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Comparison Between Different Qubit Designs for Quantum Computing

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ABSTRACT: Learning about qubit designs is essential in today's rapidly advancing quantum computing and quantum technologies. Qubits, the fundamental building blocks of quantum information processing, lie at the heart of revolutionary developments poised to transform industries, ranging from cryptography and materials science to optimization and drug discovery. Understanding the intricacies of various qubit designs is a gateway to harnessing the computational power promised by quantum computers and an exploration of the fascinating and complex world of quantum physics. In this work, we discuss the principles and criteria for qubit design and summarize the most promising approaches taken for qubit design.
KEYWORDS: Physics and Astronomy, Quantum Physics, Quantum Computing, Qubit Design, DiVincenzo criteria.

Introduction

Quantum computing has been an ever-growing field for the past decade. Unlike classical computers, which rely on bits to represent information as either 0 or 1, quantum computers use quantum bits or qubits, which can exist in multiple states simultaneously due to the principles of superposition. Quantum computers are predicted to solve specific problems significantly faster than classical computers. These problems include complex quantum simulations[1] and specific optimization tasks.[2] Quantum computing can also be used for cryptography.[3,4] Quantum computing applications are a growing field, and they grow as the computation power of quantum computers grows.

These potential applications of quantum computers have brought much attention to the field, and extensive research has been done on the design and improvement of these computers. Qubits are the smallest computation units in quantum computers, and their properties dictate the design required for computation. The first step in designing the qubit is to define the criteria a quantum computer needs to meet to be considered a practical computer design. Theoretical physicist David P. DiVincenzo proposed these properties in the 2000s.[5] DiVincenzo asserted five necessary conditions for quantum computation and two for quantum communication. DiVincenzo's criteria for quantum computing are as follows:

1) A scalable physical system with a well-characterized qubit.
2) The ability to initialize the state of the qubits to a simple fiducial state.
3) Long relevant decoherence times.
4) A "Universal" set of quantum gates.
5) A qubit-specific measurement capability.

The following two are necessary for quantum communication:

1) The ability to interconvert stationary and flying qubits.
2) The ability to transmit qubits between flying qubits between specified locations without altering them.

DiVincenzo's criteria describe the essential conditions for designing quantum computers. However, other factors need to be considered to optimize the design of the quantum computer. To design efficient quantum computers for handling quantum information, one needs to identify the merits of the design concerning the sensitivity of quantum computers to quantum noise. Quantum noises corrupt the desired evolution of the system and can cause the loss of information from a system into the environment (also known as decoherence). Two different time scales need to be defined to quantify the Quantum system sensitivity to noise. First is the time scale in which a system remains quantum-mechanically coherent, τ_Q. The second time scale is the time it takes to perform elementary unitary transformations, which involve at least two qubits, τ_{op}. The ratio of the τ_Q/τ_{op}, roughly describes the longest quantum computation that can be done before the results are impacted by noise. A subtle difficulty in the design of quantum computers is the seemingly opposing constraints. A quantum computer must be isolated to minimize the decoherence due to environmental interaction and retain its quantum properties. Still, at the same time, they have to be accessible to manipulate and apply gate operations for computations and read out the results. Therefore, the main question is how well a quantum computer can be built.

In this work, we summarize the design principles of the common qubits being used and, step by step, compare their design strength and weaknesses regarding DiVincenzo criteria. These qubit designs can be categorized into the following categories: superconductor qubits, trapped ion qubits, topological qubits, silicon-based qubits, and photonic qubits.

Qubit Design Approaches:

Before discussing the different qubit designs, one must become familiar with what a qubit is and how it differs from a

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classical bit. A qubit, short for "quantum bit," is the fundamental unit of quantum information analogous to the classical bit in classical computing. However, qubits are governed by the principles of quantum mechanics, which give them unique properties that distinguish them from classical bits. These properties are superposition, entanglement, quantum interference, and measurement properties.[6]

Classical bits of information have two possible states, 0 and 1. And they can only exist in one of these two states. However, qubits can be in a linear combination of these two states, known as superposition. Mathematically, a qubit state $|\Psi\rangle$ is described as:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

Where α and β are complex numbers and $|\alpha|^2+|\beta|^2=1$, where $|\alpha|^2$ and $|\beta|^2$ are the probabilities of finding the qubit in states 0 and 1.[6]

Another characteristic of qubits is that they can be entangled, meaning the state of one qubit depends on the state of another, regardless of the physical distance between the two qubits. In other words, the information is shared between the two qubits.

