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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)

Contents

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 practical quantum computer. Ten or 20 years from now such speculation might sound as amusing as the prediction made by *Popular Mechanics* in 1949: 'In the future, computers may weigh no more than 1.5 tonnes.'

After summarizing the characteristics of each system we discuss the strengths and weaknesses of natural and artificial atoms. Next, we take a look at hybrid systems and photon interfaces, and, finally, consider future prospects. The main issues discussed throughout the paper are collected in six tables, which can be found at the end of the paper. For readers interested in the details for a particular system, the appendix provides extended tables. The list of references at the end tries to cover some of the recent experimental progress in the coherent control of natural and artificial atoms.

2. Neutral atoms

When looking for a physical system to realize qubits (which are controllable two-level systems), perhaps the most obvious candidate is neutral atoms [13–38]. Atoms have many energy levels that have been studied extensively over the past century, and some of these energy levels are extremely stable. Indeed, with accuracies better than one part in 10^{-15}, atomic clocks provide the best available time and frequency standards. The qubits encoded in the atomic energy levels can be initialized by optical pumping and laser cooling, manipulated with electromagnetic radiation, and then measured via laser-induced fluorescence. In short, atoms provide clean, well-defined qubits (see also box 2(*a*) and (*b*) and table A1).

Neutral atoms make attractive qubit candidates also because of their weak interaction with the environment, leading to long coherence times [14, 15, 19, 30]. They can be cooled down to nK temperatures and trapped in very large numbers (millions) in microscopic arrays created by laser beams (called optical lattices). The trapping and manipulation of atoms can be done with high precision [14, 18, 19, 21]. Until recently, the individual manipulation and measurement of neutral atoms in optical lattices was not possible, but the experiments in [24, 29, 31, 32, 35] show very promising perspectives for individual addressing and readout.

While one-qubit gates can be implemented with very high fidelity [34], realizing two-qubit gates or many-qubit entangled states is challenging because the atoms interact very weakly with each other. This problem can be overcome in several ways. For instance, the atoms can first be brought into a superposition of two internal spin states. Then, as the spin-dependent lattice is moved, the atoms go to the left and to the right simultaneously colliding with their neighbors. In this way, in a single operation, a highly entangled many-qubit state can be created [13]. Unfortunately, these collisional gates are very sensitive to decoherence and are also quite slow [1]. Exchange interactions provide an alternative approach [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.

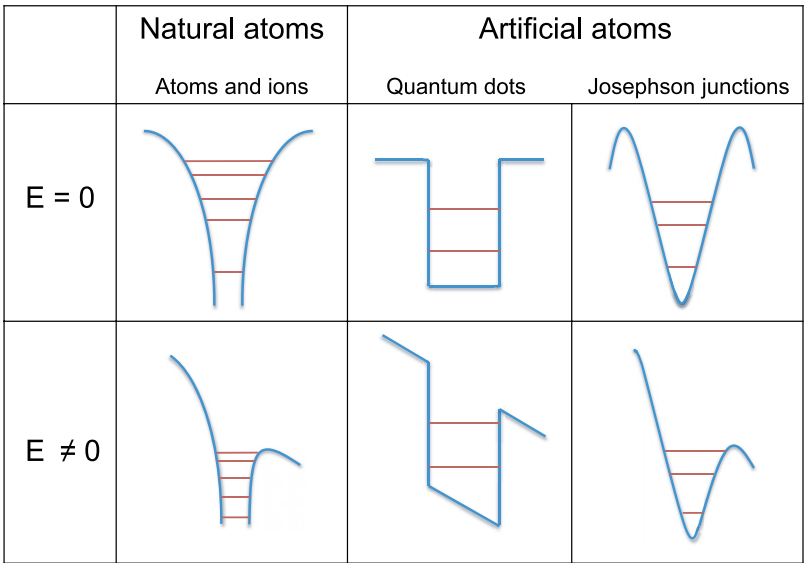
The prospect of producing many-qubit entangled states together with the possibility of single-site addressing and measurement makes neutral atoms promising for the quantum simulation of condensed-matter physics [16, 23] as well as measurement-based QC [39].

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.



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.

the state-selective displacement of the ions with an optical 'pushing' force [41]. In the latter, the displacement changes the strength of the Coulomb repulsion, leading to an additional phase, hence realizing a controlled-phase gate. Recently, a trapped ion quantum processor implementing arbitrary unitary transformations on two qubits has been realized [58].

In addition to the generation of GHZ and W entangled states, quantum algorithms [44, 49], quantum teleportation [46, 48], entanglement of distant qubits [55], quantum error correction [47] and decoherence free qubits [61] have also been demonstrated with trapped ion qubits.

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).

