Natural and artificial atoms for quantum computation

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Abstract
Remarkable progress towards realizing quantum computation has been achieved using natural and artificial atoms as qubits. This paper presents a brief overview of the current status of different types of qubits. On the one hand, natural atoms (such as neutral atoms and ions) have long coherence times, and could be stored in large arrays, providing ideal ‘quantum memories’. On the other hand, artificial atoms (such as superconducting circuits or semiconductor quantum dots) have the advantage of custom-designed features and could be used as ‘quantum processing units’. Natural and artificial atoms can be coupled with each other and can also be interfaced with photons for long-distance communications. Hybrid devices made of natural/artificial atoms and photons may provide the next-generation design for quantum computers.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The experimental realization of quantum computation (QC) has been a challenge for more than a decade. While a fully operational quantum computer that could factorize thousand-digit numbers is still a distant goal, with the new technologies for the coherent manipulation of atoms, photons and electrons, nowadays applications like quantum cryptography and quantum communication are already commercially available. Since potential QC implementations come in many shapes and sizes, it is difficult to quantify the overall progress in the field of QC. In order to assess the current state of the art in QC, a comparison between the various approaches is needed. However, because these approaches are very different (in terms of the underlying physical processes, experimental techniques, and how well the physical system is understood), we should be careful not to compare apples with oranges. We would rather like to compare apples with apples, or in our case, atoms with atoms. Therefore, in this paper we consider natural and artificial atoms for implementing QC.

Among the most successful and rapidly developing ways of realizing QC are those using natural atoms (such as neutral atoms [1] or ions [2]) and artificial atoms (such as superconducting circuits [3, 4] or spins in solids [5]). Contrasting natural and artificial atoms would help in highlighting their strengths. For the sake of comprehensiveness, other QC approaches (i.e. with nuclear spins in molecules [6, 7] or in phosphorus impurities in silicon [8, 9], photons [10, 11] and so on) are also briefly covered here. A complementary overview on qubits can be found in [12].
Although there are many exciting theoretical proposals, we will focus more on what has already been experimentally demonstrated and less on what could eventually be achieved in each system. We should stress from the beginning that our purpose is not to show that a certain system is better than others, but to review the current experimental state of the art in QC. One should also keep in mind that some approaches are more recent than others, some benefit from technologies that have been developed before, while others had to develop their own new technologies on the way, and, most importantly, each approach has to deal with specific issues whose difficulty cannot be compared.

By considering natural and artificial atoms and their potential for implementing QC, we hope to gain a broader perspective of the current status of QC. Moreover, this approach may also provide a glimpse into the future of QC. However, we would rather not attempt to make any prediction regarding what system would be the best for realizing a quantum computer. Ten or 20 years from now such speculation might sound as amusing as the prediction made in [20, 22, 25]. The effective spin–spin interaction between two atoms in a double-well potential was used to demonstrate a two-qubit SWAP gate [20]. Furthermore, with polar molecules [17] or Rydberg atoms [27, 28, 36] dipole–dipole interactions could be exploited for realizing two-qubit gates. Very recently, a CNOT gate [33], post-selective entanglement of two atoms [37] using Rydberg blockade interactions and on-demand entanglement [38] have been demonstrated.

The prospect of producing many-qubit entangled states together with the possibility of single-site addressing and measurement makes neutral atoms promising for the quantum simulation of condensed-matter physics [16, 23] as well as measurement-based QC [39].

3. Ions

While neutral atoms interact weakly among themselves, ions, being charged, interact rather strongly via Coulomb repulsion. This facilitates the implementation of two-qubit gates without compromising the long coherence times [40–64]. Also, thanks to their charge, the motion and position of the ions can be well controlled. Ions can be trapped by electrical (or magnetic) fields, laser-cooled and manipulated with high precision [2]. Quantum information can be encoded either in the internal (hyperfine or Zeeman sublevels, or the ground and excited states of an optical transition), or in the motional states (the collective motion of the ions). While the internal states exhibit very long coherence times (hyperfine transitions > 20 s [50] and optical transitions > 1 s) the motional states have typical lifetimes of < 100 ms. As in the case of neutral atoms, the initialization of the qubits can be done by optical pumping and laser cooling, and they can be measured with very high accuracy [59, 62] via laser-induced fluorescence. Scaling the current experiments to large numbers of ions is theoretically possible, but technically challenging. The proposed approaches to scalability include ion shuttling, two-dimensional ion arrays, photon interconnections, long equally-spaced strings, and two-dimensional Coulomb crystals (see [57] and box 2(c) and (d) and table A2).