Quantum interference is another feature that differentiates qubits from classical bits. In quantum computing, interference affects the probability amplitudes of a measurement's outcomes. Every possible outcome has some probability of occurring. For one qubit, the possible outcomes are 0 and 1. For two qubits, the possible outcomes are 00,01,10 and 11. Similarly, for N qubits, there are 2^N possible outcomes. This exponential growth allows quantum computers to perform calculations that are very resource-intensive for classical computers.[6]

Finally, the measurement interpretation of the qubits is different from classical qubits. When a qubit is measured, it collapses to one of the measurement basis states. The act of measurement destroys the superposition state. Therefore, state preparation and measurement need to be done several times to find the probabilities $|\alpha|^2$ and $|\beta|^2$.

- ***Superconducting qubits:***

Superconducting qubits are, in nature, just a circuit loop with an electrical current traveling through them. The differentiating feature in the superconducting qubits is that wires that make the circuit have superconducting transitions as their temperature decreases below the transition temperature. When a superconducting material reaches below its critical temperature, the repulsive force between electrons becomes slightly attractive, and Cooper pairs are formed. The Cooper pair can flow through the superconductor without scattering. Therefore, superconductors have zero electric resistance. The feature that makes the superconductor circuits a viable design for making qubits is that they are quantized, meaning they only take on discrete states. Therefore, their state can be controlled and measured using physical operations such as magnetic flux or microwave pulses.

The superconducting qubit, while a prominent qubit model in quantum computing, is only one of the oldest. In fact, it emerged years after the inception of the earliest quantum computers in the late 90s. The initial quantum computing devices encompassed trapped ion and liquid-state nuclear magnetic resonance (NMR) systems. These pioneering systems had qubits that varied considerably from the current superconducting models.

In the field of quantum computing, the NMR model stands as a distinctive form of "molecular" quantum computing, considerably different from the solid-state framework from which the initial superconducting qubits emerged. Notably, molecular qubits have the advantage of uniformity within a given quantum processor, a feature absent in solid-state qubits. Additionally, the inherent coherence times of molecular qubits are relatively more protected due to their partial insulation from the external environment. We see this advantage in trapped ion and neutral atom qubits.[7]

On the other hand, superconducting qubits are non-uniform due to their manufacturing process. Though compact, the manufacturing variability prevents exact replication, necessitating system calibrations. However, these fabrication techniques grant significant merit to superconducting qubits over molecular models. These qubits were made by using well-established processes refined over time, holding the promise of streamlined large-scale production and the potential for scalable computational operations.[8]

The three primary archetypal superconducting qubits are the phase qubit, charge qubit, and flux qubit. Numerous hybridized variations of these archetypes have been developed, including the Transom,[9] Tunable Transmon,[9] Fluxonium,[10] FluxQubit,[11] ZeroPi, FullZeroPi,[12,13] and Cos2PhiQubit.[14] In implementing any qubit, the logical quantum states $|0\rangle$ and $|1\rangle$ are mapped to distinct states within the physical system. Typically, these mappings correspond to discrete energy levels or their quantum superpositions.

These three archetypal qubit types exhibit a unique range of the Josephson energy-to-charging energy ratio. Josephson energy refers to the energy stored within Josephson junctions when a current flows through them while charging energy represents the energy required for a single Cooper pair to charge the total capacitance of the junction. Josephson's energy can be written as

$$U_J = -\frac{I_0 \Phi_o}{2\pi}\, Cos\delta \tag{2}$$

where δ is the phase difference across the junction, $\Phi 0$ is the flux quantum, which is equal to $\frac{h}{2e}$, and I_0 is the critical current parameter of the Josephson junction. Charge energy is written as

$$E_c = \frac{e^2}{2C} \tag{3}$$

Where e is the electron charge, and C is the junction's capacitance. It is important to emphasize that the cosine behavior of the Josephson energy indicates the nonlinearity of the Josephson junction, which helps to utilize only the two lowest energy states.[15]

In the area of superconducting quantum computing, the main challenge lies in the requirement for ultra-low temperatures where superconductors can exist. Additionally, fundamental challenges in designing superconducting qubits include precisely shaping the potential well and selecting particle mass. These choices are critical to ensure that the energy separation between two specific energy levels is distinct, standing apart from all other interlevel energy separations within the system. This distinctiveness is vital as these two levels serve as the logical states of the qubit. Superconductor qubits are one of the main families of the qubits being invested in, and the two leading companies using these qubits are IBM[16,17] and Google.[18] In Figure 1, the image of one of IBM's quantum processing units called osprey is shown.

