# Wiring up quantum systems

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**The emerging field of circuit quantum electrodynamics could pave the way for the design of practical quantum computers.**

HORIZONS

In the past two decades, scientists and engineers in a variety of disciplines have been excited by the idea of quantum information processing[1], in which a computation is carried out by controlling a complex collection of quantum objects. This idea seeks to combine two of the greatest advances in science and technology of the twentieth century.

The first breakthrough is the development of quantum mechanics, with its sometimes strange and counterintuitive rules that hold sway in the domain of atoms and single particles. The second is the technological revolution that followed the invention of the integrated circuit and the advent of powerful digital computers, which gave rise to the current information age. Surprisingly, the seemingly bizarre quantum-mechanical ideas of superposition and entanglement are expected to lead to a kind of natural parallel processing during computations. The unlikely marriage of these two revolutions could lead to incredible advances in computational power, at least for certain special problems.

Unfortunately, the practical challenges to making a quantum information device are daunting. To build a quantum computer, the classical bits that store information in an ordinary computer must first be replaced with quantum bits (qubits). These qubits can be composed of any quantum system with two distinct states (0 and 1), but they have the special property that they can be placed into quantum superpositions, existing in both states at once. A computation then proceeds by combining manipulations of the superpositions in single qubits (one-bit operations) and controlled interactions of multiple qubits (the quantum equivalent of logic gates). But to truly exceed the capabilities of conventional computers, the quantum engineer must acquire extremely precise control over the quantum domain, prevent any unknown evolution that affects the quantum states (decoherence), and amass many thousands of qubits. Moreover, these qubits must then be 'wired up' in complex and prescribed arrangements, so that they can interact and communicate their quantum information back and forth during the computation.

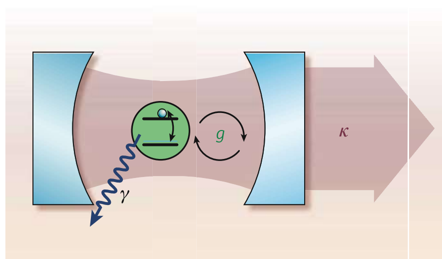



**Figure 1 | Cavity quantum electrodynamics.** **Schematic representation of a cavity quantum electrodynamics (QED) system, consisting of an atom with two energy levels interacting with a single photon mode (pink) trapped by mirrors (blue) to form a cavity. The blue dot is an electron occupying one of the energy levels. The strong coupling regime is reached when the interaction rate of the atom and a single photon ($g$) is larger than the dissipation arising from the loss of photons (at rate $\kappa$) or from emission from the atom into other modes at rate $\gamma$; in other words, when $g >> \kappa, \gamma$.**

Many different physical implementations of quantum information processors are being pursued today. Some systems comprise 'natural' candidates, such as single atoms, ions or spins, for which the manipulation of quantum states has a long history and is routine in many laboratories. Others are based on artificial systems in the solid state, such as quantum dots or superconducting circuits. These latter candidates have a certain appeal as they can be designed and fabricated using techniques borrowed from conventional electronics.

Before making a quantum information processor from solid-state systems such as superconducting circuits, two basic questions must be addressed. First, can the qubits be made from sufficiently 'atom-like' circuit elements, in which the macroscopic variables such as current and voltage can exist in controllable superpositions of distinct quantum states? And second, can we connect these qubits together in the required manner, perhaps using familiar electrical means such as actual wires, but keeping in mind that any information transported must remain in its intrinsically quantum form and exchanged as individual quanta?

The answer to the first question, originally posed[2] to test the applicability of quantum mechanics for macroscopic objects, is now at least a qualified 'yes'. Pioneering work in the 1980s on simple superconducting circuits incorporating a Josephson junction[3] (see Box 1) showed that macroscopic variables such as voltages could indeed exhibit quantum behaviour. Further work established that junctions could be considered as 'atoms with wires', which display energy-level quantization[4] and interact strongly with the electromagnetic environment[5,6]. It was not until the end of the 1990s, however, that the first evidence for coherent superpositions[7] and time-domain control of the quantum state[8] in a superconducting qubit was demonstrated.

The past decade has seen rapid progress in this field. Several different 'flavours' of superconducting qubit[9] (see Box 1) have now been demonstrated, and two qubits have been coupled to demonstrate the entanglement between them[10] and to perform simple quantum logic operations[11]. The current state-of-the-art allows for superposition states that survive for several microseconds, long enough for hundreds of operations on a single qubit. With improvements in superconducting qubit design, as well as in the materials and methods used for fabricating circuits, the lifetime of the stored quantum information may be further increased and the precision of qubit control and measurement enhanced.