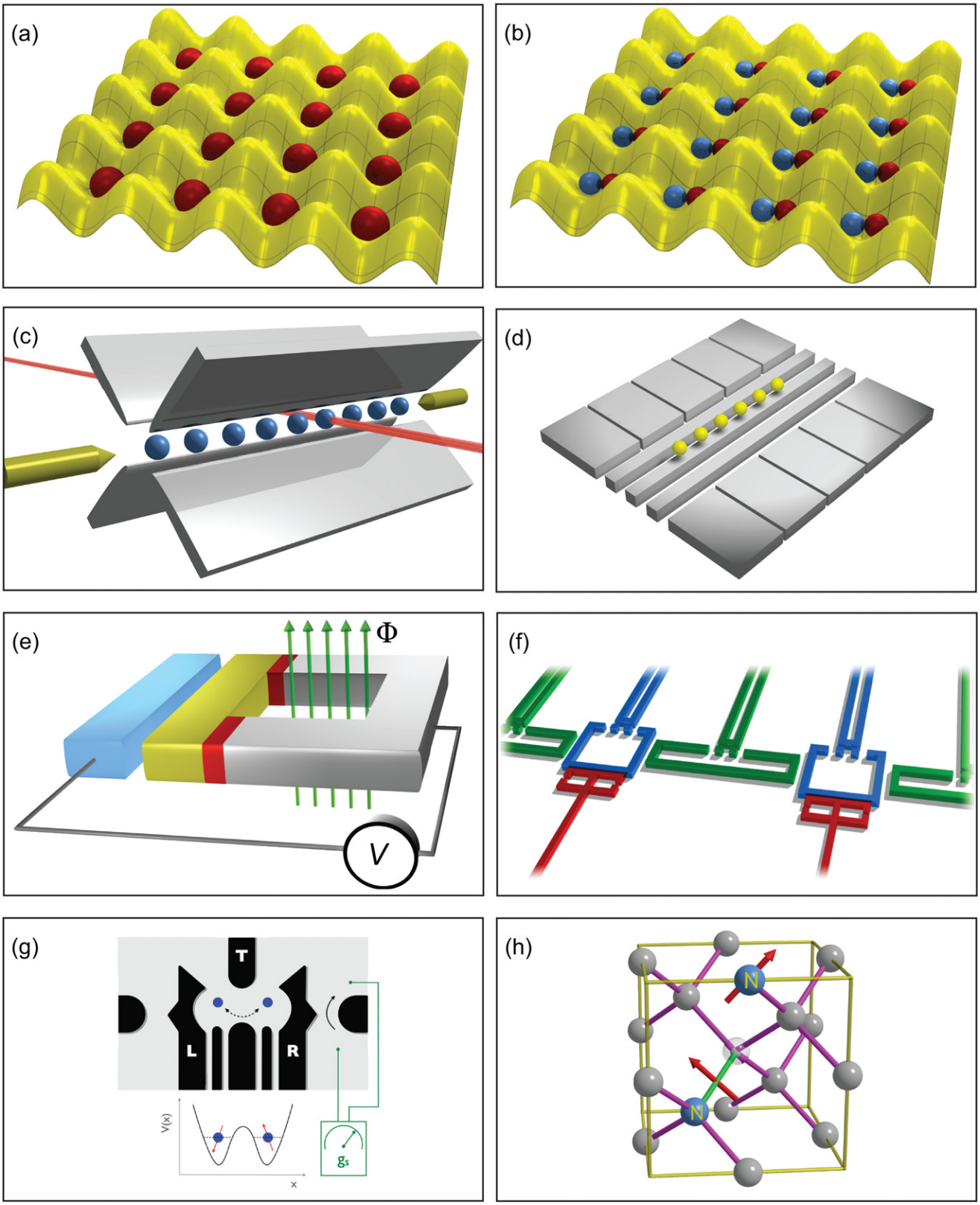
Superconducting qubits have coherence times that can reach tens of μs (see e.g. [98]), the coupling between qubits can be made strong and can be turned on and off electronically [74, 81]. In addition to direct coupling strategies, superconducting circuits can be coupled via 'cavities' [80, 83], which 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)

Box 2. Quantum bits.



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

Box 2. (Continued.)

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 Φ. 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.

and table A5 which attempts to cover, as much as possible in such a short space, several very different systems under the broad umbrella of spins) [5, 106].

Quantum dots are nanoscale structures in which electrons are trapped in all three dimensions. They can be fabricated in several ways, for example, by growth or with electrode gates in a two-dimensional electron gas. The material of choice is usually GaAs. On the other hand, NV centers are point defects in the diamond lattice, consisting of a nearest-neighbor pair made of a nitrogen atom, substituting a carbon atom, and a lattice vacancy. Although in its early stages, quantum computing with electronic and nuclear spins in an array of phosphorus donor atoms embedded in a pure silicon lattice (P : Si) has recently achieved very encouraging results [133–137].

Solid-state qubits such as quantum dots are attractive because, like superconducting circuits, they could be designed to have certain characteristics and assembled in large arrays. Furthermore, they require temperatures of up to a few K (NV centers in diamond could operate even at room temperature). The manipulation and readout can be done both electrically [118] and optically [117, 119, 123].

While Rabi oscillations have already been observed [113, 121], two-qubit gates have only been demonstrated for NV centers in diamond [109] (although a SWAP gate between logical states has been realized [110]). However, long coherence times [120, 122] have been measured for both quantum dots ($\sim\mu$s) [126, 127, 128, 129, 132] and NV centers (>5 ms) [124]. Moreover, for NV centers the entanglement between the electron and nuclear spins has also been shown [124].

Nowadays, nuclear magnetic resonance (NMR) techniques are extensively used in the context of nuclear spins in semiconductors. NMR techniques have been used for the control of nuclear spins in molecules [6, 7, 138–140], which proved very successful for realizing QC with such nuclear spin qubits [6, 7] (see also table A3). A well-known example is the factorization of $N = 15$ using Shor's algorithm [141]. Nuclear spin qubits have long coherence times (>1 s) and high-fidelity quantum gates have been demonstrated [6]. The coherent

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 semiconducting 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 (nK–μK 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^{14} Hz (optical)	1–10 GHz	GHz, 10^{13} Hz
Photon	Optical, MW	Optical, MW	MW	Optical, MW, infrared
Dimension	$\sim$2 Å	$\sim$2 Å	$\sim\mu$m	$\sim$nm
Distance between qubits	$<1\ \mu$m	$\sim5\ \mu$m	$\sim\mu$m	$\sim$10 nm[a], $\sim$100 nm[b]
Operating temperature	nK–μK	μK–mK	$\sim$mK	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%	>73% (>99%[c])
Two-qubit gates fidelity	>64%	99.3%	>90%	90%[c]
Entangled states	Bell	Bell, GHZ, W, cat	Bell, GHZ[d] W, cat	GHZ[c]
Measurement efficiency	99.9%	99.9%	>95%	99%
T_1	$\sim$s	$\sim$100 ms[e] >20 ms[f]	10 μs	$\sim$1 s[g]
T_2	$\sim$40 ms	1000 s[h]	20 μs	200 μs[g]
Q_1	$\sim10^4$	$\sim10^{13}$	$\sim10^5$	$\sim10^3$–10^4 (10^{6}[c])
Q_2	$\sim4\times10^4$	2×10^2–2×10^3 $\sim2\times10^4$	>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] T_1 for the vibrational modes.
[f] T_1 for the internal hyperfine states.
[g] 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;
[h] 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.

