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Comparing Qubit Platforms in the Race to Feasible Quantum Computing

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ABSTRACT

Quantum computing is an emerging field that has been attracting a substantial amount of interest in the scientific community lately due to the advantages of quantum information processing. The fundamental unit of quantum information that makes up a quantum computer is a qubit. Several platforms have been proposed as physical realisations of these qubits for the purpose of making quantum computing a feasible technology, yet no one platform has significantly outperformed the others. This literature review discusses the current state of the field of quantum computing, by comparing and contrasting some of the most promising qubit platforms of today. By doing so, this paper analyses each of their feasibilities for full-scale quantum computing in the future and maps out a possible trajectory for how quantum computing may progress in the next few years.

Motivation [1]

Quantum computing harnesses the quantum effects present at microscopic scales to result in a completely different model of computation when compared to the classical model of computing which has been prevalent for over the last 60 years.

It was first conceptualised in the 1980s as a way to simulate certain quantum interactions that took classical computers an impractical amount of time (Feynman, 1982). The problems that quantum computing is expected to solve relate to quantum simulation and certain specific mathematical calculations that fall under the classification of BQP (Bounded-error, Quantum Polynomial time). BQP problems encompass all P problems (the subset that can be efficiently solved by classical computers), in addition to a few NP problems like the factoring of large numbers. It does not, however, include NP-complete problems, whose efficient solution, if found, would constitute an efficient solution of all NP problems. Thus quantum computing is not a miracle technology that can be used to solve all difficult computational problems, and it will not overturn the entire paradigm of computation while replacing classical computers. Quantum computers will instead occupy a niche functionality – by solving the problems only they can (problems within BQP but outside P) and will work in tandem with classical computers once they are sufficiently developed.

It must be also noted that quantum computers provide no extra benefit over classical computers in terms of computability - a classical computer can solve any problem a quantum computer can. Their advantage lies in their ability to solve problems that would take even the most powerful supercomputers an impractical amount of time to compute.

Introduction [2]

The Qubit

The fundamental unit of quantum information that makes up the quantum computer is known as the 'quantum bit' or 'qubit'. They are the quantum analog to classical bits. The basis for qubits are quantum mechanical systems that exhibit quantum properties such as entanglement and superposition.

A qubit state can be represented as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $|\psi\rangle$ is the state vector of the qubit, $|0\rangle$ and $|1\rangle$ are the base qubit states, and α and β are the complex probability amplitudes corresponding to the states $|0\rangle$, and $|1\rangle$ respectively. It must be noted that in this representation, $|0\rangle$ and $|1\rangle$ serve only as labels for ease of use and can represent anything from the energy level of an ion to the spin of an electron. The qubit can be in either of these base states, or a superposition of them, with α^2 probability of the qubit being in state $|0\rangle$, and β^2 probability of the qubit being in state $|1\rangle$ when observed.

Qubits also demonstrate the characteristic property of entanglement, where two or more can be linked such that the quantum state of one qubit cannot be characterized independently of the others. In other words, their states are no longer separable. This property enables strong communication with a perfect instantaneous connection between qubits, which can be maintained even after they are separated. For an entangled system of qubits, adding extra qubits increases the computational power exponentially whereas adding bits in a classical computer increases the computational power only linearly.

The additional computational power that qubits provide comes with restrictions of its own. A phenomenon known as decoherence, where qubits undergo undesirable entanglement with their environment, can lead to the collapse of quantum superposition. This significantly limits the number of computations that qubits can perform and improving qubit coherence times is one of the main obstacles that needs to be overcome on the path to making quantum computing a feasible technology.

Selection of Qubit

Technically, any quantum system represented by 2 states is a qubit. Qubit physical realisations can be broadly divided into two categories: natural and synthetic. Natural qubits are innately quantum mechanical bodies that can be harnessed for quantum computation (such as ions). On the other hand, synthetic qubits have to be manufactured and are engineered into 'artificial atoms' that possess quantum-mechanical properties.

To be useful for quantum computing, qubits need to adhere to certain criteria, which were systematically laid out by physicist David DiVincenzo in 2000 (DiVincenzo, 2000). The DiVincenzo Criteria are a list of five requirements for the implementation of quantum computation. Thus, any proposed platform for the physical implementation of qubits must first satisfy the DiVincenzo Criteria to be considered viable.

The criteria are:

1. A scalable system with well-characterised qubits
2. The ability to initialise the state of the qubits to a simple fiducial state
3. Long, relevant decoherence time, much longer than gate times
4. A universal set of quantum gates
5. A qubit specific measurement capacity

Since DiVincenzo's influential paper, many qubit platforms have been proposed, such as superconductors, trapped-ions, solid-state systems, nitrogen vacancies in diamond, etc. All of these satisfy the five criteria, yet none of them have been able to perform the difficult computations that quantum computers are expected to, like factoring a 10 digit number in a matter of minutes and other such BQP problems. A natural question one might have then, is "If so many physical platforms for quantum computing have been deemed viable, then why hasn't a single fully-fledged quantum computer been built yet?" The issue that arises here is *feasibility*. The 5 DiVincenzo criteria only certify that a quantum computer built from a certain physical realisation is possible. It makes no claim about the practical considerations, such as the size of the apparatus, costs, and required engineering, that need to be taken into account.