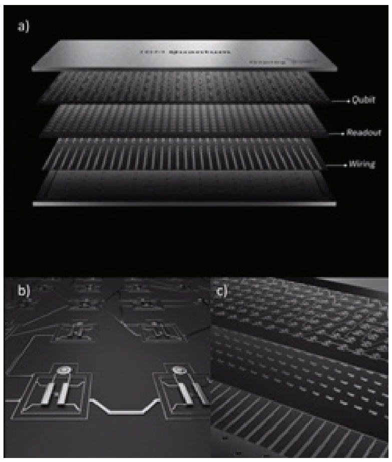

Figure 1: a) Image of Osprey, IBM's 433 qubit quantum processing unit (QPU). Layer design helps with the more versatile connectivity between qubits and helps with the scalability of QPUs. b) close-up image of qubits layer c) close-up image of qubit, readout, and wiring layers.[17]

- ***Trapped Ion and Neutral atoms***

One other approach is instead of designing physical systems that have quantum behavior. One can employ inherently quantum systems. An example was NMR quantum computing, which motivated the design of superconducting qubits. Neutral atoms and trapped ions are two other qubit designs. A trapped-ion quantum computer is another promising approach to creating a powerful quantum computer on a larger scale. This method uses electromagnetic fields to configure and suspend charged ions in free space. The qubits are stored in stable electronic states of each ion. Quantum information can be shared among the ions by their collective motion within a trap, where they interact through the Coulomb force.[19] Eighteen lasers create connections between qubit states (for individual qubit operations) and between qubit states and the ions' motion (for entanglement). The core quantum operations of a quantum computer have been successfully demonstrated with high precision in trapped-ion systems. To achieve scalability, methods are being developed to transport ions to different locations in an ion trap array, creating extensive entangled states through interconnected ion chains and combinations of these techniques. This approach holds great promise for building a scalable and versatile quantum computer. Examples of companies using trapped ions are IonQ, Quantinuum, and Oxford Ionics. Figure 2 shows a picture of the vacuum chamber that houses the electrodes for trapping the ions with the schematic of the excited and ground state for the Yb^+ ion.

In summary, Ions are naturally occurring and, as such, exhibit consistent properties unaffected by imprecise manufacturing processes. Each ion can encode a single qubit. In principle, adding more ions leads to an increase in the number of qubits. The quantum state of these ion qubits is controlled through laser light manipulation, and their readout is accomplished using fluorescence detection. This approach eliminates the necessity for intricate wiring. Furthermore, ion-trap quantum computers can operate at room temperature. Achieving microkelvin temperatures is made possible through laser cooling techniques rather than technically challenging cryogenic methods.[20]

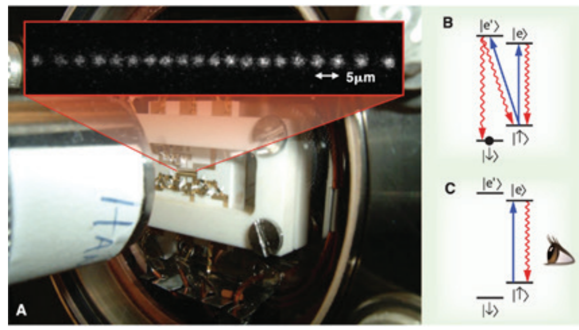

Figure 2: a) Vacuum chamber that houses electrodes for trapping atomic ions with a linear crystal of 20 confined atomic Yb^+ ions. A laser illuminates the ions, and fluorescence is imaged onto the camera. (B and C) shows the energy level diagram of the Yb^+ ion. B) presents the initialization to state $|\downarrow\rangle$ and C) fluorescence detection of the qubit state ($|\uparrow\rangle$, fluorescence, $|\downarrow\rangle$, no fluorescence).[21]

Neutral atoms, also known as "cold atoms", are made by trapping individual atoms in a vacuum using lasers as optical" tweezers". This arrangement restricts atom movement, effectively cooling them down. By subjecting these atoms to specific laser pulses, their outer electron(s) can expand into a highly excited state called a Rydberg state. This enables interactions between atoms, like entanglement, for various applications. An example is Atom Computing's setup, shown in Figure 3, which is a representative cold atom approach. This configuration involves two sets of lasers with controllers and AODs (acoustic-optic deflectors), a vacuum chamber, and a camera sensitive to photons for the result detection. To perform computations, different laser pulses are used to create interactions between atoms, including entanglement. This setup offers several advantages, including long coherence times, strong connectivity among qubits, scalability, reduced wiring complexity, and the ability to operate in both analog and digital modes.[22,23] Despite these strengths, neutral atom quantum computers are relatively new and face challenges in refining laser systems and maintaining ultra-high vacuums. Companies like Atom Computing[23] and Infleqtion[24] are actively working to overcome these challenges and make significant progress in the field. The following are the key points about neutral-atom quantum computers: 1st) Neutral-atom quantum processors use lasers to trap and cool atoms for quantum computing.