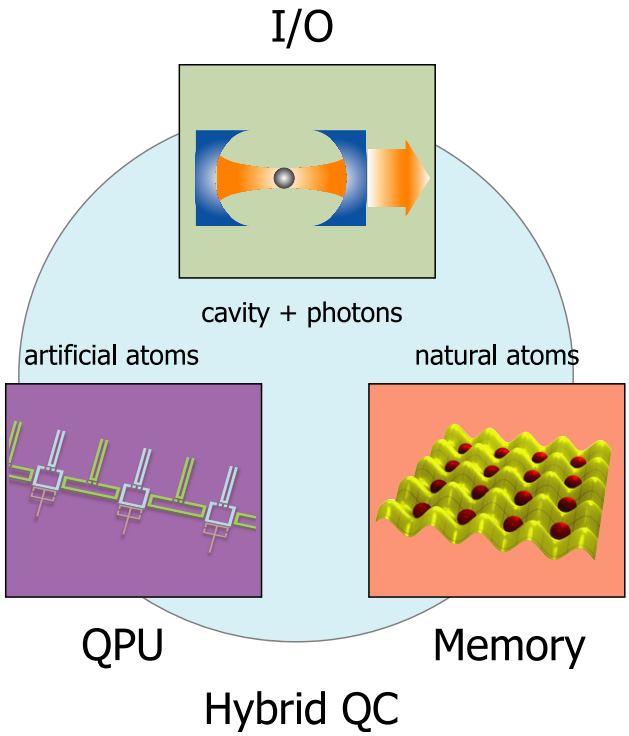


Figure 1. Schematic representation of a hybrid device consisting of natural atoms as quantum memory, artificial atoms as the 'quantum processing unit' (QPU), and an input/output (I/O) photonic interface.

Table 4. Coherence times of superconducting qubits.

Year	T1	T2 (echo)	Qubit	Ref.
1999	1 ns	—	Charge	[65]
2002	580 ns	2 ns	Charge	[66]
2002	100 ns	100 ns	Phase	[67]
2002	1.8 μs	500 ns	Hybrid (charge/phase)	[68]
2003	0.9 μs	30 ns	Flux	[69]
2006	1.9 μs	3.5 μs	Flux	[77]
2008	1.87 μs	2.22 μs	Hybrid (charge/phase)	[85]
2009	350 ns	—	Flux	[89]
2010	1.6 μs	1.3 μs	Hybrid (phase/flux)	[96]
2011	12 μs	23 μs	Flux	[98]
2011	0.2 ms	—	Charge	[101]

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%	

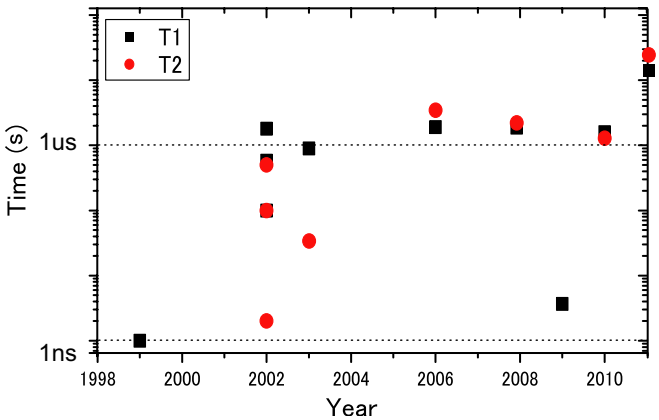


Figure 2. An example of the progress that has been achieved for superconducting circuits in the last decade. The decoherence time kept increasing, and the current trend promises decoherence times of the order of ms in the next couple of years. Visibility also increased and now it is larger than 95%.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

summarized above point out, the first-generation quantum computers may be available in the near future. Furthermore, they may come as hybrids consisting of natural atoms, artificial atoms, and photons.

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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'

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])
Operation temperature	From nK to μK
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	$\sim10^4$
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	10–10^3 (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)
Operation temperature	From μK to mK
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	$\sim10^{13}$ (single-qubit gate 50 ps) [63]
Q_2	$\sim$20000 (MS gate 50 μs) [56]; $\sim$200 (CZ gate 500 μs) [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)
Well-controlled fabrication	Yes
Flexible geometry	No
Distance between qubits	$\sim$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	$\sim$1 s (liquid state); >1 s (solid state)
Q_1	
Q_2	100 (gate time 10 ms)

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	$\sim 10\,\mu$s
Universal quantum gates	One-, two-qubit gates
Measurement	Individual measurement possible
Fabrication	
Material	Josephson junctions (Al–Al_xO_y–Al, Nb–Al_xO_yNb)
Well-controlled fabrication	Yes
Flexible geometry	Yes
Distance between qubits	$\sim\mu$m
Operation	
Qubits demonstrated	128 (fabricated) [93], 3 (entangled)
Superposition/entangled states	Yes/yes
One-qubit gates (fidelity)	Yes (99%)
Two-qubit gates (fidelity)	Yes ($>90\%$) [88]
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	23 μs [98]
Q_1	$\sim 10^5$
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	Electron spin; electron and nuclear spins in NV centers, P : Si
Scalability	High potential for scalability
Initialization	Demonstrated
Long coherence time	>1 s (QDs); ∼s (NV centers), ∼100 s (P : Si)
Universal quantum gates	One-qubit gates
Measurement	Electrical, optical
Fabrication	
Material	GaAs, InGaAs (QDs), NV centers, P : Si
Well-controlled fabrication	Yes
Flexible geometry	Yes
Distance between qubits	100–300 nm (QDs); ∼10 nm (NV centers)
Operation	
Qubits demonstrated	1 (QDs), 3 (NV centers) [124]
Superposition	Yes
One-qubit gates (fidelity)	Yes (>73% QDs [113]; >99% NV centers [130])
Two-qubit gates (fidelity)	Yes (90% NV centers [109])
Operation temperature	From mK to a few K (QDs); room temperature (NV centers)
Readout	
Readout (Fidelity)	Electrical, optical (90–92%)
Single-qubit readout possible	Yes
Manipulation	
Controls	RF, optical pulses, electrical
Types of operations	One-qubit gates (>73% gate time 25 ns)
Individual addressing	Yes
Decoherence	
Decoherence sources	Co-tunneling, charge noise, coupling with nuclear spins
T_1	>1 s (QDs) [120]; >5 ms[a] (NV centers) [124]; 6 s [133] (P : Si); 100 s [134] (P : Si)
T_2	∼270 μs [129, 128]; ∼1.8 ms (NV centers) [125]; ∼60 ms [107] (P : Si); 2 s [9] (P : Si)
Q_1	$\sim 10^3$ (gate time 180 ps); $\sim 10^4$ (gate time 30 ps) [121]; $>10^6$ (gate time ∼1 ns)
Q_2	tbd

[a] Room temperature.