Using the collective motion of the ions as data bus, high-fidelity one-, two- [53, 56] and even three-qubit [60] gates have been experimentally demonstrated. Entangled (Greenberger–Horne–Zeilinger (GHZ) and W) states of up to 14 qubits have been realized [51, 52, 64]. Two-qubit gates can also be implemented using bichromatic excitation fields that produce coherent two-qubit transitions [42, 56] or by
Box 1. Natural and artificial atoms.

| Natural atoms | Artificial atoms |
|---------------|------------------|
| Atoms and ions | Quantum dots | Josephson junctions |
| $E = 0$ | ![Diagram](image1.png) | ![Diagram](image2.png) |
| $E \neq 0$ | ![Diagram](image3.png) | ![Diagram](image4.png) |

Both natural and artificial atoms exhibit discrete energy levels, which are modified in the presence of external fields ($E \neq 0$). The applied external fields drive coherent quantum oscillations between the specific energy levels which can be used to encode the qubit states. Artificial atoms can be engineered to have certain transition frequencies while in natural atoms these are fixed.

4. Superconducting circuits

Superconducting circuits [65–100] are typically μm-scale circuits operated at mK temperatures. Although macroscopic, they can still exhibit quantum behavior, which can be harnessed for QC [3, 4, 102, 103]. Superconducting circuits are $RLC$ circuits that also include nonlinear elements, called Josephson junctions. Thanks to superconductivity, the resistance vanishes ($R = 0$), eliminating the most serious source of dissipation and noise. Now, the $LC$ circuit is a harmonic oscillator. The problem with harmonic oscillators is that they have an infinite number of equally spaced energy levels and therefore it is not possible to target only the lowest two energy levels. By introducing nonlinearity through the Josephson junction, the energy-level separation becomes nonuniform, and the lowest two levels can be used to encode the qubit [3, 4] (see also box 1). Quantum information can be encoded in different ways: in the number of superconducting electrons on a small island (charge qubit), in the direction of a current around a loop (flux qubit), or in oscillatory states of the circuit (phase qubit). These qubits can be controlled by microwaves, voltages, magnetic fields, and currents as well as measured with high accuracy [84] using integrated on-chip instruments. The characteristics of the qubits can be designed and many qubits could be coupled in arrays. Therefore, superconducting qubits are flexible and promise the realization of QC on a chip (see box 2(e) and (f) and table A4).

Superconducting qubits have coherence times that can reach tens of μs (see e.g. [98]), the coupling between qubits can be made strong and can be turned on and off electronically [74, 81]. In addition to direct coupling strategies, superconducting circuits can be coupled via ‘cavities’ [80, 83], which are actually electrical resonators (and the ‘photons’ are actually electron-density oscillations). This setup is promising for the study of circuit cavity quantum electrodynamics (circuit QED) [3, 4, 47, 72, 86].

With superconducting circuits one can now realize simple algorithms [88], and generate entangled states of three qubits [90–92] and arbitrary photon states in a resonator [104]. Other recent advances include the performance of quantum non-demolition measurements [79], the realization of multi-level quantum systems [99, 105], the violation of Bell’s inequality [87, 95], and the coupling of a mechanical resonator to a superconducting qubit [94].

5. Spins in solids

Coherent control and measurement of single spins in solids [9, 58, 106–132] is now possible, and this allows using electron spins in semiconductor quantum dots [116], or electron spins together with nuclear spins in nitrogen-vacancy (NV) color centers in diamond [115] for QC purposes (see box 2(g) and (h))
Quantum bits can be constructed using a variety of different possible building blocks, of various sizes and properties. As a result, each technology has its unique advantages and challenges.

(a), (b) Hundreds of thousands of neutral atoms can be trapped and cooled at the minima of an optical lattice—the periodic potential created by interfering counter-propagating laser beams. The long-lived internal energy levels of neutral atoms are
used to encode quantum information. Neutral atom qubits can be manipulated with laser radiation and observed via their laser-induced fluorescence. The typical separation between lattice sites is $<1 \mu m$, which makes individual addressing challenging. Neutral atoms interact weakly with the environment, which protects them from decoherence. There are several mechanisms for entangling neutral atoms: through state-dependent displacement of the lattice, that results in a highly entangled many-qubit state created in a single operation; through exchange interactions; or via the interaction between two atoms in a double-well potential. Neutral atoms in optical lattices are ideal systems for quantum simulation. (a) illustrates the idea of trapping neutral atoms in periodic optical potentials; one neutral atom qubit is trapped at each lattice site; (b) shows one possible mechanism for creating multi-particle entanglement starting with two atoms in different spin states, trapped in each lattice site.