In 2018, Professor John Preskill coined the term 'NISQ' (Noisy Intermediate-Scale Quantum) to describe the level of quantum computing that will be available in the near future (Preskill, 2018). Quantum computation was expected to cross the 50 qubit barrier (as indicated by 'intermediate'), and supersede even the best supercomputers at certain tasks. This significant milestone has already been achieved with the superconducting qubit modality in a 53 qubit system (Arute et al., 2019). This is referred to as quantum supremacy: a benchmark for quantum computing where the quantum processor can outperform the best classical processor at a specific task. 'Noisy' indicates that qubit control will remain imperfect due to error-correcting codes necessitating many more physical qubits than currently available. It is this era that quantum computation currently finds itself in.

Scope of this Review

Comparing different qubit implementations is difficult since researchers still haven't settled on universal parameters to judge them against. For the purposes of this paper, the two parameters that the qubit implementations will be judged by are expected to have a direct consequence on how successful they will be in navigating through the current NISQ stage given their current capabilities.

To this effect, we shall explore 4 promising qubit platforms, taking examples of two natural and two synthetic implementations respectively: trapped ions, neutral atoms, semiconductor quantum dots, and superconducting circuits. The two parameters I will base my comparison on are:

Scalability

To build a practical quantum computer, one that provides an advantage over what classical computers can deliver, qubit systems must be scaled up to sizes much greater than that which currently exist. Scalability involves more than just increasing the number of qubits in the system: it necessitates that we can also perform high-fidelity control and readout operations as well as maintain entanglement between the qubits. In other words, the quality of the computation achieved needs to remain intact while the system increases in size. The scalability of the qubit platform is perhaps the most important parameter determining its success in the quest for full-scale quantum computation too since full-scale error correction needs a large number of physical qubits.

This section will discuss the currently implemented, as well as proposed architectures for scaling up each of the qubit systems. It will also describe certain factors that need to be taken into account, such as the reproducibility of qubits. It will conclude with a quantitative overview of what has currently been achieved with regard to the scalability of the platform realisation.

Qubit Quality

This section will take a more quantitative approach.

Long decoherence times compared to the gate operation times are a requirement as per DiVincenzo's criteria. All of the qubit realisations considered in this paper have fulfilled this basic requirement. Nevertheless, a longer decoherence time translates to a decreased frequency of errors caused by random qubit dephasing. Additionally, it is generally accepted that ratios of 10^4 to 10^5 between the decoherence and gate operation time will be sufficient to satisfy the threshold for fault-tolerant quantum computing when it does emerge (Marinescu, 2016, p. 56).

Gate-operation times will be considered too. Whereas a larger ratio between qubit decoherence times and gate-operation times is essential for a particular qubit realisation to even be possible, absolute gate times play an important but more subtle role. As the qubit modality is scaled up to solve more real-world problems like Shor's factoring algorithm, and the number of gates required per computation increases drastically, the absolute gate operation times will play a large role in determining the speed of the calculation itself.

Gate-fidelity is also an important metric as it measures the "correct-ness" of a gate operation. This is important, since the higher the gate fidelities, the more accurate the computation will be. It also determines whether error-correction codes can be applied to a certain qubit platform, depending on whether the error rate falls within the threshold for the particular code. An example of such is surface code, with an error rate threshold of 0.01 (Wang et al., 2009), corresponding to 99% gate fidelity. However, for the purposes of feasibility, this number gives an under-estimate, since accounting for a 1% error rate would require many more physical qubits than are currently available. Therefore in the NISQ era, where quantum computing systems are expected to remain intermediate in size, a smaller error rate and thus greater fidelity (for both single and two-qubit gates) than 99% must be demonstrated to feasibly implement error correction.

These 3 factors, taken together, can be addressed as the so-called "quality" of the qubit and compared numerically against other physical qubit realisations. It can therefore provide a valuable quantitative metric to judge qubit platforms.

The literature review, consisting of the bulk of this paper, will serve as an exploration of the implementation of the four qubit platforms. For each of the four, a uniform structure will be followed, giving the reader a sense of parallelism in order to make the comparisons that will eventually be drawn in the discussion seem more natural and apparent. The structure will be as follows.

First, an overview of what the qubit is will be provided and its basic method of functionality will be described. The review will then transition into an analysis of the current status of the qubit platform with regard to the scalability and qubit quality. The overview alongside the 2 sections meant for comparison will be numbered for easier reference in the discussion section as well as for the reader.

Literature Review [3]

Trapped-Ion (3.1.0)

The trapped-ion implementation was first proposed by Ignacio Cirac and Peter Zoller in 1995 (Cirac & Zoller, 1995). In this model, ions confined within traps serve as the qubits that make up the quantum computer's building blocks.

Group II ions such as Yb^+ (Noek et al., 2013) are typically confined in radiofrequency (RF) Paul traps with oscillating electric fields (Leibfried et al., 2003) or in microfabricated surface traps (Chiaverini et al., 2005), with the ions residing in potential minima. In the former, the potential minima take the form of RF nulls and can either be point traps, where the ions are confined at a point in 3 dimensions, or linear traps, where there is zero RF field along a line and the ions are trapped in a linear array. In the latter, electrodes are arranged in a planar geometry and the potential minima are located above the surface.

Pairs of internal electronic states of ions are implemented as the base qubit states $|0\rangle$ and $|1\rangle$. They can be any combination of long-lived levels, differentiated by the separation of their energy levels. The 2 most predominant ones are hyperfine levels, separated by gigahertz frequencies; and optical levels, separated by frequencies of hundreds of terahertz.