References

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.

[1] Bloch I 2008 Quantum coherence and entanglement with ultracold atoms in optical lattices *Nature* **453** 1016–22

[2] Blatt R and Wineland D J 2008 Entangled states of trapped atomic ions *Nature* **453** 1008–15

[3] Clarke J and Wilhelm F K 2008 Superconducting quantum bits *Nature* **453** 1031–42

[4] You J Q and Nori F 2005 Superconducting circuits and quantum information *Phys. Today* **58** 42–7

[5] Hanson R and Awschalom D D 2008 Coherent manipulation of single spins in semiconductors *Nature* **453** 1043–9

[6] Vandersypen L M K and Chuang I L 2005 NMR techniques for quantum control and computation *Rev. Mod. Phys.* **76** 1037–69

[7] Baugh J *et al* 2007 Quantum information processing using nuclear and electron magnetic resonance: review and prospects arXiv:0710.1447v1

[8] Kane B E 1998 A silicon-based nuclear spin quantum computer *Nature* **393** 133–7

[9] Morton J J L, Tyryshkin A M, Brown R M, Shankar S, Lovett B W, Ardavan A, Schenkel T, Haller E E, Ager J W and Lyon S A 2008 Solid-state quantum memory using the 31P nuclear spin *Nature* **455** 1085–8

[10] Gisin N and Thew R 2007 Quantum communication *Nature Photon.* **1** 165–71

[11] Kok P, Munro W J, Nemoto K, Ralph T C, Dowling J P and Milburn G J 2007 Linear optical quantum computing with photonic qubits *Rev. Mod. Phys.* **79** 135

[12] Ladd T D, Jelezko F, Nakamura Y, Laflamme R, Monroe C and O'Brien J L 2010 Quantum computers *Nature* **464** 45–53

[13] Mandel O, Greiner M, Widera A, Rom T, Hänsch T W and Bloch I 2003 Controlled collisions for multi–particle entanglement of optically trapped atoms *Nature* **425** 937–40

[14] Schrader D, Dotsenko I, Khudaverdyan M, Miroshnychenko Y, Rauschenbeutel A and Meschede D 2004 Neutral atom quantum register *Phys. Rev. Lett.* **93** 150501

[15] Treutlein P, Hänsch T W, Hommelhoff P, Steinmetz T and Reichel J 2004 Coherence in microchip traps *Phys. Rev. Lett.* **92** 203005

[16] Jaksch D and Zoller P 2005 The cold atom Hubbard toolbox *Ann. Phys.* **315** 52–79

[17] Micheli A, Brennen G K and Zoller P 2006 A toolbox for lattice–spin models with polar molecules *Nature Phys.* **2** 341–7

[18] Miroshnychenko Y, Alt W, Dotsenko I, Forster L, Khudaverdyan M, Meschede D, Schrader D and Rauschenbeutel A 2006 Quantum engineering: an atom-sorting machine *Nature* **442** 151

[19] Yavuz D D, Kulatunga P B, Urban E, Johnson T A, Proite N, Henage T, Walker T G and Saffman M 2006 Fast ground state manipulation of neutral atoms in microscopic optical traps *Phys. Rev. Lett.* **96** 063001

[20] Anderlini M, Brown B L, Lee P J and Sebby-Strabley J, Phillips W D and Porto J V 2007 Controlled exchange interaction between pairs of neutral atoms in an optical lattice *Nature* **448** 452–6

[21] Beugnon J *et al* 2007 Two-dimensional transport and transfer of a single atomic qubit in optical tweezers *Nature Phys.* **3** 696–9

[22] Hayes D, Julienne P S and Deutsch I H 2007 Quantum logic via the exchange blockade in ultracold collisions *Phys. Rev. Lett.* **98** 070501

[23] Lewenstein M, Sanpera A, Ahufinger V, Damski B, Sen(De) A and Sen U 2007 Ultracold atomic gases in optical lattices: mimicking condensed matter physics and beyond *Adv. Phys.* **56** 243–379

[24] Nelson K D, Li X and Weiss D S 2007 Imaging single atoms in a three-dimensional array *Nature Phys.* **3** 556–60

[25] Trotzky S, Cheinet P, Folling S, Feld M, Schnorrberger U, Rey A M, Polkovnikov A, Demler E A, Lukin M D and Bloch I 2008 Time-resolved observation and control of superexchange interactions with ultracold atoms in optical lattices *Science* **319** 295–9

[26] Gaetan A, Miroshnychenko Y, Wilk T, Chotia A, Viteau M, Comparat D, Pillet P, Browaeys A and Grangier P 2009 Observation of collective excitation of two individual atoms in the Rydberg blockade regime *Nature Phys.* **5** 115–8

[27] Saffman M, Walker T G and Mølmer K 2010 Quantum information with Rydberg atoms *Rev. Mod. Phys.* **82** 2313

[28] Urban E, Johnson T A, Henage T, Isenhower L, Yavuz D D, Walker T G and Saffman M 2009 Observation of Rydberg blockade between two atoms *Nature Phys.* **5** 110–4

[29] Würtz P, Langen T, Gericke T, Koglbauer A and Otto H 2009 Experimental demonstration of single-site addressability in a two-dimensional optical lattice *Phys. Rev. Lett.* **103** 080404

[30] Deutsch C, Ramirez-Martinez F, Lacroute C, Reinhard F, Schneider T, Fuchs J N, Piechon F, Laloe F, Reichel J and Rosenbusch P 2010 Spin self-rephasing and very long coherence times in a trapped atomic ensemble *Phys. Rev. Lett.* **105** 020401

[31] Fuhrmanek A, Bourgain R, Sortais Y R P and Browaeys A 2011 Free-space lossless state detection of a single trapped atom *Phys. Rev. Lett.* **106** 133003