(c), (d) Ions trapped in electromagnetic fields have been used to encode and manipulate quantum information. The internal energy levels representing the qubit basis states are long-lived and can be easily excited with laser radiation. The typical distance between trapped ions is $5 \mu m$ or more which facilitates addressing and readout of individual ions. High-efficiency readout is achieved by monitoring the laser-induced fluorescence. Ions in the same potential have a common center-of-mass vibrational mode that can be used as data bus to realize entangling operations. Many-particle entanglement and high-fidelity two-qubit gates have already been demonstrated in experiments. (c) shows a linear trap, while (d) a planar trap. These recently developed micrometer-scale ion traps (d) provide flexibility in manipulating the positions of the ions in two and three dimensions. Nowadays the main focus is on scaling these experiments to large numbers of ions. This can be achieved by moving the ions in the trapping potentials around in complex microstructures, trapping single ions at specific locations in custom-designed lattice geometries created in arrays of microtraps, or by entangling the ions with flying qubits (photons).

(e), (f) Superconducting qubits are micrometer-sized electric circuits based on Josephson junctions. A superconducting qubit (e) can be manipulated using the applied electric voltage $V$ and magnetic flux $\Phi$. Similarly, the qubit can be read out through the small electric or magnetic signal that it produces. Additional circuit elements, called couplers, can be used to provide tunable interactions between the qubits, as shown in (f), allowing the creation of entanglement and the performance of two-qubit gates. Decoherence times have improved from the nanosecond to the microsecond scale over the past decade and are expected to improve further in the future.

(g), (h) Spins in solids arise in a number of distinct realizations. The collective spin state of two electrons trapped in a sub-micrometer-scale semiconductor-based double quantum dot structure can be used as a qubit, as shown in (g). In the traditional approach, magnetic fields are used to manipulate the qubit, but recent techniques using electric fields and exploiting the exchange and spin–orbit interactions have been developed as well. The qubit is read out by monitoring its response to an applied electric signal. NV centers in diamond, shown in (h), also provide alternative spin qubits. The spin of one electron in the NV chemical bond can be manipulated and read out using magnetic fields and optical-frequency electromagnetic fields. These qubits have long coherence times, on the millisecond timescale. It would be highly desirable to controllably place multiple qubits in an ordered arrangement in the diamond crystal and couple them to each other, such that entanglement and two-qubit gates would be achieved.
control of up to 12 qubits has also been realized [140]. However, this approach to QC proved difficult to scale up to tens or hundreds of qubits, so NMR techniques are now being applied for the control of nuclear spins in semiconductors. One direction is solid-state NMR [138], but NMR is also merging with electron spin resonance (ESR) methods, so it also becomes relevant for NV centers in diamond and for phosphorus in silicon QC.

6. Comparing natural and artificial atoms

The main characteristics of natural and artificial atoms are displayed in tables 1 and 2. In table 1 $T_1$ (relaxation time) is the average time that the system takes for its excited state to decay to the ground state; $T_2$ (decoherence or dephasing time) represents the average time over which the qubit energy-level difference does not vary. We denote by $Q_1$ (quality factor) the number of one-qubit quantum gates that can be realized within the time $T_2$, and by $Q_2$ (quality factor) the number of two-qubit quantum gates that can be realized within the time $T_2$. For implementing QC we are mainly interested in the following aspects: controllability, scalability and interfaceability. The latter will also be discussed in the following section.

The qubit energy-level splittings are comparable for natural and artificial atoms—microwave frequencies (for ions and superconducting circuits) and optical frequencies (for neutral atoms, ions and some semiconductor quantum dots). Box 1 displays schematically the potential energies and discrete energy levels for natural and artificial atoms in the absence ($E = 0$) and in the presence ($E \neq 0$) of an external field. While natural atoms are usually driven using optical or microwave radiation, artificial atoms like superconducting circuits can be driven by currents and voltages, magnetic fields, as well as microwave photons. Optically driven artificial atoms, such as some semiconductor quantum dots, have also been demonstrated. Artificial atoms can be engineered to have a large dipole moment or particular transition frequencies. Depending on the intended application this tunability may prove quite useful.

In natural atoms, motional states can also be exploited for encoding the qubits or as data bus. The motional frequency can be controlled, but the cooling of these modes is usually necessary if they are to be used for QC purposes. For artificial atoms, resonators can play a similar role to the motional modes. The frequency of these resonators can also be controlled, and they can be cooled much like atoms. For instance, the temperature of superconducting circuits can be decreased using cooling techniques inspired from atomic physics, such as sideband or Sisyphus cooling [142, 143]. Natural atoms have many energy levels which can be used to encode information. Levels that are well protected against decoherence (i.e. magnetic-field-independent hyperfine transitions [144]) could be used for memory qubits, while fast transitions could be used for implementing two-qubit gates. Furthermore, realizing qubits in natural atoms is straightforward.

