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 preexisting 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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