[32] Gibbons M J, Hamley C D, Shih C-Y and Chapman M S 2011 Nondestructive fluorescent state detection of single neutral atom qubits *Phys. Rev. Lett.* **106** 133002

[33] Isenhower L, Urban E, Zhang X L, Gill A T, Henage T, Johnson T A, Walker T G and Saffman M 2010 Demonstration of a neutral atom controlled-NOT quantum gate *Phys. Rev. Lett.* **104** 010503

[34] Olmschenk S, Chicireanu R, Nelson K D and Porto J V 2010 Randomized benchmarking of atomic qubits in an optical lattice *New J. Phys.* **12** 113007

[35] Sherson J F, Weitenberg C, Endres M, Cheneau M, Bloch I and Kuhr S 2010 Single-atom-resolved fluorescence imaging of an atomic Mott insualtor *Nature* **467** 68

[36] Weimer H, Muller M, Zoller P, Lesanovsky I and Buchler H P 2010 A Rydberg quantum simulator *Nature Phys.* **6** 382

[37] Wilk T, Gaëtan A, Evellin C, Wolters J, Miroshnychenko Y, Grangier P and Browaeys A 2010 Entanglement of two individual neutral atoms using Rydberg blockade *Phys. Rev. Lett.* **104** 010502

[38] Zhang X L, Isenhower L, Gill A T, Walker T G and Saffman M 2010 Deterministic entanglement of two neutral atoms via Rydberg blockade *Phys. Rev.* A **82** 030306

[39] Kay A, Pachos J K and Adams C S 2006 Graph-state preparation and quantum computation with global addressing of optical lattices *Phys. Rev.* A **73** 022310

[40] Turchette Q A, Wood C S, King B E, Myatt C J, Leibfried D, Itano W M, Monroe C and Wineland D J 1998 Deterministic entanglement of two trapped ions *Phys. Rev. Lett.* **81** 3631

[41] Cirac J I and Zoller P 2000 A scalable quantum computer with ions in an array of microtraps *Nature* **404** 579–81

[42] Sackett C A *et al* 2000 Experimental entanglement of four particles *Nature* **404** 256–9

[43] Schmidt-Kaler F, Häffner H, Riebe M, Gulde S, Lancaster G P T, Deuschle T, Becher C, Roos C F, Eschner J and Blatt R 2003 Realization of the Cirac–Zoller controlled-NOT quantum gate *Nature* **422** 408

[44] Gulde S, Riebe M, Lancaster G P T, Becher C, Eschner J, Häffner H, Chuang I L, Blatt R and Schmidt-Kaler F 2003 Implementation of the Deutsch–Jozsa algorithm on an ion-trap quantum computer *Nature* **421** 48–50

[45] Leibfried D *et al* 2003 Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate *Nature* **422** 412

[46] Barrett M D *et al* 2004 Deterministic quantum teleportation of atomic qubits *Nature* **429** 737–9

[47] Chiaverini J *et al* 2004 Realization of quantum error correction *Nature* **432** 602–5

[48] Riebe M *et al* 2004 Deterministic quantum teleportation with atoms *Nature* **429** 734–7

[49] Chiaverini J *et al* 2005 Implementation of the semiclassical quantum Fourier transform in a scalable system *Science* **308** 997–1002

[50] Häffner H *et al* 2005 Scalable multiparticle entanglement of trapped ions *Nature* **438** 643–6

[51] Häffner H *et al* 2005 Robust entanglement *Appl. Phys.* B **81** 151

[52] Leibfried D *et al* 2005 Creation of a six-atom Schrödinger cat state *Nature* **438** 639–42

[53] Riebe M, Kim K, Schindler P, Monz T, Schmidt P O, Korber T K, Hansel W, Haffner H, Roos C F and Blatt R 2006 Process tomography of ion trap quantum gates *Phys. Rev. Lett.* **97** 220407

[54] Stick D, Hensinger W K, Olmschenk S, Madsen M J, Schwab K and Monroe C 2006 Ion trap in a semiconductor chip *Nature Phys.* **2** 36–9

[55] Moehring D L, Maunz P, Olmschenk S, Younge K C, Matsukevich D N, Duan L-M and Monroe C 2007 Entanglement of single-atom quantum bits at a distance *Nature* **449** 68–71

[56] Benhelm J, Kirchmair G, Roos C F and Blatt R 2008 Towards fault–tolerant quantum computing with trapped ions *Nature Phys.* **4** 463–6

[57] Kielpinski D 2008 Ion-trap quantum information processing: experimental status *Front. Phys. China* **3** 365–81

[58] Hanneke D, Home J P, Jost J D, Amini J M, Leibfried D and Wineland D J 2010 Realization of a programmable two-qubit quantum processor *Nature Phys.* **6** 13–6

[59] Myerson A H, Szwer D J, Webster S C, Allcock D T C, Curtis M J, Imreh G, Sherman J A, Stacey D N, Steane A M and Lucas D M 2008 High-fidelity readout of trapped-ion qubits *Phys. Rev. Lett.* **100** 200502

[60] Monz T, Kim K, Hansel W, Riebe M, Villar A S, Schindler P, Chwalla M, Hennrich M and Blatt R 2009 Realization of the quantum Toffoli gate with trapped ions *Phys. Rev. Lett.* **102** 040501

[61] Monz T *et al* 2009 Realization of universal ion trap quantum computation with decoherence free qubits *Phys. Rev. Lett.* **103** 200503

[62] Burrell A H, Szwer D J, Webster S C and Lucas D M 2010 Scalable simultaneous multi-qubit readout with 99.99% single-shot fidelity *Phys. Rev.* A **81** 040302

[63] Campbell W C, Mizrahi J, Quraishi Q, Senko C, Hayes D, Hucul D, Matsukevich D N, Maunz P and Monroe C 2010