Unlike natural atoms of the same species, which are indistinguishable, no two artificial atoms will be perfectly alike. With the latest advances in microfabrication, artificial atoms can be made with increasing accuracy and uniformity. However, this is an extra challenge. While natural atoms are readily available and one only needs to trap them by means of optical or electrical fields and then cool them to low temperatures, artificial atoms have to be carefully designed and fabricated. Furthermore, atom and ion trapping technologies have been in use for quite a while, but for artificial atoms the techniques are more recent.

Artificial atoms can be produced in large numbers and ‘wired’ together on a chip. Therefore, extending current experiments to large numbers of artificial atoms should, in principle, not be a problem. Neutral atoms can be loaded by thousands or millions in optical lattices; however, individual addressing has not yet been fully demonstrated [29]. Meanwhile, in the case of ions, although several proposals are available, scaling to large numbers is a challenge. Natural atoms are not wired so they can form almost any 2D or 3D configuration; however, for artificial atoms the wiring itself may impose some geometric limitations. Neutral atom and trapped ion qubits can also be moved around easily. This flexibility may prove advantageous for certain applications.

Both natural and artificial atoms can be coupled with photons via cavity QED [3, 4, 86], which could provide a means of realizing large-scale QC and long-distance quantum communication (see also [145]). The physics of cavity QED is the same regardless of the nature of the atom or cavity, but, for artificial atoms (e.g. circuit QED) the coupling strength is several orders of magnitude larger than for natural atoms [3, 4, 86]. Several exciting experiments demonstrating the coupling between cavities and natural or artificial atoms have been performed (see, for instance, [80, 83, 146–148] and the review in [103]).

As for the operating conditions, natural atoms can be coherently manipulated only in an ultrahigh vacuum at very low temperatures ($\mu$K for neutral atoms and mK for ions). Artificial atoms are also operated at low temperatures (mK in the case of superconducting circuits or a few K for semiconductor quantum dots), but there are some candidates for room-temperature qubits, including very long coherence times for NV centers in diamond (note that their $T_1$ is temperature dependent).

7. Photons

Photons can also make good qubits and they can carry quantum information over long distances hardly being affected by noise or decoherence. The qubit states can be encoded, for example, in the polarization of a single photon, and one-qubit gates can be easily realized with optical elements [11, 149]. Unfortunately optical QC has a serious drawback: the difficulty in implementing two-qubit gates. Realizing the nonlinearity required for entangling two qubits is challenging, so alternatives such as the teleportation of nondeterministic quantum gates have been investigated [149]. While this approach is still impractical due to the large amount of required resources, another solution may be found in measurement-based QC.
Table 1. Comparison between natural and artificial atoms.

|                      | Natural atoms | Artificial atoms |                  |
|----------------------|---------------|------------------|-----------------|
|                      | Neutral atoms | Trapped ions     | Supercond. circuits | Spins in solids |
| Energy gap           | GHz (hyperfine), 10^{14} Hz (optical) | GHz (hyperfine), 10^{13} Hz (optical) | 1–10 GHz | GHz, 10^{13} Hz |
| Photon               | Optical, MW   | Optical, MW      | MW              | Optical, MW, infrared |
| Dimension            | ~2 Å          | ~2 Å             | ~μm            | ~nm |
| Distance between qubits | <1 μm         | ~5 μm            | ~μm            | ~10 nm\(^a\), ~100 nm\(^b\) |
| Operating temperature | nK–μK        | μK–mK            | ~μK            | mK–300 K |
| Qubit interactions   | Collisions, exchange | Coulomb | Capacitive, inductive | Coulomb, exchange, dipolar |
| Cooling              | Doppler, Sisyphus, evaporative | Doppler, sideband | Cryogenic | Cryogenic |
| Cavity               | Optical, MW   | Optical, vib. modes | Transmission line, LC circuit | Optical, MW |

\(^a\) Distance between qubits for NV centers.
\(^b\) Typical distances between quantum dots.

Table 2. Comparison between natural and artificial atoms in view of implementing QC.

Hereafter, MW stands for microwaves and SC for superconducting.

|                      | Natural atoms | Artificial atoms |                  |
|----------------------|---------------|------------------|-----------------|
|                      | Neutral atoms | Trapped ions     | Supercond. circuits | Spins in solids |
| # entangled qubits   | 2\(^a\)       | 14               | 3 (4\(^b\))     | 1 (3\(^c\)) |
| One-qubit gates fidelity | 99%          | 99%              | 99%             | 99% (>99\(^c\)) |
| Two-qubit gates fidelity | ~64%        | 99.3%            | >90%            | 90% |
| Entangled states     | Bell          | Bell, GHZ, W, cat | Bell, GHZ\(^d\) | GHZ\(^e\) |
| Measurement efficiency | 99.9%       | 99.9%            | >95%            | 99% |
| \(T_1\)             | ~s            | ~100 ms\(^f\)   | 10 μs           | ~1 s\(^g\) |
| \(T_2\)             | ~40 ms        | 1000 s\(^h\)    | 20 μs           | 200 μs\(^i\) |
| \(Q_1\)             | ~10^4         | ~10^{13}        | ~10^3           | ~10^3–10^4 |
| \(Q_2\)             | ~4 \times 10^4 | 2 \times 10^3–2 \times 10^3 | >100           | tbd |
| Interfaceable with   | Photons, SC circuits | Photons, SC circuits | Photons, atoms, ions | Photons |

