energies and coupling terms.

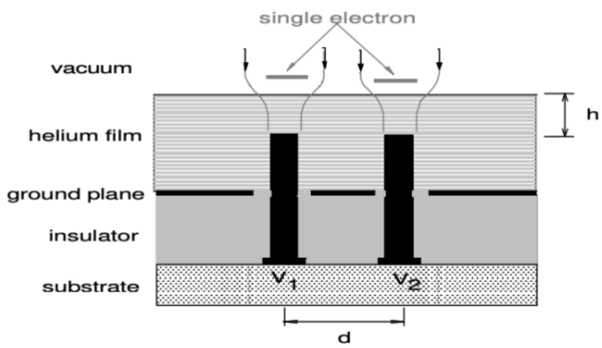
4.8.3 Topological Quantum Computing using Majorana Fermions

An exciting qubit modality is based on something called Majorana fermions, a fermion which is its own antiparticle. There are several efforts going on trying to realize a Majorana qubit using a combination of superconducting and semiconducting materials, which feature a strong spin-orbit interaction. Majorana qubits have been theoretically shown to exhibit topological protection, a resilience to noise that's unlike the resilience afforded by quantum error correction. The challenge is that they're extremely hard to realize, and to date, there's been no definitive demonstration of Majorana qubit featuring this protection.

4.8.4 Polar Molecules and Molecular Ions

In this, ions of molecules are trapped and controlled in a similar manner to atomic ions.

4.8.5 Electrons on Liquid Helium



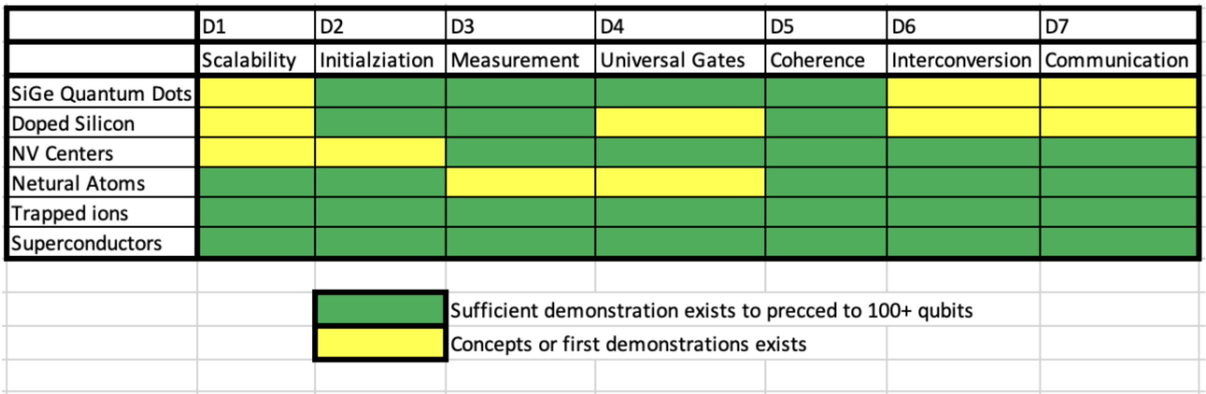
These are basically free electrons that form an electron lattice on the surface of liquid helium and can be controlled using electron spin resonance techniques.

5. Comparing Qubit Modalities

In this section, we will compare all the qubit candidates mentioned in section 4.1 to section 4.7.

5.1 DiVincenzo Criteria

First, we will see how they perform against the DiVincenzo Criteria mentioned in section 2.



This is a slightly subjective assessment. Yellow indicates that concepts or first demonstrations may exist, but the technology is not ready to scale up to ~100 qubit level.

Starting with the first DiVincenzo criteria, D1, scalable systems, the most mature are neutral atoms, trapped ions and superconducting qubits. All have demonstrated or have coming prototypes with 50+ qubits in the near future. Silicon germanium and doped silicon qubits are yellow because they will require high wire counts to address their qubits and those wires need to be routed with high density due to relatively small qubit geometry.

Next, for initialization, D2, most technologies are doing well. The one exception is NV centers, where the strong laser used to initialize the qubit can sometimes, by accident, remove an electron. This makes the defect charge neutral, destroying the qubit until it is reset.

For measurement D3, neutral atoms are extremely slow and limit the ultimate clock speed of the system; that's why it is yellow.

Taking about D4, SiGe Quantum dots were only recently able to demonstrate two-qubit gates. Neutral atoms and silicon germanium are yellow because even though they have demonstrated two-qubit gates, they have relatively low fidelity.

In terms of D5, all these technologies perform fairly well.

For D6 and D7, there has been no work for quantum dots and doped silicon, but it is expected to follow the same method of conversion to microwave photons as the superconducting circuits' approach.

From this, we can clearly see that trapped ions and superconducting qubits have made the most progress, and that is the reason they are viewed as leading candidates for qubit realizations.

5.2 Summary and Benchmarking

The following table summarizes the qubit implementations and gives their benchmarks discussed in section 3. This provides a snapshot of the current state of technologies for the qubits mentioned in sections 4.1 to 4.7.

		Superconducting	Trapped ions	Silicon Quantum Dots	Impurity Doped Silicon		Impurity Centers	Trapped Neutral atoms
Qubit Modality	Materials	Al	Yb^+, Ca^+, Sr^+, Be^+, Ba^+, Mg^+	Isotopically purified Si, SiGe	Phosphorus doped isotopically purified silicon		Nitrogen Vacancies in Diamond	Rb, Cs, Ho
	Control	Microwaves	Microwaves, Photons	Baseband, Microwave	Microwaves		Microwaves, Photons	Microwaves, Photons
	State	Phase/Charge/Flux	Atomic state of e^-	Electron spin	Electron Spin	Nuclear spin	Nuclear+ e^- spin	Rydberg state
State-of-art times (ns)	T_1	50,000	10^{14}	10^9	5 x 10^9	10^{14}	10^8	5 x 10^9
	T_2	1,00,000	5 x 10^{12}	4,00,000	1,00,000	10^9	2 x 10^7	10^9
	1Q Gate	10	2,000	100	200	1,00,000	10,000	10,000
	2Q Gate	40	30,000	200	1.6	??	25,000	3,000
	RO	200	30,000	1,000	10^6	5 x 10^8	50,000	1.5 x 10^8
Fidelity	1Q	99.90%	99.996%	99.60%	99.90%	99.90%	99.90%	99.9%
	2Q	99.0%	99.8%	80%	86.7%	??	82%	80%
	RO	99%	99.99%	99%	94.00%	99.90%	94%	99.90%

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