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2nd) Atoms can be manipulated and arranged using lasers with specific wavelengths. 3rd) Different laser pulses create interactions between atoms, like entanglement. 4th) Neutral atom quantum computers have advantages like long coherence times and strong connectivity. 5th) Challenges include refining laser systems and maintaining ultra-high vacuums.

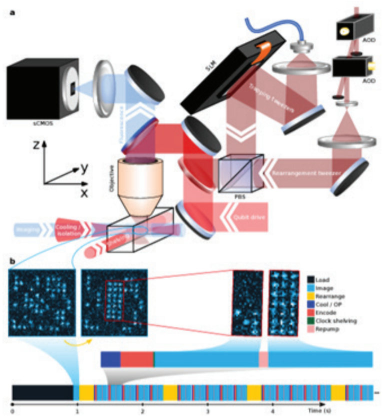

Figure 3: a) The optical tweezer system's key components for trapping, rearranging, manipulating, and reading the state of nuclear spin qubits. The primary setup involves a static trap array generated through a spatial light modulator (SLM). To manipulate the trapped particles, rearrangement light is guided by a pair of crossed acoustic-optic deflectors (AODs) and combined with the trapped light via a polarizing beam splitter (PBS). Additionally, qubit drive light is integrated with both of these beams using a dichroic mirror. All these optical beams are directed into the microscope objective, facilitated by another dichroic mirror, which also transmits the collected atom fluorescence signal at 461 nm to the imaging system. This imaging system, in turn, forms an image on the commercial CMOS camera. b) In the experimental sequence timing, we load the trap array initially and repeat this process several times (the specific count varies depending on the probability of atom loss in each experiment). Afterward, we execute a rearrangement step to completely populate the computational array, thereby establishing a register of qubits.[25]

- ***Topological qubits:***

Topological qubits are a type of qubit used in quantum computing that leverages the principles of topology to protect quantum information from errors. They are designed to be more robust against certain types of quantum decoherence and errors, which are significant challenges in building practical quantum computers.

A topological quantum computer is a quantum computer proposed first by Russian-American physicist Alexei Kitaev in 1997.[26] In mathematics; topology is the study of the features of shapes that do not change when you stretch or squish them, known as smooth deformation. A common example in topology is the comparison between a donut and a coffee cup – even though they look different, they both have the same basic structure with a single hole. So, if you take a small bite from the donut or chip piece off the cup, they still have that same structure. But if you were to do something more drastic, like cutting the donut in half or breaking the cup's handle, you'd change their basic structure by getting rid of the hole.[26]

In quantum computing, this involves using anyons, which are quasi-particles that exist in two-dimensional space. There are different kinds of anyons. The anyons being used for quantum computing are known as non-abelian anyons. Abelian refers to a mathematical property in a group in which the result of applying group operations on two group members is not dependent on the order of operation. Therefore, in the non-abelian anyons, the result is dependent on the path's topology. The path of the operation can be considered as a string; when you exchange two anyons, this path is braided. When anyons are braided, their quantum states change in a manner that only depends on the topology of the path.[27]

The main advantage of topological qubits is their inherent resistance to local errors. Because the information is stored in a global property of the system (the braiding of anyons), it is less susceptible to local perturbations that can cause errors in other types of qubits.[28]

However, creating and manipulating anyons in a controlled manner is experimentally challenging, and scaling up the number of qubits and performing complex operations remains an even more significant challenge. Since topological qubits are still under development, no benchmark results from them can be used with other qubit designs. However, they are mentioned here since their resistance to smooth deformation will be useful in the error correction process.

- ***Silicon Qubits:***

Building quantum bits (qubits) using silicon offers two compelling advantages. The first reason lies in the extensive groundwork laid by classical microelectronics on silicon. Despite the inherent differences in how silicon quantum computers would function operating at cryogenic temperatures, for instance, the unparalleled advancements in silicon's material quality, crystal growth, and fabrication techniques make it the foremost contender among materials.[29] Even harnessing a fraction of the global investment in silicon for qubit development could propel silicon-based qubits far ahead of other solid-state options.

The second, less evident advantage is silicon's exceptional magnetic purity. In highly purified and isotopically enriched silicon, spins experience an exceptionally pristine magnetic environment. This is because 95.3% of naturally occurring silicon isotopes have a spin-0 configuration, resulting in a "closed shell" of nuclear moments that generate no external magnetic field. Combined with nearly flawless chemical quality at a part-per-billion level, the system resembles a "vacuum" regarding magnetic noise properties.[30]

The experimental confirmations of this lack of magnetic noise come from magnetic resonance experiments on bulk silicon crystals. These crystals are isotopically enriched with 99.9995% ^{28}Si and are probed using inductive and optical techniques. These experiments focus on sparsely distributed phosphorus impurities, acting as donors within the material at a density of 10^{15} cm^{-3} (one in every 100 million atoms).[31] These donors behave analogously to suspended single-charged ions for conduction electrons. Notably, these "ions" remain isolated within an extremely quiet material, exhibiting minimal motion due to lattice vibrations.[32] In Figure 4, the two examples of silicon qubits are shown. The first is the qubits based on the quantum dots, and the second design is by doping silicon with phosphorus and using the nuclei of the dopant instead of electrons for a two-level system.