\(^a\) Large entangled states can also be realized with collisional gates.
\(^b\) Entanglement of the ground state of four qubits.
\(^c\) NV centers in diamond.
\(^d\) Only generated for one and two resonators and not for many qubits.
\(^e\) NV centers in diamond.
\(^f\) \(T_1\) for the vibrational modes.
\(^g\) \(T_1\) for the internal hyperfine states.
\(^h\) Of the order of ms for NV centers at room temperature and of the order of minutes at 1 K; of the order of seconds for P : Si;
\(^i\) In optical clocks \(T_1, T_2 > 10\) min has been observed.
Table 3. Interfacing different types of qubits for future scalability or realizing long-range quantum communication. The asterisk denotes the cases that have been experimentally realized and the dash means that, to the best of our knowledge, no proposal exists yet.

|        | Atoms | Ions | Cavity | Spins | SC |
|--------|-------|------|--------|-------|----|
| Atoms  | ✓     | ✓    | ✓      | —     | ✓  |
| Ions   | ✓     | ✓    | ✓      | —     | ✓  |
| Cavity | ✓     | ✓    | ✓      | ✓     | ✓  |
| Spins  | —     | —    | ✓      | —     | ✓  |
| SC     | ✓     | ✓    | ✓      | ✓     | ✓  |

For the moment photons may not be practical as memory or computation qubits, but they are certainly the best ‘flying qubits’. Recent advances in quantum communication and, in particular, quantum key distribution are reviewed in [10].

8. Hybrids

Exploiting the advantages of both natural and artificial atoms in hybrid systems provides exciting prospects for realizing QC. For instance, ions [150, 151] and atoms [152, 153] interfaced with superconducting circuits are now being investigated. As recent results point out neutral atoms and ions could also be interfaced with each other [154, 155]. While cavity QED with atoms and ions has been studied for some time now [86, 145], solid-state cavity QED is more recent [80, 83, 86, 148]. For natural atoms strong coupling has been demonstrated [146, 147]. As mentioned before, in circuit QED the coupling strength is many orders of magnitude larger than in cavity QED, which is very promising for the study of quantum optics on a chip. As shown in table 3, all systems discussed in the previous sections can be coupled with other systems. It is interesting to note that superconducting circuits can be coupled with different types of natural atoms, spins in solids [156–158] and with photons.

Natural atoms, with their long decoherence times, are envisaged by many as quantum memories [159], while the tunable artificial atoms may be used for the ‘quantum processing unit’. Both natural and artificial atoms may be coupled with photons via a cavity. Note that a necessary requirement is for the coupling timescale to be shorter than the decoherence time. Such cavities could be used as input/output interfaces and for long-distance communication. Perhaps the first functional quantum computer will be a complex hybrid system made of natural atoms, artificial atoms, and photons. Such a hybrid device is represented schematically in figure 1. Several types of hybrids are discussed in [160].

9. Prospects

In both natural and artificial atoms, almost all the basic requirements for realizing QC [161] have been demonstrated (i.e. (i) a scalable system with well-characterized qubits; (ii) initialization of the qubits; (iii) reasonably long decoherence times; (iv) a universal set of quantum gates; (v) measurement of the qubits). Tables 1–6 and figure 2 provide a brief snapshot of the current progress and experimental status for several types of qubits.

The current challenges are to attain increased controllability (and minimize decoherence) and scale the existing systems to tens and hundreds of qubits and many-gate operations. At this stage, new milestones, such as the creation of many-particle entangled states, the implementation of small quantum algorithms, and other applications (e.g. quantum simulation), and the realization of quantum communication by interfacing the qubits with photons, are being targeted.