But how can we address the second question and realize the quantum connections between qubits? For communicating quantum information between real atoms, optical photons are natural candidates[12]. They have many advantages, including rapid propagation and the ability to be guided on optical fibres for many kilometres without being lost. Superconducting qubits also interact electromagnetically, but because of their much smaller energy-level separations, the 'photons' they best couple with lie in the microwave range of the spectrum (frequencies of 3–30 GHz, or wavelengths of 1–10 cm). Several authors[13–22] have speculated that such microwave photons could be a route to connecting qubits, and recent experiments[23–30] have demonstrated qubit–photon couplings in superconducting circuits. This approach is similar to the branch of atomic physics known as cavity quantum electrodynamics (cavity QED), which studies the interaction of photons and atoms at the quantum level. The new field, dubbed 'circuit QED', offers a tentative 'yes' to the second key question about whether we can create quantum devices with interconnected qubits.

Here we begin by discussing the physics of cavity QED with real atoms, and then introduce the analogous circuit QED system, in which microwave photons are coupled to superconducting qubits acting as artificial atoms. As we will see, the tight confinement of microwaves on a chip naturally leads to extremely strong 'atom–photon' coupling, offering new possibilities for fundamental experiments on the light–matter interaction and interacting quantum systems. After reviewing various experiments in circuit QED that have been performed to date, we will point out some of the outstanding issues and future directions for this rapidly progressing field.

## An atom meets a photon

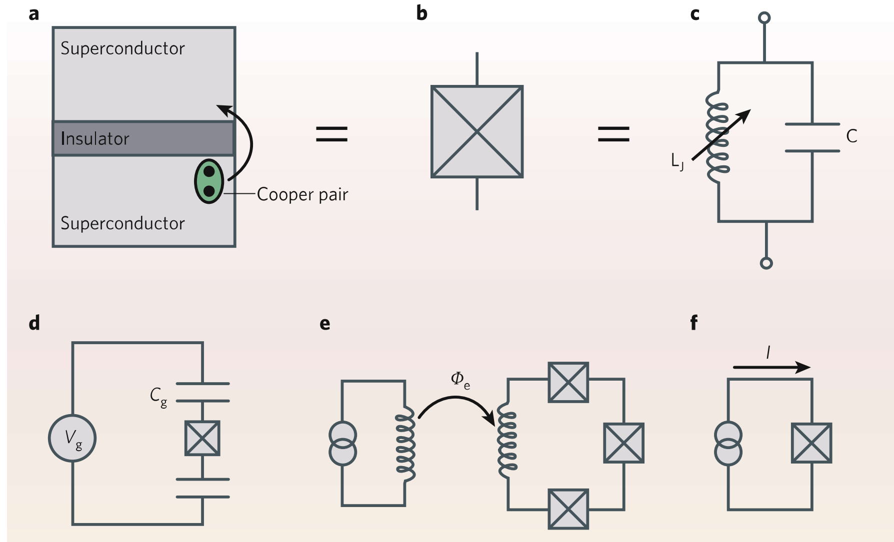
Cavity QED[31–33] is the physicist's prototype system for studying the interaction of light and matter at the quantum level. At its simplest, it consists of a single atom with just two relevant quantum states, coupled to a single mode of the electromagnetic field, defined for example by a pair of mirrors (Fig. 1). A photon in the cavity, bouncing back and forth between the mirrors, can be absorbed by the atom; conversely, if the atom is excited, it can decay by emitting a photon into the cavity. The rate of this atom–light interaction ($g$) is proportional both to the dipole moment of the atom and to the electric field of the photon at the atom's location (see Box 2, overleaf). Unfortunately, in any real system, other undesired processes can take place, such as a loss of photons from the cavity (at rate $\kappa$) resulting from imperfect mirrors, or the decay of the atom (at rate $\gamma$) into other channels.

The 'strong coupling regime' of cavity QED is obtained when the rate of absorption or emission of a single photon by the atom is more rapid than any of the rates of loss ($g >> \kappa,\gamma$). In this case, an excited atom in an initially empty cavity will emit one (and only one) photon, which can then be trapped and reabsorbed again (at rate $2g$), a phenomenon known as vacuum Rabi oscillations. The presence of the cavity has made the spontaneous emission from the atom, usually an irreversible process, into a coherent and reversible oscillation. Entering this regime dramatically reveals the quantum nature of the electromagnetic field, allows the experimenter to make and measure non-classical states of light, and makes experiments in nonlinear optics possible at the level of a single photon. In the language of quantum computation, strong coupling means that quantum information can be exchanged back and forth between the atom and the photon many times before it is lost for ever.