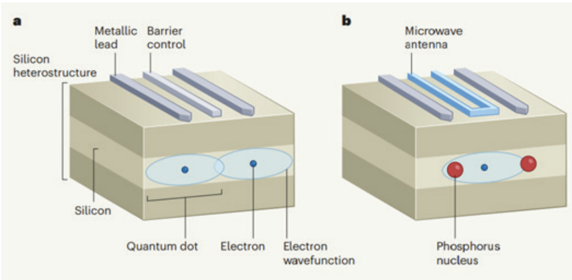

Figure 4: Examples of silicon qubits are based on a) quantum dots, these traps contain single electrons at the interface of semiconductor materials. b) A similar goal can be achieved by doping phosphorus and using its nuclei instead of electrons. A microwave antenna controls nuclei interactions.[33]

Silicon qubits, also known as spin qubits, use the spin states of electrons or holes confined in silicon quantum dots or donor atoms dopped in silicon.[34] This qubit can be divided into three types: 1st) Quantum dot spin qubit, 2nd) Donor spin qubit, and 3rd) Hole spin liquid. Figure 4.a shows an example of a quantum dot design, and Figure 4.b shows an example of a design using phosphorus as the electron donor.[33]

The ground state preparation in silicon qubits happens by applying electrostatic potentials using gate electrodes. Then, the control and gate operation happen via microwave pulses that cause the transition between different states.[35] Finally, the readout in these qubits happens by using the electron's charge that its spin is used to make the qubit. By tunneling that electron to a different channel and measuring the charge, one can measure what state was occupied by the electron.[36]

- ***Photonic Qubits:***

Utilizing photons as carriers of information offers evident benefits. Photons represent pristine and decoherence-resistant quantum systems, allowing for high-fidelity single-qubit operations. Simultaneously, using photons as "flying qubits" becomes crucial for tasks related to quantum information handling, encompassing communication-based quantum information science.

In 2001, a paper published in Nature Journal by Emanuel Knill and Raymond LaFlamme from Los Alamos National Lab and Gerald Mulburn from the University of Queensland, Australia (known as KLM) presented a concept for quantum computing using linear optics.[37] Prior to this publication, the prevailing belief was that a quantum computer, to possess the characteristics of a universal Turing machine, would require specific nonlinear interactions among qubits within quantum gates.

Implementing a CNOT gate optically faces challenges due to the inherent aversion of photons to interact with one another. This issue is also observed in all-optical classical computers. Although there are methods to induce light-to-light interaction, such as within nonlinear optical materials and single atoms within optical cavities can interact with single photons in ways resembling CNOT or similar gates in quantum optics, the efficiencies remain notably low. Furthermore, the associated implementation costs are considerably high. Consequently, the scalability of these systems to create entire networks essential for a universal quantum computer becomes intricate or potentially unachievable. The publication of KLM's concept for quantum computing with linear optics triggered a shift in how optical quantum computing was conceptualized. Their proposal suggested that a universal optical quantum computer could be constructed using basic elements like light sources, beam splitters, and photon detectors.[38]

KLM's approach circumvents the need for direct nonlinear interactions between photons by utilizing post-selection. Their method sends sets of photons, including signal and ancilla (test) photons, through a linear optical system. The detection of ancilla photons determines the success of a computation iteration. If detection doesn't occur as intended, the iteration is discarded until the desired outcome is achieved. At this point, entanglement and measurement collapse are exploited through post-selection, enabling the signal photons to have the selected quantum states.[39] This process creates effective nonlinearity induced by the collapse of the entangled state, effectively utilizing entanglement and measurement collapse to prepare functional quantum states. However, this approach introduces non-determinism as many iterations are discarded.[40]

While KLM could reduce the noise by using more ancillary photons, this approach inflates implementation size and costs, making it impractical. Nonetheless, their contribution was critical as it introduced the notion of linear quantum computing. This idea encouraged further refinements, efficiency improvements, and scalability enhancements by subsequent researchers. These advancements often depend on photonic integrated circuits (PICs), a technology evolving in tandem with quantum computing. A significant advantage of photons is their non-interacting nature. They remain unaffected by their surroundings, making them excellent information carriers through fiber optics and proficient qubits for conveying quantum information. A photon's quantum superposition can be established by simply passing it through a lossless polarizing crystal, and this superposition can persist as long as the photon travels. This durability means that even storing a photon in a coiled kilometer-long fiber is feasible without significantly sacrificing size. Hence, the properties that make photons superior for information transmission also grant them minimal susceptibility to decoherence. With the development of KLM schemes, the non-interacting quality of photons ceased to be an obstacle. In summary, photonic qubits are the leading candidates for quantum communication.[41]