‘Quantum supercomputers’ for factorizing large numbers are still a distant goal. The first generation of practical quantum computers may be either specialized devices for scientific applications like quantum simulations [162], or integrated in complex quantum networks [145]. As the very positive results...
Table 5. Progress in the implementation of superconducting qubits quantum gates.

| Year | Operation       | Qubits | Mechanism                                      | Ref.          |
|------|-----------------|--------|-----------------------------------------------|---------------|
| 2003 | CNOT gate       | 2      | Direct coupling; gate relies on zz component  | [71]          |
| 2003 | Entangled energy levels | 2 | Direct xy coupling                           | [70]          |
| 2005 | iSWAP; Entanglement | 2 | Direct xy coupling                           | [73]          |
| 2006 | iSWAP; Entanglement | 2 | Direct xy coupling                           | [76]          |
| 2006 | Entangled energy levels | 4 | Direct coupling                              | [75]          |
| 2006–7 | Controllable coupling | 2 | Coupling mediated by additional circuit element | [74, 78]     |
| 2007 | CNOT gate       | 2      | Direct coupling; gate relies on zz component  | [82]          |
| 2007 | iSWAP           | 2      | xy coupling to cavity; gate mediated by cavity| [83]          |
| 2007 | iSWAP           | 2      | xy coupling mediated by cavity               | [80]          |
| 2007 | iSWAP           | 2      | Coupling mediated by additional circuit element; gate relies on xy coupling | [81] |
| 2009 | CPhase          | 2      | zz coupling mediated by auxilliary energy levels | [88]        |
| 2010 | Entanglement    | 3      | xy coupling                                 | [90]          |
| 2010 | Entanglement    | 3      | zz coupling mediated by auxilliary energy levels | [91]        |
| 2011 | 3-qubit gate    | 3      | Coupling mediated by auxilliary energy levels | [97]          |

Table 6. Progress in the number of qubits and fidelities for different operations on trapped ions. CZ stands for the Cirac–Zoller scheme [163], and MS for the Mølmer–Sørensen scheme [164].

| Year | Operation      | Mechanism | Qubits | Fidelity | Ref.          |
|------|----------------|------------|--------|----------|---------------|
| 1998 | Entanglement   | CZ         | 2      | 70%      | [40]          |
| 2000 | Entanglement   | MS         | 2      | 83%      | [42]          |
|      |                 |            | 4      | 57%      |               |
| 2003 | CNOT gate      | CZ         | 2      | 71.3%    | [43]          |
| 2003 | Entanglement   | Geometric  | 2      | 97%      | [45]          |
| 2005 | Entanglement   | CZ         | 4      | >76%     | [52]          |
|      |                 |            | 5      | >60%     |               |
|      |                 |            | 6      | >50%     |               |
| 2005 | Entanglement   | CZ         | 4      | 85%      | [51]          |
|      |                 |            | 5      | 76%      |               |
|      |                 |            | 6      | 79%      |               |
|      |                 |            | 7      | 76%      |               |
|      |                 |            | 8      | 72%      |               |
| 2006 | CNOT gate      | CZ         | 2      | 92.6%    | [53]          |
| 2008 | Entanglement   | MS         | 2      | 99.3%    | [56]          |
| 2009 | Toffoli gate   | CZ         | 3      | 74%      | [60]          |
| 2010 | Entanglement   | MS         | 10     | 62.9%    | [64]          |
|      |                 |            | 12     | 39.6%    |               |
|      |                 |            | 14     | 46.3%    |               |

Figure 2. An example of the progress that has been achieved for superconducting circuits in the last decade. The decoherence time kept increasing, and the current trend promises decoherence times of the order of ms in the next couple of years. Visibility also increased and now it is larger than 95%. The black squares show $T_1$ and the red dots $T_2$.

Appendix. Tables summarizing the main characteristics of different systems in view of realizing quantum computation

In the following tables, $T_1$ (relaxation time) is defined as the average time that the system takes for its excited state to decay to the ground state; $T_2$ (decoherence time) represents the average time over which the qubit energy-level difference does not vary; $Q_1$ (quality factor) represents the number of one-qubit quantum gates that can be realized within the time $T_2$; $Q_2$ (quality factor) represents the number of two-qubit quantum gates that can be realized within the time $T_2$. The following abbreviation is used: tbd for ‘to be demonstrated’

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Table A1. Neutral atoms.

| **Neutral atoms** | **Qubits** | Internal states (ground hyperfine states); motional states (trapping potential eigenstates) |
|-------------------|-----------|-----------------------------------------------------------------------------------------------|
| **Scalability**   |           | Demonstrated in optical lattices; possible in arrays of cavities, atom chips                  |
| **Initialization**|           | Both internal (optical pumping) and motional (laser cooling) states                           |
| **Long coherence time** |           | Several seconds [15, 19, 30]                                                                 |
| **Universal quantum gates** | One-, two-qubit gates (several proposals)                                                   |
| **Measurement**   |           | Fluorescence: ‘quantum jump’ technique                                                      |

**Fabrication**

- **Material**: Trapped neutral atoms: Rb, Li, K, Cs, etc
- **Well-controlled fabrication**: Yes
- **Flexible geometry**: Yes (especially in optical lattices)
- **Distance between qubits**: A few hundred nm to a few µm [1]