The challenge for realizing strong-coupling cavity QED is to maximize the vacuum Rabi frequency (see Box 2) while simultaneously minimizing the decay ($\kappa,\gamma$). Obviously, it helps to have an atom that is a strong emitter, with a large dipole moment. To enhance the coupling further, the photon's energy should be confined in the smallest cavity possible, so that the corresponding electric fields are spread over the minimum volume. Equivalently, one can imagine that the mirrors act to reflect the photon past the atom repeatedly, giving many chances for the interaction to take place. At the same time, the atom should be as decoupled as possible from other influences, and the cavity loss kept small. A further difficulty is the placement and trapping of a single atom at the desired location in the cavity.

Despite the obvious technical challenges, there are several examples of strong-coupling cavity QED using real atoms. For optical photons trapped between mirrors, the vacuum Rabi splitting, which indicates strong coupling, was first observed back in 1992 (ref. 34). Another approach[35–38] uses 'Rydberg atoms', which are highly excited atomic states that have very large

**Box 1 | Superconducting qubits**




In a superconductor well below its transition temperature, electrons are strongly bound together in 'Cooper pairs', enabling electrical signals to propagate with very low dissipation. Superconducting qubits are based on Josephson junctions, which are made by two pieces of superconductor separated by an insulating layer thin enough to allow tunnelling of Cooper pairs (**a**). A Josephson junction is usually denoted in circuit diagrams as a box with a cross (**b**).

A dissipation-free supercurrent can then flow through the junction, which turns out to be equivalent to a nonlinear inductor[10]. The physical realization of the junction (**c**), with two electrodes separated by an insulator, makes an LC circuit (a capacitor, C, and inductor, $L_J$, in parallel), which is the electrical equivalent of a harmonic oscillator.

The Josephson junction is a very special oscillator, however, as it combines nonlinearity with low dissipation. The nonlinearity means that the energy levels can be anharmonic (not regularly spaced) and, with the right circuit configuration, two low-lying states can be obtained that are sufficiently separated from the others so that the junction can be treated as a quantum two-level system, or a qubit. The typical energy separation is large enough to probe at millikelvin temperatures in cryogenic refrigerators.

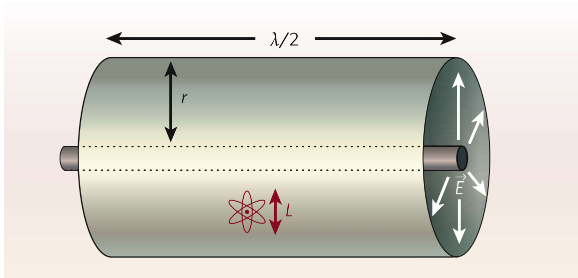
Three main 'flavours' of superconducting qubit have been used, classified according to the variables by which they are controlled and excited. The simplest qubit is the charge qubit (**d**), or Cooper-pair box, which consists of an isolated Josephson junction placed between the plates of a capacitor. Applying a voltage ($V_g$) to the capacitor ($C_g$) induces a charge difference between the two sides of the junction. Alternatively, one can say that the qubit responds to electric fields.

The second type is the flux qubit (**e**), consisting of a superconducting ring interrupted by one or more (often three, as here) Josephson junctions. A current through an external inductor generates a magnetic flux ($\Phi_e$) threading the loop, which induces clockwise or anticlockwise circulating supercurrents. This qubit couples to magnetic fields.

The third type of qubit is the phase qubit (**f**), consisting of a single Josephson junction connected to a current source. Current ($I$) flowing through the junction alters the phase difference between the two sides of the junction.

All three flavours of qubit have been used successfully, and the ability to make and control superpositions has been demonstrated. The typical lifetime of a quantum superposition is on the order of a microsecond, allowing hundreds of single-qubit operations. Experiments with two and three qubits coupled to each other, including the generation of entangled states and the operation of a conditional-NOT logic gate, have also been performed. **R.J.S. & S.M.G.**