Discussed nonlinear optics are used to make qubits using different properties of light. Polarization qubits use the polarization states of photons, such as horizontal and vertical polarization of photons. And any other polarization can be written as the superposition of these two states.[42] Another photonic qubit design uses photons' paths to encode information in photonic qubits. These qubits can be manipulated using linear optical elements like beam splitters, wave plates, and phase shifters. Single-photon detectors are being used to read out these qubits.[43]

Before starting to compare the DiVincenzo criteria for each of the qubit designs, we will also mention different approaches to quantum computing; all the qubit designs that we mentioned before are all of the computation method known as universal gate model quantum computer, in which logical

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gates are applied by applying physical gate on the qubits. Another approach is Quantum annealing. Quantum annealing, encompassing adiabatic quantum computation, is a quantum computing technique employed to discover optimal solutions for complex problems with numerous potential solutions. This method capitalizes on unique quantum properties inherent to quantum physics, such as quantum tunneling, entanglement, and superposition. In this work, we refrain from discussing the qubit designs for quantum annealers since they use a benchmark that is different from universal gate qubits, and a comparison of these qubits on the same level may introduce deceiving results.[43]

DiVincenzo criteria comparison:

In this part, we only consider the first five DiVincenzo criteria to compare the different qubit designs.

- ***A scalable physical system with well-characterized qubit:***

One of the primary hurdles facing the field of quantum computing revolves around scalability. This refers to the capability of expanding both the quantity and quality of qubits within a quantum computing system, all while maintaining optimal performance and reliability. Scalability is pivotal in attaining quantum advantage, the point at which quantum computers can surpass classical counterparts in specific tasks. However, several limiting factors constrain scalability. These include the availability and affordability of appropriate materials and hardware, the complexities of governing and interconnecting qubits, the delicate balance between coherence time and gate speed, and the additional demands of error correction and fault tolerance. Presently, the most extensive quantum computers have around 50 to 500 qubits, a considerable distance from the thousands or millions of qubits required for practical, real-world applications. Between the qubit designs, superconductors and silicon qubits are easier to scale since the manufacturing technology for producing them is the same as the technology to produce silicon chips. In this case, the challenge will be the qubit connection design and possible ways to control and limit the noise in the qubits.

The problematic aspect of neutral atoms and trapped ions is designing a large-scale laser to trap and control the qubits. Photonic qubits are very useful for information transportation; however, their gate operations are only partially developed since the photons do not interact easily. Therefore, this is the first obstacle that needs to be overcome before designing scalable quantum processing units.

- ***The ability to initialize the state of the qubits to a simple fiducial state:***

Initializing the state of qubits to a simple fiducial state is important in quantum computing for several reasons: 1) standardization: simple fiducial states serve as standardized starting points for quantum algorithms and operations. This consistency ensures that quantum computations begin from a well-defined and understood initial state. It simplifies the analysis and comparison of different quantum algorithms. 2) error mitigation: quantum systems are susceptible to various errors, such as noise and decoherence. Starting with a known fiducial state makes it easier to detect and correct errors that may occur during quantum operations. It provides a reference point against which deviations can be measured and corrected. 3) algorithm design: many quantum algorithms are designed to take advantage of specific initial states. Initializing qubits to a simple fiducial state can make it easier to implement these algorithms efficiently. For example, some quantum algorithms exploit that qubits start in a state of all zeros or a specific superposition state. 4) quantum state preparation: some quantum computations require specific quantum states as inputs. Initializing qubits to a desired fiducial state is often the first step in preparing these states for subsequent quantum operations. For example, specific quantum simulations may require initializing qubits to represent a particular quantum system's ground state. 5) benchmarking and validation: fiducial states are useful for benchmarking and validating quantum hardware. By initializing qubits to a known state, researchers can assess the performance and accuracy of quantum processors. This is particularly important as quantum computing technology continues to advance. 6) Simplifying Quantum Gates: Some quantum gates and operations are more straightforward to implement when qubits are in specific fiducial states. For instance, gates that flip individual qubit states are easier to apply when qubits start in a known state.

In summary, initializing qubits to a simple fiducial state provides a foundation for quantum computations, helps in error detection and correction, facilitates algorithm design, and simplifies the benchmarking and validation of quantum hardware. It is a fundamental step in quantum computing that enhances the reliability and efficiency of quantum algorithms and systems.