Ultrafast gates for single atomic qubits *Phys. Rev. Lett.* **105** 090502
[64] Monz T, Schindler P, Barreiro J T, Chwalla M, Nigg D, Coish W A, Harlander M, Haensel W, Hennrich M and Blatt R 2011 14-qubit entanglement: creation and coherence *Phys. Rev. Lett.* **106** 130506
[65] Nakamura Y, Pashkin Y A and Tsai J S 1999 Coherent control of macroscopic quantum states in a single-Cooper-pair box *Nature* **398** 786
[66] Nakamura Y, Pashkin Yu A, Yamamoto T and Tsai J S 2002 Charge echo in a Cooper-pair box *Phys. Rev. Lett.* **88** 047901
[67] Martinis J M, Nam S, Aumentado J and Urbina C 2002 Rabi oscillations in a large Josephson-junction qubit *Phys. Rev. Lett.* **89** 117901
[68] Vion D, Aassime A, Cottet A, Joyez P, Pothier H, Urbina C, Esteve D and Devoret M H 2002 Manipulating the quantum state of an electrical circuit *Science* **296** 886
[69] Chiorescu I, Nakamura Y, Harmans C J P M and Mooij J E 2003 Coherent quantum dynamics of a superconducting flux qubit *Science* **299** 1869
[70] Berkley A J, Xu H, Ramos R C, Gubrud M A, Strauch F W, Johnson P R, Anderson J, Dragt A J, Lobb C J and Wellstood F C 2003 Entangled macroscopic quantum states in two superconducting qubits *Science* **300** 1548
[71] Yamamoto T, Pashkin Y A, Astafiev O, Nakamura Y and Tsai J S 2003 Demonstration of conditional gate operation using superconducting charge qubits *Nature* **425** 941
[72] Wallraff A, Schuster D I, Blais A, Frunzio L, Huang R S, Majer J, Kumar S, Girvin S M and Schoelkopf R J 2004 Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics *Nature* **431** 162
[73] McDermott R, Simmonds R W, Steffen M, Cooper K B, Cicak K, Osborn K D, Oh S, Pappas D P and Martinis J M 2005 Simultaneous state measurement of coupled Josephson phase qubits *Science* **307** 1299
[74] Hime T, Reichardt P A, Plourde B L T, Robertson T L, Wu C-E, Ustinov A V and Clarke J 2006 Solid-state qubits with current-controlled coupling *Science* **314** 1427–9
[75] Grajcar M *et al* 2006 Four-qubit device with mixed couplings *Phys. Rev. Lett.* **96** 047006
[76] Steffen M, Ansmann M, Bialczak R C, Katz N, Lucero E, McDermott R, Neeley M, Weig E M, Cleland A N and Martinis J M 2006 Measurement of the entanglement of two superconducting qubits via state tomography *Science* **313** 1423–5
[77] Yoshihara F, Harrabi K, Niskanen A O, Nakamura Y and Tsai J S 2006 Decoherence of flux qubits due to $1/f$ flux noise *Phys. Rev. Lett.* **97** 167001
[78] Harris R *et al* 2007 Sign- and magnitude-tunable coupler for superconducting flux qubits *Phys. Rev. Lett.* **98** 177001
[79] Lupascu A, Saito S, Picot T, Harmans C J P M, de Groot P C and Mooij J E 2007 Quantum non-demolition measurement of a superconducting two-level system *Nature Phys.* **3** 119–25
[80] Majer J *et al* 2007 Coupling superconducting qubits via a cavity bus *Nature* **449** 443–7
[81] Niskanen A O, Harrabi K, Yoshihara F, Nakamura Y, Lloyd S and Tsai J S 2007 Quantum coherent tunable coupling of superconducting qubits *Science* **316** 723–6
[82] Plantenberg J H, de Groot P C, Harmans C J P M and Mooij J E 2007 Demonstration of controlled-NOT quantum gates on a pair of superconducting quantum bits *Nature* **447** 836
[83] Sillanpää M A, Park J I and Simmonds R W 2007 Coherent quantum state storage and transfer between two phase qubits via a resonant cavity *Nature* **449** 438–42
[84] Picot T, Lupascu A, Saito S, Harmans C J P M and Mooij J E 2008 Role of relaxation in the quantum measurement of a superconducting qubit using a nonlinear oscillator *Phys. Rev.* B **78** 132508
[85] Schreier J A *et al* 2008 Suppressing charge noise decoherence in superconducting charge qubits *Phys. Rev.* B **77** 180502
[86] Schoelkopf R J and Girvin S M 2008 Wiring up quantum systems *Nature* **451** 664–9
[87] Ansmann M *et al* 2009 Violation of Bell's inequality in Josephson phase qubits *Nature* **461** 504
[88] DiCarlo L *et al* 2009 Demonstration of two-qubit algorithms with a superconducting quantum processor *Nature* **460** 240–4
[89] Manucharyan V E, Koch J, Glazman L I and Devoret M H 2009 Fluxonium: single Cooper-pair circuit free of charge offsets *Science* **326** 113
[90] Neeley M *et al* 2010 Generation of three-qubit entangled states using superconducting phase qubits *Nature* **467** 570
[91] DiCarlo L, Reed M D, Sun L, Johnson B R, Chow J M, Gambetta J M, Frunzio L, Girvin S M, Devoret M H and Schoelkopf R J 2010 Preparation and measurement of three-qubit entanglement in a superconducting circuit *Nature* **467** 574
[92] Sun G, Wen X, Mao B, Chen J, Yu Y, Wu P and Han S 2010 Tunable quantum beam splitters for coherent manipulation of a solid-state tripartite qubit system *Nature Commun.* **1** 51
[93] Harris R *et al* 2010 Experimental investigation of an eight-qubit unit cell in a superconducting optimization processor *Phys. Rev.* B **82** 024511
[94] O'Connell A D *et al* 2010 Quantum ground state and single-phonon control of a mechanical resonator *Nature* **464** 697
[95] Palacios-Laloy A, Mallet F, Nguyen F, Bertet P, Vion D, Esteve D and Korotkov A N 2010 Experimental violation of a Bell's inequality in time with weak measurement *Nature Phys.* **6** 442–7
[96] Steffen M, Kumar S, DiVincenzo D P, Rozen J R, Keefe G A, Rothwell M B and Ketchen M B 2010 High coherence hybrid superconducting qubit *Phys. Rev. Lett.* **105** 100502
[97] Mariantoni M 2011 private communication
[98] Bylander J, Gustavsson S, Yan F, Yoshihara F, Harrabi K, Fitch G, Cory D G, Nakamura Y, Tsai J-S and Oliver W D 2011 Noise spectroscopy through dynamical decoupling with a superconducting flux qubit *Nature Phys.* **7** 565–70
[99] Neeley M *et al* 2009 Emulation of a quantum spin with a superconducting phase qudit *Science* **325** 722–5
[100] Tyryshkin A M *et al* 2011 Electron spin coherence exceeding seconds in high purity silicon arXiv:1105.3772
[101] Kim Z, Suri B, Zaretskey V, Novikov S, Osborn K D, Mizel A, Wellstood F C and Palmer B S 2011 Decoupling a Cooper-pair box to enhance the lifetime to 0.2 ms *Phys. Rev. Lett.* **106** 120501
[102] Makhlin Y, Schoen G and Shnirman A 2001 Quantum-state engineering with Josephson-junction devices *Rev. Mod. Phys.* **73** 357
[103] You J Q and Nori F 2011 Atomic physics and quantum optics using superconducting circuits *Nature* **474** 589
[104] Hofheinz M *et al* 2009 Synthesizing arbitrary quantum states in a superconducting resonator *Nature* **459** 546–9
[105] Nori F 2009 Quantum football *Science* **325** 689
[106] Loss D and DiVincenzo D P 1998 Quantum computation with quantum dots *Phys. Rev.* A **57** 120–6
[107] Tyryshkin A M, Lyon S A, Astashkin A V and Raitsimring A M 2003 Electron spin relaxation times of phosphorus donors in silicon *Phys. Rev.* B **68** 193207
[108] Jelezko F, Gaebel T, Popa I, Gruber A and Wrachtrup J 2004 Observation of coherent oscillations in a single electron spin *Phys. Rev. Lett.* **92** 076401