**Operation**

- **Qubits demonstrated**: \(>10^6\) (stored), 2 (entangled)
- **Superposition/Entangled states**: Yes/Yes
- **One-qubit gates (Fidelity)**: Yes (99.98%)
- **Two-qubit gates (Fidelity)**: Yes (SWAP > 64% [20]); CNOT (73% [33])

**Readout**

- **Readout (Fidelity)**: Laser-induced fluorescence (99.9%)
- **Single-qubit readout possible**: Yes

**Manipulation**

- **Controls**: Optical fields, microwave
- **Types of operations**: One-, two-qubit gates, entanglement
- **Individual addressing**: tbd [24, 29, 31, 32, 35]

**Decoherence**

- **Decoherence sources**: Photon scattering, heating, stray fields, laser fluctuations
- **T\(_1\)**: \(\sim s\)
- **T\(_2\)**: \(\sim 40\) ms
- **\(Q_1\)**: \(\sim 10^4\)
- **\(Q_2\)**: \(\sim 40,000\)

Table A2. Trapped ions.

| **Trapped ions** | **Qubits** | Internal states (hyperfine or Zeeman sublevels, optical); motional states (collective oscillations) |
|-------------------|-----------|-----------------------------------------------------------------------------------------------|
| **Scalability**   |           | Ion shuttling, arrays, photon interconnections, long strings                                  |
| **Initialization**|           | Both internal (optical pumping) and motional (laser cooling) states                           |
| **Long coherence time** | Internal: hyperfine > 20 s, optical > 1 s; motional: \(\sim 100\) ms |
| **Universal quantum gates** | One-, two-, three-qubit gates |
| **Measurement**   |           | Fluorescence: ‘quantum jump’ technique                                                      |

**Fabrication**

- **Material**: Atomic ions: Ca\(^+\), Be\(^+\), Ba\(^+\), Mg\(^+\), etc
- **Well-controlled fabrication**: Yes
- **Flexible geometry**: Yes
- **Distance between qubits**: A few µm to tens of µm

**Operation**

- **Qubits demonstrated**: \(10^3\) to \(10^5\) (stored), 14 (entangled) [64]
- **Superposition/entangled states**: Yes/Yes (2–14 ions, fidelities 99.3%–46%) [64]
- **One-qubit gates (fidelity)**: Yes (99%)
- **Two-qubit gates (fidelity)**: Yes (CNOT > 99.3% [56]; Toffoli 71.3% [60]; gate time 1.5 ms)

**Readout**

- **Readout (fidelity)**: Laser-induced fluorescence (99.9%)
- **Single-qubit readout possible**: Yes

**Manipulation**

- **Controls**: Optical, microwave, electric/magnetic fields
- **Types of operations**: One-, two-, three-qubit gates, entanglement
- **Individual addressing**: Yes

**Decoherence**

- **Decoherence sources**: Heating, spontaneous emission, laser, magnetic field fluctuations
- **T\(_1\)**: a few minutes (hyperfine), 1 s (optical), 100 ms (motional)
- **T\(_2\)**: 15 s
- **\(Q_1\)**: \(\sim 10^{13}\) (single-qubit gate 50 ps) [63]
- **\(Q_2\)**: \(\sim 20,000\) (MS gate 50 \(\mu\)s) [56]; \(\sim 200\) (CZ gate 500 \(\mu\)s) [53]
Table A3. Nuclear spins manipulated by NMR.

|                        |                                                                 |
|------------------------|-----------------------------------------------------------------|
| **NMR**                |                                                                 |
| Qubits                 | Nuclear spin                                                    |
| Scalability            | Not available in liquid-state NMR; possible for solid-state NMR |
| Initialization         | Demonstrated                                                   |
| Long coherence time    | >1 s                                                           |
| Universal quantum gates| One-, two-, three-qubit gates                                   |
| Measurement            | Single-qubit measurement not available                         |
| **Fabrication**        |                                                                 |
| Material               | Organic molecules (alanine, chloroform, cytosine)              |
| Flexible geometry      | No                                                              |
| Distance between qubits| ~Å                                                              |
| **Operation**          |                                                                 |
| Qubits demonstrated    | 7, 12 (entangled) liquid-state [140]; >100 (correlated) solid state |
| Superposition/entangled states | Yes/yes                                      |
| One-qubit gates (fidelity) | Yes (>-98%)                                           |
| Two-qubit gates (fidelity) | Yes (>98% CNOT and SWAP)                                      |
| Operation temperature  | Room temperature                                               |
| **Readout**            |                                                                 |
| Readout (fidelity)     | Voltage in neighboring coil induced by precessing spins, 99.9% |
| Single-qubit readout possible | No                                                    |
| **Manipulation**       |                                                                 |
| Controls               | RF pulses                                                      |
| Types of operations    | One-, two-, three-qubit gates                                  |
| Individual addressing  | No                                                             |
| **Decoherence**        |                                                                 |
| Decoherence sources    | Coupling errors                                                |
| $T_1$                  | >1 s (liquid state); >1 min (solid state)                      |
| $T_2$                  | ~1 s (liquid state); >1 s (solid state)                       |
| $Q_1$                  | 100 (gate time 10 ms)                                         |
| $Q_2$                  | >100 (gate time 10–50 ns)                                     |