Not all qubits are created equal when initializing them to a simple fiducial state. Different types of qubits have varying properties and requirements for initialization. The specific method and ease of initializing qubits depend on the physical implementation of the qubit. Here are a few examples of qubit types and their initialization challenges: 1) Superconducting qubits are typically initialized by cooling them to extremely low temperatures and applying microwave pulses. The initialization process can be relatively straightforward but may require precise control over the microwave signals and the cooling equipment. 2) Trapped ion qubits in trapped ion and neutral atoms systems can be more complex. It often involves manipulating the internal energy levels of the ions using laser beams. Achieving the desired initial state may require careful timing and control of laser pulses. 3) Quantum information can also be encoded in photonic qubits (e.g., using polarization states). Initializing photonic qubits may involve generating single photons and manipulating their polarization states using wave plates or other optical elements. 4) Quantum dots or semiconductor defects can serve as spin qubits. Initialization often involves preparing the electron or nuclear spin to a specific state using magnetic fields and microwave or radiofrequency pulses.

The exact details of initializing qubits can vary even within the same qubit type, as different experimental setups and hardware configurations may be used. Additionally, the control and precision required for initialization can differ significantly. Some qubits, such as photonic, superconductor, and silicon

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qubits, are more forgiving or easier to initialize accurately than others.

Long relevant decoherence times:

Long relevant decoherence times are crucial for qubits in quantum computing for several reasons: 1) Longer decoherence times reduce the probability of errors during quantum operations. Decoherence is a process in which quantum information becomes increasingly susceptible to external noise and environmental interactions. With longer decoherence times, there is a larger window of time during which quantum operations can be executed accurately, minimizing the impact of errors. 2) Quantum algorithms often involve a series of quantum gates and operations that must be executed in a precise sequence. Long decoherence times allow for more extensive and intricate quantum computations, enabling the execution of complex algorithms that require many quantum gates. 3) To build large-scale, fault-tolerant quantum computers, error correction codes are employed to mitigate the effects of errors. Longer decoherence times provide more flexibility in implementing these error correction codes, allowing for multiple rounds of error correction before quantum information is lost. 4) Quantum memory elements are crucial for storing intermediate results in quantum algorithms and building quantum communication systems. Longer decoherence times are essential for maintaining the integrity of stored quantum information, which is necessary for the correct functioning of such systems. 5) In practical quantum applications, especially in fields like cryptography, optimization, and material simulation, longer decoherence times are necessary to perform computations or simulations over extended periods. This is vital for addressing real-world problems efficiently. 6) Achieving quantum advantage, where quantum computers outperform classical computers in specific tasks, often requires long decoherence times. Complex issues that offer quantum advantage may involve lengthy computations, making long coherence times a prerequisite for demonstrating quantum superiority.

In summary, long decoherence times are essential for the practicality and utility of quantum computing. They enable the execution of complex algorithms, facilitate quantum error correction, support quantum memory and communication, and are fundamental to unlocking the full potential of quantum technology for various applications. Below, we summarize the comparison of decoherence time between different qubits by the end of 2022. As shown in Table 1, neutral atoms and trapped ions have the advantage here since they interact less with the environment.

Table 1: Summary of the reported performance of different qubits by the end of 2022.[44]

Modality	Superconducting	Trapped Ion	Photonic	Neutral Atom	Silicon Spin
Number of Qubits	127Q	32Q	20 Photons/ 216 Qumode	100Q	2Q
T2 Lifetime	Short $15\mu s - 256\mu s$	Long $2s - 50s$	Short $150\mu s$	Long $0.2s - 10s$	Mixed $1s - 0.5s$
2Q Gate fidelity	High $99\% - 99.7\%$	High 98.5%-99.2%	Promising 98%	Promising 97.4%	Promising 90%-98%
Gate Speed	Fast $10ns - 196ns$	Mixed $1\mu s - 3ms$	Ver Fast $1ns$	Medium $1\mu s$	Fast $0.8s - 80ns$

- ***A "universal" set of quantum gates:***

Often referred to as a universal gate set, it is a specific set of quantum gates that can approximate any unitary transformation on a quantum state with arbitrary precision. This universal gate set is a fundamental concept in quantum computing, as it allows for constructing a wide range of quantum algorithms. While the exact gate set can vary slightly depending on the specific quantum hardware, some commonly used gates include 1) Pauli-X, Pauli-Y, and Pauli-Z Gates, the single-qubit gates that are similar to classical bit flips and phase flips and are essential for manipulating qubits independently. 2) Hadamard gate is the gate that creates superposition states. It is crucial for many quantum algorithms, including quantum search and quantum teleportation. 3) CNOT (Controlled-NOT) gate: this two-qubit gate acts as a conditional bit flip, making it a fundamental gate for creating entanglement and implementing various quantum algorithms. 4) T-gate, which introduces a π/4 phase shift to a qubit state. 5) Rz Gate: this single-qubit gate rotates around the Z-axis, allowing for more general quantum state manipulations. In Figure 5, these single qubit gates are shown. For each gate, the matrix representation of the gate and the evolution of the qubit state is shown after the gate is applied.