[109] Jelezko F, Gaebel T, Popa I, Domhan M, Gruber A and Wrachtrup J 2004 Observation of coherent oscillation of a single nuclear spin and realization of a two-qubit conditional quantum gate *Phys. Rev. Lett.* **93** 130501
[110] Petta J R, Johnson A C, Taylor J M, Laird E A, Yacoby A, Lukin M D, Marcus C M, Hanson M P and Gossard A C 2005 Coherent manipulation of coupled electron spins in semiconductor quantum dots *Science* **309** 2180–4
[111] Childress L, Gurudev Dutt M V, Taylor J M, Zibrov A S, Jelezko F, Wrachtrup J, Hemmer P R and Lukin M D 2006 Coherent dynamics of coupled electron and nuclear spin qubits in diamond *Science* **314** 281–5
[112] Hanson R, Mendoza F M, Epstein R J and Awschalom D D 2006 Polarization and readout of coupled single spins in diamond *Phys. Rev. Lett.* **97** 087601
[113] Koppens F H L, Buizert C, Tielrooij K J, Vink I T, Nowack K C, Meunier T, Kouwenhoven L P and Vandersypen L M K 2006 Driven coherent oscillations of a single electron spin in a quantum dot *Nature* **442** 766–71
[114] Stegner A R, Boehme C, Huebl H, Stutzmann M, Lips K and Brandt M S 2006 Electrical detection of coherent 31p spin quantum states *Nature Phys.* **2** 835–8
[115] Gurudev Dutt M V, Childress L, Jiang L, Togan E, Maze J, Jelezko F, Zibrov A S, Hemmer P R and Lukin M D 2007 Quantum register based on individual electronic and nuclear spin qubits in diamond *Science* **316** 1312–6
[116] Hanson R, Kouwenhoven L P, Petta J R, Tarucha S and Vandersypen L M K 2007 Spins in few-electron quantum dots *Rev. Mod. Phys.* **79** 1217
[117] Mikkelsen M H, Berezovsky J, Coldren L A, Stoltz N G and Awschalom D D 2007 Optically detected coherent spin dynamics of a single electron in a quantum dot *Nature Phys.* **3** 770–3
[118] Nowack K C, Koppens F H L, Nazarov Y V and Vandersypen L M K 2007 Coherent control of a single electron spin with electric fields *Science* **318** 1430–3
[119] Xu X, Sun B, Berman P R, Steel D G, Bracker A S, Gammon D and Sham L J 2007 Coherent optical spectroscopy of a strongly driven quantum dot *Science* **317** 929–32
[120] Amasha S, MacLean K, Radu I P, Zumbuhl D M, Kastner M A, Hanson M P and Gossard A C 2008 Electrical control of spin relaxation in a quantum dot *Phys. Rev. Lett.* **100** 046803
[121] Berezovsky J, Mikkelsen M H, Stoltz N G, Coldren L A and Awschalom D D 2008 Picosecond coherent optical manipulation of a single electron spin in a quantum dot *Science* **320** 349–52
[122] Chirolli L and Burkard G 2008 Decoherence in solid state qubits *Adv. Phys.* **57** 225
[123] Gerardot B D, Brunner D, Dalgarno P A, Ohberg P, Seidl S, Kroner M, Karrai K, Stoltz N G, Petroff P M and Warburton R J 2008 Optical pumping of a single hole spin in a quantum dot *Nature* **451** 441–4
[124] Neumann P, Mizuochi N, Rempp F, Hemmer P, Watanabe H, Yamasaki S, Jacques V, Gaebel T, Jelezko F and Wrachtrup J 2008 Multipartite entanglement among single spins in diamond *Science* **320** 1326–9
[125] Balasubramanian G *et al* 2009 Ultralong spin coherence time in isotopically engineered diamond *Nature Mater.* **8** 383–7
[126] Barthel C, Reilly D J, Marcus C M, Hanson M P and Gossard A C 2009 Rapid single-shot measurement of a singlet-triplet qubit *Phys. Rev. Lett.* **103** 160503
[127] Foletti S, Bluhm H, Mahalu D, Umansky V and Yacoby A 2009 Universal quantum control of two-electron spin quantum bits using dynamic nuclear polarization *Nature Phys.* **5** 903
[128] Barthel C, Medford J, Marcus C M, Hanson M P and Gossard A C 2010 Interlaced dynamical decoupling and coherent operation of a singlet-triplet qubit *Phys. Rev. Lett.* **105** 266808
[129] Bluhm H, Foletti S, Mahalu D, Umansky V and Yacoby A 2010 Enhancing the coherence of a spin qubit by operating it as a feedback loop that controls its nuclear spin bath *Phys. Rev. Lett.* **105** 216803
[130] de Lange G, Wang Z H, Ristè D, Dobrovitski V V and Hanson R 2010 Universal dynamical decoupling of a single solid-state spin from a spin bath *Science* **330** 60
[131] Nadj-Perge S, Frolov S M, Bakkers E P A M and Kouwenhoven L P 2010 Spin–orbit qubit in a semiconductor nanowire *Nature* **468** 1084
[132] Bluhm H, Foletti S, Neder I, Rudner M, Mahalu D, Umansky V and Yacoby A 2011 Dephasing time of GaAs electron-spin qubits coupled to a nuclear bath exceeding 200 μs *Nature Phys.* **7** 109
[133] Morello A *et al* 2010 Single-shot readout of an electron spin in silicon *Nature* **467** 687
[134] McCamey D R, Van Tol J, Morley G W and Boehme C 2010 Electronic spin storage in an electrically readable nuclear spin memory with a lifetime >100 seconds *Science* **330** 1652–6
[135] Witzel W M, Carroll M S, Morello A, Cywiński L and Das Sarma S 2010 Electron spin decoherence in isotope-enriched silicon *Phys. Rev. Lett.* **105** 187602
[136] Simmons C B *et al* 2011 Tunable spin loading and T_1 of a silicon spin qubit measured by single-shot readout *Phys. Rev. Lett.* **106** 156804
[137] Simmons S, Brown R M, Riemann H, Abrosimov N V, Becker P, Pohl H J, Thewalt M L W, Itoh K M and Morton J J L 2011 Entanglement in a solid-state spin ensemble *Nature* **470** 69–72
[138] Suter D and Mahesh T S 2008 Spins as qubits: quantum information processing by nuclear magnetic resonance *J. Chem. Phys.* **128** 052206
[139] Peng X, Liao Z, Xu N, Qin G, Zhou X, Suter D and Du J 2008 Quantum adiabatic algorithm for factorization and its experimental implementation *Phys. Rev. Lett.* **101** 220405
[140] Negrevergne C, Mahesh T S, Ryan C A, Ditty M, Cyr-Racine F, Power W, Boulant N, Havel T, Cory D G and Laflamme R 2006 Benchmarking quantum control methods on a 12-qubit system *Phys. Rev. Lett.* **96** 170501
[141] Vandersypen L M K, Steffen M, Breyta G, Yannoni C S, Sherwood M H and Chuang I L 2001 Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance *Nature* **414** 883–7
[142] Grajcar M, van der Ploeg S H W, Izmalkov A, Il'ichev E, Meyer H-G, Fedorov A, Shnirman A and Schon G 2008 Sisyphus cooling and amplification by a superconducting qubit *Nature Phys.* **4** 612–6
[143] Nori F 2008 Atomic physics with a circuit *Nature Phys.* **4** 589
[144] Langer C *et al* 2005 Long-lived qubit memory using atomic ions *Phys. Rev. Lett.* **95** 060502
[145] Kimble H J 2008 The quantum internet *Nature* **453** 1023–30
[146] Colombe Y, Steinmetz T, Dubois G, Linke F, Hunger D and Reichel J 2007 Strong atom–field coupling for Bose–Einstein condensates in an optical cavity on a chip *Nature* **450** 272–6
[147] Herskind P F, Dantan A, Marler J P, Albert M and Drewsen M 2009 Realization of collective strong coupling with ion Coulomb crystals in an optical cavity *Nature Phys.* **5** 494–8
[148] Englund D, Faraon A, Fushman I, Stoltz N, Petroff P and Vuckovic J 2007 Controlling cavity reflectivity with a single quantum dot *Nature* **450** 857–61