After the ions are loaded into their traps, the qubits are optically pumped into the fiducial state of $|1\rangle$. The methodology of gate operation via state transition is dependent on the type of trapped-ion qubit. For optical qubits, a laser with a resonant frequency equal to the state transition is utilised whereas gate operations on hyperfine qubits can be performed either with lasers using stimulated Raman Coupling or with microwaves directly addressing the gigahertz energy level splitting.

The state-dependent readout is carried out by lasers as well. Using contemporary methods, readout fidelities of over 99.9% have been achieved within microseconds (Crain et al., 2019; Myerson et al., 2008).

Scalability (3.1.1)

Due to the identical nature of ions, concerns about the reproducibility of the qubits are reduced and the need for system calibrations to account for minute differences in qubit design are minimised. Among the different types of trapped-ion qubits, optical qubits are regarded to have the most potential in terms of scalability.

Thus far, most quantum computing demonstrations with trapped-ions have been performed with the use of linear arrays (Debnath et al., 2016; Figgatt et al., 2017; Monz et al., 2011). Although in principle, more than a thousand ion qubits could be stored in such macroscopic RF traps, one would have little to no meaningful control over these ions with respect to manipulation of states and readout. The largest linear arrays with which control and readout have been demonstrated have about 100 ion qubits, but these have yet to demonstrate entanglement operations with satisfactory fidelity between arbitrary qubits in the system, a feature that would be necessary for large-scale quantum computing.

These shortcomings can be attributed to the decrease of the speed and fidelity of 2 qubit gates as the number of ions in the chain increases. As the size of the ion chain increases, its mass increases as does the average distance between ions. This in turn leads to a decrease in the coupling strength between arbitrary ions, causing a decrease in speed of 2 qubit gates. Fidelity decreases due to the increased susceptibility among the normal modes used to mediate the 2-qubit interaction to unwanted spectral crosstalk interaction, as well as to noise-induced heating in the system if the gates take longer. A way to circumvent this problem is to break up the long linear chain into smaller modules. High-fidelity entanglement operations can be performed within the modules and they can then be reconfigured such that entangling gates can be performed between ions of formerly different modules (Kaufmann et al., 2017). The ions can subsequently be returned to their original modules. However, the SWAP gates required to perform this operation are time-consuming and error-prone.

Two alternative architectures proposed to scale trapped-ion quantum computers with the use of modules are with 2-dimensional arrays (Kielpinski et al., 2002) and photonic interconnects (Monroe et al., 2014). In the former, modules each consisting of a few ion qubits are arranged in a 2D array.

The introduction of a second dimension opens up the possibility of shuttling the ions themselves between modules to transfer quantum information. This can be done between any qubits in the plane without incurring the significant time and error costs of swapping quantum information via entangling gates or chain reordering operations.

For photonic interconnects, remote entanglement between ions of different modules is carried out using communication ions. Two communication ions in different modules are excited using lasers so that they emit a photon entangled with the ion's internal state. The photons then interfere on a 50/50 beamsplitter. Single-photon detectors on the output ports of the beamsplitter then simultaneously detect the photons. This results in entanglement between the two communication ions and thus opens up a quantum information transfer channel between the modules.

However, the two proposed architectures above have not yet been implemented for direct quantum computation due to difficulties in engineering their complex architectures.

In terms of scalability achieved so far, trapped-ion qubits are on the lower end of the spectrum. The difficulties of implementing the necessary optical and electronic control have slowed progress toward larger numbers of trapped ions as compared with other technologies where analogous control elements are integrated into the qubit chip itself.

Despite these shortcomings, trapped-ions have made notable progress in terms of scalability recently, culminating in the startup Ionq building a quantum computer composed of 32 ions (*Introducing the World's Most Powerful Quantum Computer*, n.d.).

Qubit Quality (3.1.2)

Typical sources of decoherence for trapped-ion qubits are spontaneous random emissions from the ions themselves or qubit energy level shifts as a result of fluctuating fields.

Trapped-ion qubits have extremely long decoherence times, ranging from 0.2 seconds in optical qubits (Bermudez et al., 2017) to 600 seconds in hyperfine qubits (Wang et al., 2017). The absolute two-qubit gate operation times for trapped-ion qubits are also quite long at 1.6 μs (Schäfer et al., 2018).

The large ratio between the decoherence and gate operation time of around 10^9 (in fact it is the highest among all qubit types) means that decoherence of the quantum states of the qubit due to coupling to the environment is minimal and thus this reduces the frequency at which error correction is required.

However, the long absolute gate operation times prove to be a hindrance when it comes to the speed of the computation. Since practical quantum algorithms have a significant number of operations, a trapped-ion quantum computer may take a considerable amount of time performing a computation even if it is ultimately accurate. Due to the gate speed in classical computers currently exceeding the gate speed of trapped-ion quantum computers by a factor of 10^4, achieving quantum supremacy may prove to be a difficult task for the implementation of trapped-ions as qubits.

Trapped ions also boast high gate fidelities. Single-qubit rotations demonstrating fidelities of 99.9999% have been demonstrated (Harty et al., 2014), which is the highest among all the other qubit modalities. In addition, the fidelities demonstrated for the two-qubit gates necessary for entanglement have shown impressive results, with 99.9% for hyperfine qubits (Ballance et al., 2016) and 99.6% for optical qubits (Gaebler et al., 2016). These results are only rivaled by the two-qubit gates with superconducting qubits.