Table A4. Superconducting circuits.

|                        |                                                                 |
|------------------------|-----------------------------------------------------------------|
| **Superconducting circuits** |                                                                 |
| Qubits                 | Flux, phase states, charge; also hybrids                        |
| Scalability            | High potential for scalability                                  |
| Initialization         | Demonstrated for all types of qubits                            |
| Long coherence time    | ~ 10 μs                                                        |
| Universal quantum gates| One-, two-qubit gates                                           |
| Measurement            | Individual measurement possible                                 |
| **Fabrication**        |                                                                 |
| Material               | Josephson junctions (Al–Al, O, –Al, Nb–Al, O, Nb)              |
| Flexible geometry      | Yes                                                             |
| Distance between qubits| ~μm                                                             |
| **Operation**          |                                                                 |
| Qubits demonstrated    | 128 (fabricated) [93], 3 (entangled)                            |
| Superposition/entangled states | Yes/yes                                      |
| One-qubit gates (fidelity) | Yes (99%)                                           |
| Two-qubit gates (fidelity) | Yes (>90%)                          |
| Operation temperature  | mK                                                              |
| **Readout**            |                                                                 |
| Readout (fidelity)     | SET, SQUID (>95%) [84], cavity frequency shift [72]            |
| Single-qubit readout possible | Yes                                                    |
| **Manipulation**       |                                                                 |
| Controls               | Microwave pulses, voltages, currents                            |
| Types of operations    | One-, two-, three-qubit gates, entanglement                     |
| Individual addressing  | Yes                                                             |
| **Decoherence**        |                                                                 |
| Decoherence sources    | Electric and magnetic noise, 1/f noise                         |
| $T_1$                  | 0.2 ms [101]                                                    |
| $T_2$                  | 25 μs [98]                                                     |
| $Q_1$                  | ~10⁵                                                           |
| $Q_2$                  | >100 (gate time 10–50 ns) [88]                                  |
Table A5. Spins in solids. Here, QDs stand for quantum dots, NV centers for nitrogen-vacancy centers in diamond and P : Si for phosphorous on silicon.

| Spins in solids | Qubits | Scalability | Initialization | Long coherence time | Universal quantum gates | Measurement | Fabrication | Material | Well-controlled fabrication | Flexible geometry | Distance between qubits | Operation | Qubits demonstrated | Superposition | One-qubit gates (fidelity) | Two-qubit gates (fidelity) | Operation temperature | Readout | Single-qubit readout possible | Manipulation | Controls | Types of operations | Individual addressing | Decoherence | Decoherence sources | decoherence times | decoherence times |
|----------------|--------|-------------|----------------|--------------------|------------------------|-------------|-------------|----------|-----------------------------|-----------------|------------------------|-----------|------------------------|----------------|------------------------|------------------------|------------------------|---------|-----------------------------|-----------|-----------|-------------------|-------------------|--------------|-------------------|----------------|----------------|
|                |        |             |                |                    | One-qubit gates        |             | GaAs, InGaAs (QDs), NV centers, P : Si | Yes       | Yes                          | Yes              | 100–300 nm (QDs); ~10 nm (NV centers) | 1 (QDs), 3 (NV centers) | Yes                     | Yes                  | Yes (> 73% QDs [113]); > 99% NV centers [130]) | Yes (90% NV centers [109]) | From mK to a few K (QDs); room temperature (NV centers) | Electrical, optical (90–92%) | RF, optical pulses, electrical | One-qubit gates (> 73% gate time 25 ns) | Yes                             | Co-tunneling, charge noise, coupling with nuclear spins | $T_1$ > 1 s (QDs) [120]; > 5 ms (NV centers) [124]; 6 s [133] (P : Si); 100 s [134] (P : Si) | $T_2$ ~ 200 μs [129, 128]; ~ 1.8 ms (NV centers) [125]; ~ 60 ms [107] (P : Si); 2 s [9] (P : Si) | $Q_1$: ~ 10$^6$ (gate time 180 ps); ~ 10$^8$ (gate time 30 ps) [121]; > 10$^9$ (gate time ~ 1 ns) | $Q_2$: tbd

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Due to space limitations we list a small subset of recent, relevant papers, mostly experimental results. The very few theory papers cited here introduce parameters used in the experimental papers cited, and also in the tables (e.g. as in table 6). For more references on the theoretical aspects, please refer to the various more specialized reviews listed below.

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