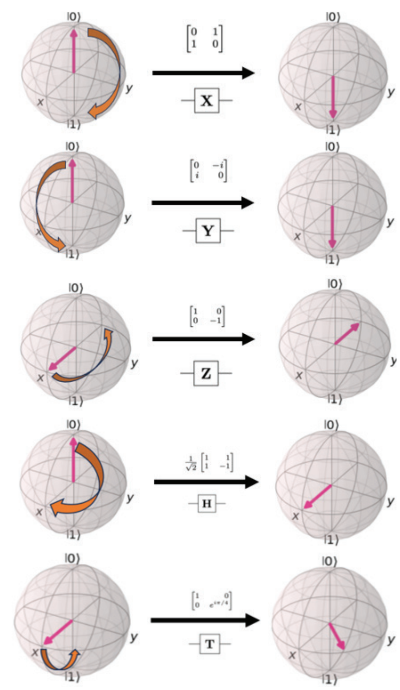

Figure 5: Schematic of how the X, Y, Z, H, and T gates work. On the left, the starting state of spin is shown, and on the right, the spin state is shown after the gate operation. On top of the arrow, the matrix representing the gate is shown, and on the bottom of the arrow, the symbol for the gate is presented.

These gates and some additional single-qubit and two-qubit gates form a universal gate set commonly used in various qubit designs, including superconducting qubits, trapped ion qubits, and others. Implementing these gates accurately and coherently is a critical factor in the design and performance of quantum hardware. It is important to mention that both single-qubit and two-qubit gates are essential for gate-based computation. We can refer to Table 1 to compare the two-qubit gate fidelity,

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and we can see that trapped ions and superconducting qubits have the advantage here. One other factor is the gate speed. The faster the gate speed, the more gate operation is done before the decoherence of the qubit. In this case, superconductor qubits and silicon qubits have the advantage.

- ***A qubit-specific measurement capability:***

Different qubit designs can exhibit variations in their measurement capabilities due to the underlying physical principles and measurement techniques employed. Here are some aspects of qubit-specific measurement capabilities in various qubit designs: Superconducting qubits are often measured using microwave resonators. These qubits are coupled to resonators, and their state information is extracted by measuring the resonator's electromagnetic response. The measurement is typically non-destructive, allowing for subsequent quantum operations. Superconducting qubits are known for their high-fidelity readout capabilities, enabling accurate state measurements. In trapped ion systems, qubit measurements are often achieved by detecting fluorescence emitted by the ions. When an ion undergoes a quantum state change, it can emit a photon whose properties (such as polarization or frequency) carry information about the ion's state. This non-destructive measurement allows for repeated measurements and high fidelity. Photonic qubits are typically measured using various optical components, such as beam splitters, wave plates, and detectors. The quantum state of a photonic qubit is often mapped onto the state of photons, and measurements are made on these photons to determine the qubit's state. Photonic qubits offer the advantage of being naturally suited to optical measurements and can be transmitted over long distances for quantum communication. Spin qubits implemented in semiconductor materials can be measured using electrical or optical techniques. Electrical measurements involve monitoring the charge state of the qubit, while optical measurements may involve using lasers to probe and manipulate the qubit's spin state.

It is important to note that the specific measurement capabilities and techniques can vary between different qubit designs and within the same qubit design, depending on the experimental setup and hardware configuration. Researchers continually work on improving measurement fidelity and efficiency in various qubit technologies to advance the field of quantum computing.

Conclusion

In today's evolving realm of quantum computing and quantum technologies, delving into the intricacies of qubit designs plays a crucial role. Qubits, serving as the cornerstone of quantum information processing, are pivotal components in groundbreaking advancements set to revolutionize various industries. They represent the key to transformative developments poised to reshape sectors across the technological landscape. This field can be overwhelming for newcomers. Therefore, this review article discusses the main principles and criteria that should be met in qubit design. We compared DiVincenzo criteria for superconductor, trapped ion, neutral atom, silicon, and photonic qubits. It is discussed that superconducting qubits are leading the qubit design in quantum computers since they satisfy all the Divincenzo criteria and are easier to scale to make larger processing units. Trapped ions and neutral atoms come next, especially with longer decoherence time than superconductor qubits. However, they are more challenging to scale in comparison with superconducting qubits. Photonic qubits show their advantage regarding quantum information transfer, but gate operation is difficult in this qubit design. The other qubit designs are still young and under development.

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