**Box 2 | The fine-structure limit for cavity QED**




A simple calculation[31,53] shows that the coupling strength (the vacuum Rabi frequency) of an atom and a photon in cavity quantum electrodynamics (QED) has an upper limit given by fundamental constants. A photon excites the atom by moving one of its electrons into a larger orbit; the 'dipole moment' ($d = eL$, with units of charge × distance, where $e$ is the electron charge) is a measure of the size of the atom, and also determines how strongly the atom interacts with a given electric field. The vacuum Rabi frequency is thus given by $g = dE_0/\hbar$, where $E_0$ is the root-mean-square electric field at the location of the atom due to vacuum fluctuations ($\hbar$ is the Planck constant). The vacuum fluctuations exist in both electric and magnetic fields, and have an amplitude equal to that due to half a photon. A simple estimate of this electric field can be obtained by adding up the density of energy ($\varepsilon_0 E^2/2$) stored in the electric fields, which must be equal to half the energy of a photon (remembering that half of this energy is also stored in magnetic fields):

$$\frac{\hbar\omega}{4} = \frac{\varepsilon_0}{2}\int E^2 dV = \frac{\varepsilon_0}{2} E_0^2 V$$

where $\varepsilon_0$ is the permittivity of free space, $\omega$ is the transition frequency of the atom/cavity and $V$ is the volume of the cavity. Thus, the field strength increases as the volume of the cavity is decreased and the photon is more tightly confined. However, a typical three-dimensional cavity used with real atoms will have a volume that is many cubic wavelengths.

In circuit QED, we can use a one-dimensional transmission-line cavity, like the simple coaxial geometry shown here, which must be half a wavelength long but can be much smaller in the transverse direction, and have a volume, $V = \pi r^2 \lambda/2$, much less than a cubic wavelength. This leads to a greatly enhanced field strength:

$$E_0 = \frac{1}{r}\sqrt{\frac{\hbar\omega^2}{2\pi^2\varepsilon_0 c}}$$

where we have used the fact that the wavelength $\lambda = 2\pi c/\omega$ and $c$ is the speed of light. Multiplying this field strength by the dipole moment, we can express the vacuum Rabi frequency in dimensionless units:

$$\frac{g}{\omega} = \left(\frac{L}{r}\right)\sqrt{\frac{e^2}{2\pi^2\varepsilon_0\hbar c}} = \left(\frac{L}{r}\right)\sqrt{\frac{2\alpha}{\pi}}$$

we find that the dimensionless combination of the fundamental physical constants of electromagnetism, the fine-structure constant $\alpha = e^2/4\pi\varepsilon_0\hbar c \sim 1/137$, has appeared. The best situation is to arrange a cavity whose transverse size is small enough that the atom completely fills the transverse dimension ($L/r \sim 1$), and then the coupling can be several per cent. In comparison, because the three-dimensional cavities in either optical or microwave cavities have bigger sizes and the real atoms used have smaller dipole moments, the largest couplings possible so far have much smaller $g/\omega$, on the order of $10^{-6}$. The large interactions achievable in the one-dimensional cavities of circuit QED make it easier to attain the strong-coupling limit. **R.J.S. & S.M.G.**

dipole moments and low energy transitions at ~50 GHz. In this case, the photons are in the microwave domain and the cavity consists of a superconducting metallic box a few wavelengths (several centimetres) across. Other efforts have focused on strong coupling with semiconductor quantum dots as the emitters; these have the potential advantage of emitting at infrared wavelengths close to those used for telecommunication[39–41]. The coupling of internal states of an atomic ion to its motion in a trap[42,43] can also be understood as a realization of strong-coupling cavity QED, because it contains the same essential ingredients of a two-level system (the ion) interacting with a harmonic oscillator (the quantized motion of the ion, or phonons).

Many beautiful experiments have been done in the past two decades using these strongly coupled cavity QED systems, performing textbook demonstrations of fundamental quantum phenomena such as decoherence and entanglement. A spectacular recent achievement is the ability to perform quantum 'non-demolition' experiments, in which photons in a microwave cavity can be monitored without destroying them, revealing the progressive collapse of the wavefunction under successive measurements[44,45]. Other efforts have developed quantum 'applications', such as the creation of sources of non-classical light and single photons on demand[46], or the detection of single atoms and the cooling and manipulation of their motion.

The ability to control the interactions of atoms and single photons in a quantum-mechanical way has intriguing implications for quantum computation and communication. Photons in a cavity[47,48], or phonons in an ion trap[49], can be used to generate entanglement and make a 'quantum bus' to communicate quantum information between multiple atoms. But the technical difficulties of achieving sufficiently strong coupling, trapping many atoms, and then individually addressing and controlling them, make it difficult at present to build large-scale quantum systems.