Neutral Atom (3.2.0)

The model of quantum computation using neutral atoms was initially proposed in 2000-2001 in 2 influential papers (Jaksch et al., 2000; Lukin et al., 2001). In this model, atoms of neutral alkali metals like Rb in optical arrays form the basis for qubits.

To initialise the atoms in the array, they are first laser-cooled to reduce their temperatures to near absolute zero. They are then confined in traps implemented by either lasers or magnetic fields. For this review, optical traps will be considered. A simple example of such a trap would be the use of optical tweezers. They are red-detuned laser beams that hold an atom (and therefore a qubit) in their focal point. An array of such traps produces an array of neutral atom qubits capable of quantum computational tasks, which can be arranged in 1D (Endres et al., 2016), 2D (Barredo et al., 2016), as well as 3D geometries (Wang et al., 2015).

Similar to the trapped-ion platform, the basis qubit states $|0\rangle$ and $|1\rangle$ are encoded in long-lived internal electronic states of the atom such as the hyperfine levels. The qubits are initialised to their fiducial states by optical pumping.

Single-qubit gate operations are achieved by driving atomic transitions using laser beams tightly focused on a single atom, or by microwaves, for which the targeted atom's resonance needs to be shifted using magnetic fields or laser beams. Two-qubit gates would seem to be a hindrance for neutral atom qubits due to their weak interactions with each other; however, this problem is solved by exciting atoms to Rydberg states. A Rydberg atom exhibits a strong dipolar interaction and produces a phenomenon known as the Rydberg blockade, which prohibits more than one atom in a small volume from being simultaneously excited to a Rydberg state. This can be used to produce entanglement between two atoms using a three pulse sequence.

The readout of the neutral atom array is typically done by taking a fluorescence image at the end of the computational process. It is performed such that each atom in the state $|0\rangle$ will appear bright, whereas atoms in the state $|1\rangle$ remain dark.

Scalability (3.2.1)

As with other types of natural qubits, all neutral atom qubits are identical. This feature greatly reduces the complexity of the control system required to address the qubits as well as enhancing the connectivity between the atoms in the register. However, this proves to be a disadvantage too, in that the homogeneity of the atomic qubits renders them susceptible to unwanted crosstalk during qubit operations.

Quantum computing with neutral atoms has already demonstrated control of a substantial number of qubits, with recent experiments in 1D, 2D, and 3D geometries showing control of up to 50 atomic qubits (Bernien et al., 2017; Wang et al., 2016; Xia et al., 2015). Each dimensional implementation has its strengths and weaknesses: qubits in 2D and 3D geometries have a greater ability for implementing error correction due their increased number of proximal qubits; however, addressing atoms in a 3D geometry proves to be exceedingly difficult without inducing crosstalk. Thus the 2D approach is typically favoured, with individual addressing using lasers normal to the plane containing the qubits.

The weak interactions between the ground states of the atoms contained in the array are instrumental to the system's scalability. They enable qubit arrangements with array periods of just a few μm being capable of qubit-specific optical addressing without compromising coherence times. This means that up to ten thousand atoms can be trapped in a 0.5 mm 2D array and a million atoms can be trapped in a 0.5 mm 3D array. The promise of such dramatic scaling is a major attraction to the neutral atom model of quantum computing.

Despite the neutral atom platform's success so far in terms of scalability, there are still several factors that limit the size of their arrays that need to be overcome to navigate the challenges of the NISQ era. A primary example is simply that larger arrays require more laser power due to the increase in the number of traps.

Another, more subtle hindrance that arises is the balancing act that needs to be maintained between the desired trap depth and detuning from the nearest optical transitions. The trap depth decreases as the detuning increases, the former being an undesirable outcome since a larger trap depth decreases the probability of the atom in the site being knocked out due to collisions with neighbouring gas atoms. As the qubit system is scaled up, the frequency of such collisions increases, thus requiring a greater trap depth to maintain all the atoms in the array. So it would seem that minimizing detuning would be the way forward. However, a certain level of detuning from the resonant frequency of the optical transition needs to be maintained to keep the photon scattering rate below a certain threshold, which would otherwise cause the system to heat up and the qubits to decohere.

Qubit Quality (3.2.2)

The archetypal neutral atom qubit implemented in the hyperfine levels of an Rb atom is weakly coupled to the environment, which results in long coherence times of the order of 10 seconds (Wang et al., 2016). Similar to the trapped-ion platform of qubit implementation, the gate operation times are on the order of μs, with a 2019 experiment demonstrating an entanglement operation requiring 1.2 μs (Levine et al., 2019). The ratio of 10^7 between the coherence and gate-operation times reflects favourably on the viability of the platform. However, unlike trapped-ions, where the μs gate-operation times are disadvantageous with regards to the overall speed of the computation, the neutral atom implementation sidesteps this problem on account of its capability of performing multiple gate operations at the same time on different clusters of atoms. This feature is known as parallelisation and it helps to reduce the overall computational time.