[149] O'Brien J L 2007 Optical quantum computing *Science* **318** 1567–70
[150] Tian L, Rabl P, Blatt R and Zoller P 2004 Interfacing quantum-optical and solid-state qubits *Phys. Rev. Lett.* **92** 247902
[151] Tian L, Blatt R and Zoller P 2005 Scalable ion trap quantum computing without moving ions *Eur. Phys. J.* D **32** 201–8
[152] Verdú J, Zoubi H, Koller Ch, Majer J, Ritsch H and Schmiedmayer J 2009 Strong magnetic coupling of an ultracold gas to a superconducting waveguide cavity *Phys. Rev. Lett.* **103** 043603
[153] Petrosyan D, Bensky G, Kurizki G, Mazets I, Majer J and Schmiedmayer J 2009 Reversible state transfer between superconducting qubits and atomic ensembles *Phys. Rev.* A **79** 040304
[154] Zipkes C, Palzer S, Sias C and Kohl M 2010 A trapped single ion inside a Bose–Einstein condensate *Nature* **464** 388
[155] Doerk H, Idziaszek Z and Calarco T 2010 Atom–ion quantum gate *Phys. Rev.* A **81** 012708
[156] Kubo Y *et al* 2010 Strong coupling of a spin ensemble to a superconducting resonator *Phys. Rev. Lett.* **105** 140502
[157] Schuster D I *et al* 2010 High-cooperativity coupling of electron-spin ensembles to superconducting cavities *Phys. Rev. Lett.* **105** 140501
[158] Wu H, George R E, Wesenberg J H, Mølmer K, Schuster D I, Schoelkopf R J, Itoh K M, Ardavan A, Morton J J L and Briggs G A D 2010 Storage of multiple coherent microwave excitations in an electron spin ensemble *Phys. Rev. Lett.* **105** 140503
[159] Simon C *et al* 2010 Quantum memories. A review based on the European integrated project "Qubit Applications (QAP)" *Eur. Phys. J.* D **58** 1
[160] Wallquist M, Hammerer K, Rabl P, Lukin M and Zoller P 2009 Hybrid quantum devices and quantum engineering *Phys. Scr.* **T137** 014001
[161] DiVincenzo D P 1995 Quantum computation *Science* **270** 255–61
[162] Buluta I M and Nori F 2009 Quantum simulators *Science* **326** 108–11
[163] Cirac J I and Zoller P 1995 Quantum computations with cold trapped ions *Phys. Rev. Lett.* **74** 4091
[164] Mølmer K and Sørensen A 1999 Multiparticle entanglement of hot trapped ions *Phys. Rev. Lett.* **82** 1835