However, the neutral atom platform runs into a significant problem with regard to its gate fidelities. Considering 2D and 3D geometries, single-qubit gates have been performed with around 99.9% fidelities (Wang et al., 2016; Xia et al., 2015). Progress in achieving satisfactory two-qubit gate fidelities has been slow: till 2016, entangling gates had demonstrated a maximum of about 80% gate fidelity (Jau et al., 2016; Maller et al., 2015). This was far below the required threshold for many error correction codes and seemed to be the principal restriction for the feasibility of the platform. However, as a result of extensive research in this area, gate fidelities of 2-qubit operations have seen a marked improvement, and in 2019, gate operations with fidelities of 96.5% were demonstrated (Levine et al., 2019).

This is still under the required minimum threshold for implementing error correction codes, and there is scope for further improvement. Proposed techniques to do so include improved laser sources with reduced noise that researchers hope can be used to increase the gate fidelities of the neutral atom platform in the near future.

Semiconductor quantum dot (3.3.0)

The idea of using the spin of a single electron in a semiconductor quantum dot as a qubit was first proposed by Daniel Loss and David DiVincenzo in 1998 (Loss & DiVincenzo, 1998).

A semiconductor quantum dot is a device akin to a classical transistor where instead of a gate electrode mediating the flow of electrons across the channel, three independently biased electrodes are applied. These shape the potential landscape between the source and the drain to form a potential energy minimum known as a potential well.

To confine electrons within this well, the temperature is lowered to below 4K which decreases the thermal energy of the system below the energy required to add or remove electrons from the well. The host material for these quantum dots can be a variety of materials ranging from GaAs to graphene; however, this review will focus on Si since most modern demonstrations of semiconductor quantum dots have used Si as their base substrate (Angus et al., 2007; Simmons et al., 2007). The simplest spin qubit is a single electron confined in such a potential well, where the basis qubit states |0〉 and |1〉 correspond to the spin of the electron. This is called a spin-½ qubit and it is this design that will be referred to in this review for simplicity. Arrays of quantum dots can be formed by integrating them monolithically on a chip, and for further expansion, the use of on-chip quantum links has been proposed (Vandersypen & Eriksson, 2019).

Single qubit manipulation can be typically performed either via electric or magnetic excitations. Magnetic excitations resonant with the energy difference between the qubit states drive the spin transitions directly. In contrast, resonant electrical excitations result in the electron oscillating inside the quantum dot which in turn causes the electron to experience an oscillating effective magnetic field which causes qubit rotations.

Readout of the qubit state is done by performing a spin-to-charge conversion. This can be achieved by only allowing spin-up electrons to tunnel out of the quantum dot. A charge sensor measures the electron occupation of the well and thus indirectly determines the electron spin and qubit state. This particular process of readout can also be used to initialise the qubit since it results in only electrons with a known spin residing in the quantum dot.

Scalability (3.3.1)

As a result of semiconductors being the dominant technology in the classical computer industry, there is a lot of pre-existing work on scaling up semiconductor technologies.

A single chip can theoretically store millions of integrated qubits implemented via semiconductor quantum dots, however, very little has been achieved experimentally thus far: with only 4 semiconductor spin qubits controlled in the same device (Ito et al., 2018). This failure to produce experimental results can in large part be ascribed to the difficulties in working with the solid-state environment of the qubit, where scaling up introduces a variety of problems.

Semiconductor spin qubits are synthetic qubits that have to be manufactured. The uniformity requirement of the qubits makes this a challenge and results in low yield rates of fabrication in many laboratories. Disorder and noise in the system also need to be minimized to maintain the fidelity of the gate operations and this is done by modifying the voltages on the electrodes to compensate for the material defects. Additionally, semiconductor quantum dot qubits run into a problem characteristic of other solid-state systems in that each qubit necessitates at least one wire connected off-chip for communication with the rest of the system.

There is concern that such inconvenient essentialities could hamper the chances of feasible quantum computing with semiconductor quantum dots, however, many new propositions have been posited that seek to overcome these challenges.

A notable example is the use of on-chip quantum links to overcome the issue of communication between faraway qubits that arises in large systems. This seeks to create networks of interconnected qubit registers by connecting physically distant qubit modules wirelessly. A promising approach to such quantum links is to use microwave photons that have been proven to have significant coupling strength with electron spin qubits (Landig et al., 2018). The microwave photons are expected to indirectly mediate coupling between the concerned qubits while being stored in on-chip superconducting resonators. Alternatively, shuttling the electrons themselves is also an option. This can be done by changing the voltage applied on the gate electrons so that the potential well with the electron inside is shuttled across the chip, ensuring proximity with the qubit it needs to interact with.

Notwithstanding the experimental hiccups with the semiconductor spin platform, their scalability is still regarded favourably due to promising propositions along with the simple fact that their base substrate is Silicon, the same as classical computers. Besides proving that Si information processing is scalable and possible, it also serves as a practical advantage. Due to the transistors of classical circuits utilising the same gate electrodes that semiconductor quantum dots do, integrating the classical and quantum circuits to form quantum co-processors providing situational speed-ups to classical computers is a real possibility and feasible in the near future. Semiconductor spin qubits are also getting more and more attention from researchers, and several groups are endeavouring to scale up the semiconductor quantum dot platform to 10 qubits in addition to achieving large-scale integration within the next decade.

And finally, similar to natural qubit platforms, semiconductor spin qubits can also be made extremely compact, with the average spacing between qubits only 100 nm and each electron in the qubit being confined with 400 nm^2 of space.

Qubit Quality (3.3.2)

Due to the solid-state environment that the electron in the quantum dot resides in, the qubits are at a higher risk of undergoing decoherence due to environmental noise. Thus engineering the environment to minimise its effective noise is a key requirement when it comes to semiconductor spin qubits.

As a result of extensive engineering, the electrons in the quantum dots almost behave like electrons in a vacuum. This has allowed for a qubit coherence time of 20 μs with purified Si (Yoneda et al., 2018) despite the noisy domain the qubits reside in. Semiconductor spin qubits have the capacity to perform two-qubit gate operations in a short time interval, with a recent demonstration carrying out a CNOT operation in about 200 ns (Zajac et al., 2018).

The engineering involved in implementing this particular qubit modality has also allowed for effective qubit control and high gate fidelities of above 99.9% (Yoneda et al., 2018). Despite the challenges faced by the execution of two-qubit gates due to the high-frequency charge noise, researchers have demonstrated the former with 98% fidelity (Huang et al., 2019). This was achieved under suboptimal conditions, making it reasonable to assume that fidelities of up to 99% could be within reach.

The high gate fidelities that have already been achieved with only the first forays into experimentation with semiconductor spin qubits are testament to their potential as a feasible qubit modality; proving that once 2D arrays are practically demonstrated with quantum dots, error correction codes like surface code will be viable to carry out fault-tolerant quantum computing in the near future.

Superconducting (3.4.0)

Unlike the other qubits platforms that have been discussed so far, superconducting qubits are macroscopic entities a few millimetres in size. They are implemented in the form of a solid-state LC electrical circuit, composed of aluminium strips and plates. They can behave as electrical resonators, storing (electrical) energy oscillating at the signature resonance frequency of the circuit. At the low temperatures that superconducting circuits operate at, this can take the form of equidistant quantized energy levels. Subsequently, a non-linear inductor in the form of a Josephson Junction is introduced in the circuit, resulting in non-equidistant energy level spacings.

This finally transforms the circuit into a true artificial atom and therefore allows it to behave as a qubit since each of the energy level transitions can now be uniquely addressed. These circuits can then be fabricated on the 2D surface of a chip similar to other solid-state qubit platforms.

The basis qubit states of the superconducting qubit are typically implemented as the two lowest energy levels of this anharmonic oscillator and are commonly referred to as the ground state and excited state.

The easiest way to initialise superconducting qubits to their fiducial states is just to wait for some time for the qubit to relax to its ground state. This method is slow due to its inherently passive nature, and thus developing quicker initialisation methods is an active area of research.

One such technique involves using a tunable resonator to externally initialise the system composed of a qubit coupled to an engineered environment (Tuorila et al., 2017).

The state transitions necessary to perform single-qubit gate operations are driven by microwave transitions resonant to the qubit transition frequency. There are many possible techniques of enacting two-qubit gates, but they all necessitate the superconducting system to have a coupling term in their Hamiltonians, typically in the form of $\sigma_X\sigma_X$ or $\sigma_Y\sigma_Y$. A common method is as follows. Two qubits are tuned to a certain frequency and subsequently, the evolution operator of the mutual coupling term over a specific time period produces a two-qubit gate such as the iSWAP, thus completing the universal gate set. This particular example is used to couple Xmon qubits, a popular subcategory of superconducting qubits

Readout of the qubit state is performed by coupling the superconducting qubit to photons in a linear readout resonator. This produces a dispersive readout, with low photon numbers emitted depending on the qubit state. The number of photons emitted via this process is subsequently amplified to maintain a sufficiently high readout fidelity.

Scalability (3.4.1)

Similar to other solid-state qubit platforms, superconducting qubits have to be manufactured.

The fabrication process subjects 2D films of superconducting material (like Al) to additive and subtractive techniques, before subsequently integrating them on suitable substrates (like Si), producing a superconducting circuit chip. Conveniently, the manufacture of superconducting circuits is based on the known semiconductor microfabrication process, which has been extensively studied for classical computation. This has allowed superconducting qubits to utilise pre-existing chip-making technologies, which, in turn, has resulted in the platform having a noticeably faster pace in scaling up than other synthetic qubit implementations.

Due to the established manufacturing process, superconducting qubits also hold a notable advantage when it comes to their designability. Particularly, this has let researchers exert control of specific properties of the qubit, allowing them to adjust the qubit energy levels and their coupling strength to other areas of the system, which further increases the platform's potential for scalability. This is achieved by tuning the underlying circuit parameters in the form of the capacitance, inductance, and Josephson energy of the qubit.

The ease of qubit control in terms of coupling follows naturally from the high designability of their systems. The coupling of qubits necessary to perform 2-qubit gates is relatively straightforward when compared to other qubit platforms. The fact that superconducting qubits can be manipulated using microwaves is also a huge pro since it means that commonly available commercial microwave equipment can be used in experiments involving superconducting circuits. The capabilities of such levels of qubit control are expected to provide a boost to the moderate levels of system scaling in the NISQ era.

In this way, the required manufacturing which presents itself as a significant disadvantage of other synthetic qubits modalities as compared to natural ones works in the favour of superconducting qubits.

However, superconducting qubits still have certain disadvantages with regards to their scalability that need to be addressed. A notable issue for feasibility is the low-temperature requirement (of around a few milliKelvin) combined with the macroscopic nature of the superconducting qubit. This necessitates large and powerful dilution refrigerators to preserve the quantum nature of the system, which prove to be quite expensive. The storage capabilities of such cryostats also need further development and they need to be made more cost-effective before superconducting systems can expand beyond the NISQ stage. Increasing the size of superconducting quantum computers is further limited by managing decoherence in their large systems. Nevertheless, these are not absolute physical limitations and researchers are making consistent incremental improvements to system sizes.

The most convincing demonstration of quantum computing has been carried out using superconducting qubits: Google's Sycamore Quantum Information Processor demonstrated quantum supremacy with a system of just 53 superconducting qubits in 2019 (Arute et al., 2019). To put this into perspective, a system of 53 superconducting qubits *significantly* (between 3 and 9 orders of magnitude) outperformed the best classical algorithm performed on the best supercomputer at a given task in terms of the computational time. Quantum supremacy tends to be a bit of a misnomer since it in no way proves quantum computers superior to classical ones; it was achieved for a task (in this case random number generation) specifically chosen due to the difficulty classical computers face in its solving as well as its compatibility with current NISQ devices. There is still a long way to go in scaling qubit systems and this event, however historic, is only a small fraction of what quantum computing is expected to one day achieve.

Nevertheless, viewed simply through the lens of the scalability potential of the superconducting qubit platform, the demonstration of quantum supremacy cements this platform's status as one of the most exciting and promising implementations of today.

As surprising as it may seem, the 53 qubit system used to demonstrate quantum supremacy is not currently the record for the highest number of superconducting qubits controlled in a system, having been overshadowed in terms of size within the span of just a year. IBM's Quantum Hummingbird processor currently controls 65 qubits and represents the apex of the superconducting qubit modality in terms of scalability (*IBM's Roadmap For Scaling Quantum Technology*, 2020).

Qubit Quality (3.4.2)

As with other solid-state qubit platforms, a superconducting qubit is susceptible to environmental noise, typically from the dielectrics of the surrounding metal or from other sources of energy radiation.

The resulting short coherence times of superconducting qubits are widely regarded as their primary disadvantage. The various architectures of superconducting qubits that are available today were all developed at least in part due to an effort to increase their coherence times. The most popular type, the transmon qubit, demonstrates coherence times between 50 and 100 µs, with a 2017 experiment exhibiting a coherence time of 80 µs (Ristè et al., 2017; Takita et al., 2016).

One might worry that such short coherence times compared to other leading platforms such as trapped-ions might hamper the chances of superconducting qubits being a viable option due to the resulting error rate. However, the short coherence times are more than made up for by their proportionately short gate-operation times, which are on the order of tens to hundreds of nanoseconds, with the fastest demonstration of 18 ns (Barends et al., 2019; Sheldon et al., 2016). This results in the ratio between the coherence times and gate operation times $\approx 10^4$, which is large enough to satisfy the 3rd DiVincenzo criteria as well as the estimated threshold for fault-tolerant quantum computing. The short gate operation times also contribute to shorter computational times, which will be instrumental to the platform's ability to outperform classical computers as quantum computing is scaled up and solves real-world problems with a substantial number of gate operations.

Additionally, superconducting qubits have high gate fidelities. Single-qubit gate fidelities of 99.95% have been reported (Sheldon et al., 2016), while a 2019 experiment demonstrated a two-qubit iSWAP-like gate with 99.66% fidelity (Barends et al., 2019). This falls inside the threshold of the capabilities of today's error correction codes, which has allowed for limited demonstrations of error correction to the superconducting qubit system using surface code.

Discussion [4]

We have explored 4 qubit platforms and provided metrics that can be used to compare them to each other. It is evident that they vastly differ in many aspects - even the principles that they operate on are completely different in some instances. An example of the above would be the neutral atom platform functioning on the concepts of atomic physics whereas superconducting qubits are based on solid-state physics. The fact that such seemingly disparate areas of physics can produce the same functionality with regard to quantum computation is testament to the versatility of the field and presents the possibility of researchers developing newer and better platforms in the future that may outperform even the best of today's technology. Nevertheless, in this review, we have established the basic principles that all such modalities must adhere to, and the current obstacles to the feasibility of them all. We now move on to a more direct comparison between the platforms addressed in this paper, to better quantify the current state of play of each.

In the table below, we numerically gauge the metrics of each qubit platform against one another. The best-case scenarios of each one are considered. It must be noted that these values are subject to change due to the rapid developments in the quantum computing industry, and will likely be outdated within the next few years. Instead, this table should serve as a quantitative summary of the states of the best qubit platforms as of 2021, and therefore provide a helpful guide to where each platform stands in the quest for building a feasible quantum computer.

Table 1: The current status of qubit platforms, quantitatively summarized

Platform	Trapped-Ion	Neutral Atom	Semiconductor spin	Superconducting
Highest no. of qubits controlled	32	50	4	65
Coherence time	600s	10 s	20 µs	80 µs
Gate operation times	1.6 µs	1.2 µs	200 ns	18 ns
Coherence : Gate-operation	10^9	10^7	10^2	10^4
Single-qubit gate fidelity	99.9999%	99.9%	99.9%	99.95%
Two-qubit gate fidelity	99.9%	96.5%	98%	99.66%

When it comes to scalability, the nature of the qubit plays a significant role. Qubits typically need to be identical for universal qubit manipulation and readout. Due to the homogeneity inherent in natural qubits, they require considerably less tuning and adjustment and are thus usually easier to scale up. Among the natural qubits, the neutral atom platform outperforms the others by virtue of its inert nature which allows for packing the qubits in a relatively small area (Sec 3.2.1). In contrast, synthetic modalities necessitate engineering prior to their implementation as qubits. In most cases, this is a disadvantage, where it leads to low yield and inefficiency in the manufacturing process. However, in the premier synthetic qubit platforms, researchers can actually leverage this drawback to allow for unique identification and addressing of qubits. Certain synthetic qubit platforms can even be integrated with the classical circuits by virtue of their similarities (Sec 3.3.1). This can especially benefit the industry to enable quantum co-processors for the purposes of enabling situational speed-ups to classical computations in order to solve problems that fall under the classification of being classically hard but solvable by quantum algorithms in polynomial time. As it stands today, we are very much still in the intermediate scale of quantum computing. There is still a long way to go in crossing the so-called quantum chasm of a million qubits and before full-scale quantum computing is made a reality, it is far more likely that the implementation of practical quantum co-processors within the next decade or two will be the next milestone. In the near future, it seems that synthetic qubits hold the edge, as was shown by the demonstration of quantum supremacy performed using superconducting qubits (Sec 3.4.1). However, when it comes to the feasibility of full-scale quantum computing with millions of qubits, the fact that natural qubits require no manufacturing is in their favour. With the proposed architectural modifications to the trapped-ion platform (which happens to be the best qubit platform with respect to gate-fidelity), it is expected to be a strong contender against the superconducting qubit in the quest for full-scale quantum computing.

As is evident in Table 1, the coherence and gate-operation times of the different qubit modalities vary by a large margin. The natural qubits are typically observed to have a much longer decoherence time than the synthetic ones, whose best coherence times are under 100 µs. As previously mentioned (Sec 3.3.2), this can be attributed to the surrounding noise that synthetic qubits have to contend with in addition to the practical difficulties in engineering a perfectly isolated quantum system that can also be controlled with sufficient fidelity.

To complement this disadvantage, synthetic qubits have much shorter gate operation times. This factor can be seen as a major reason for the demonstration of quantum supremacy being done using superconducting circuits and not any of the natural qubit platforms: despite the advantage that their inherent quantum nature provides them, natural qubits are unable to keep pace with the much faster frequency that operations are performed on classical computers. This hampers the success of platforms that are otherwise promising such as the trapped-ion implementation.

However, synthetic qubits cannot make up for their short coherence times entirely, and natural qubits are far ahead in terms of the ratio between the coherence and gate operation times. The most successful qubit implementations (which include the platforms considered in this review with the exception of the semiconductor quantum dot) have all satisfied the minimum threshold (in terms of this ratio) required for fault-tolerant quantum computing already, but there is room for improvement. Researchers continuously augment both coherence and gate-operation times, and the greater the ratio is when fault-tolerant quantum computing emerges, the better placed that particular platform will be.

Increasing this ratio can happen by increasing the coherence time or by decreasing the gate-operation time. For natural qubits like trapped-ions, decreasing the gate-operation time seems to be the way forward since their coherence times are already satisfactory, and doing so would make them more capable of outperforming classical computers at certain tasks. Conversely, the challenge in need of addressing with regard to most synthetic qubit modalities is increasing their coherence times to a level that can at least reach the threshold for fault-tolerant quantum computing by further advancements in engineering the qubit environment.

The gate fidelities of most of the implementations that have been considered in this paper are high. Most notably, the trapped ion implementation's exceedingly high gate fidelities (Sec 3.1.2) make up for its shortcomings in the area of scalability by reducing the amount of error correction required and thus minimising the number of physical qubits required in the system to implement error correction codes. This serves to cement its place as one of the leading platforms in the race for building a practical, feasible quantum computer. Unlike the coherence and gate operation times, the gate fidelities for a particular qubit platform does not seem to be too dependent on its type, as indicated by the lower gate fidelities of the neutral atom platform, the other example of natural qubits taken in this paper. In fact, the high error rate resulting from the sub-par gate fidelities is the primary disadvantage of the neutral atom implementation when it comes to achieving feasibility, since it doesn't satisfy the bare minimum requirement for implementing error correction codes.

As for the synthetic qubits, there isn't much correlation either. Superconducting qubits satisfy the threshold required for error correction with their high single and two-qubit gate fidelities (Sec 3.4.2), solidifying their position as a successful qubit platform. Semiconductor quantum dots have not yet met the requirement of 99% gate fidelity for applying surface code, and coupled with the low scaling it has achieved thus far, this proves that the semiconductor platform has a long way to go to implement error-correction and achieve competitive status with the rest of the qubit platforms considered in this paper.

Conclusion [5]

In this paper, the current state of the leading physical qubit realisations in relation to their feasibility as a platform for quantum computers has been explored. Their feasibilities have been analysed on the basis of parameters such as their scalability, coherence times, gate operation times, and gate fidelities. The review also presents an idea of what to expect in the future for each of these qubit platforms and quantum computing as a whole.

Limitations

A significant limitation of this review is the fact that only four qubit platforms were considered. They were chosen as representatives of current qubit platforms, but they cannot be said to speak for the entire breadth of the field. Further research can be done on platforms such as the ones based on optical qubits and topological qubits to enhance one's understanding of the field. This review has also omitted the mathematical formalisms of quantum mechanics that explain the physics behind qubit operation, so one could look into that for a deeper understanding of the topic of quantum computing.

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