## Quantum optics on a chip

Circuit QED is a more recent attempt to bring about strong coupling within an integrated superconducting circuit[22]. This approach offers the prospect of reaching an upper limit for strong coupling. Josephson-junction qubits (see Box 1) can play the role of the atom or the matter component, but how can we trap a photon on a chip? At the microwave frequencies emitted by superconducting qubits, photons can exist in three-dimensional form as standing waves in a metallic box a few wavelengths across, like those used in the Rydberg-atom experiments. In the world of electrical circuits, however, photons can also be understood as the quantized excitations of any electromagnetic resonator, including the simple combination of an inductor and a capacitor[50]. Such an electrical oscillator can in principle be much smaller than a wavelength in all dimensions, so that the 'photons' are confined very tightly indeed, and are effectively zero-dimensional. Another possibility is that photons are confined in one dimension and travel along a transmission line, not unlike the coaxial cable used for TV transmission. A key realization[22] was that strong coupling might be achieved as a result of the tight transverse confinement, while still having a long 'wire' that can transport signals from place to place.

An implementation of circuit QED using a transmission-line resonator whose electric fields are coupled to a superconducting charge qubit is shown in Figure 2a. A central superconducting wire running between two ground planes defines the transmission line. Gaps in the wire, placed an integer number of half-wavelengths (a few centimetres) apart, are the 'mirrors' used to form a cavity, which is the microwave version of the Fabry–Pérot geometry used in optics. The size and shape of the gaps controls the rate at which photons enter and leave the cavity, and the entire structure can be made using conventional microelectronic fabrication techniques. Such superconducting transmission lines have been extensively studied in the past. But recent experiments at temperatures close to absolute zero, where they are used as detectors for astrophysics[51,52], have shown that photons can make up to a million bounces before being lost (the 'cavity quality factor', $Q$, is $10^6$). This means that the losses are remarkably low — a gigahertz photon travels back and forth a total distance of 10 kilometres before being lost.

The qubit, an isolated Josephson junction, is placed between the wire and the ground planes, at or near an antinode of the standing wave of the voltage on the line, so it couples to the electrical fields of the transmission line. Exciting the qubit corresponds to transporting one or a few pairs of bound electrons (known as Cooper pairs) from one electrode of the junction to the other. This means that the dipole moment of this artificial atom is very large, often more than four orders of magnitude greater than the typical value for an electronic transition of a real atom. Because the qubit's size and shape are adjustable, the dipole coupling can also be engineered by having the atom essentially fill the transverse dimension of the cavity, which means that the vacuum Rabi frequency (expressed as a fraction of the photon frequency) approaches a maximum value[53] of a few per cent, set by the fine-structure constant (see Box 2). In comparison, the best values obtained so far using real atoms in either optical or microwave cavities are much smaller, of the order of one part in $10^6$. The very large interactions achievable in circuit QED make it easier to attain the strong coupling limit of cavity QED. Another advantage of circuit QED is that it avoids the difficulties of cooling and trapping the atom, as the qubit can be fabricated at precisely the desired location inside the cavity.

Several experiments with superconducting qubits in the past few years have accessed the regime of strong coupling, and have recapitulated many classic results from quantum optics. Strong coupling with circuit QED was first achieved in 2004 (refs 23, 24), and a device like that shown in Figure 2b has been used[23] to observe vacuum Rabi splitting in a solid-state, artificial system. When transmission through the cavity was measured when the qubit was tuned into resonance, two separate peaks (the vacuum Rabi splitting) could be resolved (see Fig. 3a, overleaf), corresponding to coherent superpositions of a single photon in the transmission line and a single excitation of the qubit. A more recent experiment[54] with an optimized qubit now approaches the fine-structure limit, with a dimensionless coupling strength of about 2.5%, yielding the large splitting shown in Figure 3b. Other experiments have observed vacuum Rabi oscillations in the time domain[25] and demonstrated a maser based on a single artificial atom[30].

Circuit QED has also been used for quantum communication and coupling between qubits. A source of non-classical microwaves has been demonstrated, for example, in which single photons are produced on demand[27]. This experiment also showed that the quantum information contained in a superposition state of a qubit could be mapped onto the photon state, demonstrating the conversion between a standing and a flying qubit, a milestone for quantum computation. Finally, a cavity has been used to realize a solid-state quantum bus, with a quantum state being transferred from one qubit to another using a microwave photon as the intermediary. This last achievement was made simultaneously in experiments with phase qubits[29] and charge qubits[28]. Taken together, these experiments indicate that communication between small prototype systems of several qubits, wired together with photons and cavities, is possible. The combination of techniques and concepts from quantum optics, in conjunction with the technology for superconducting quantum circuits, is likely to lead to continued rapid progress.

The combination of circuit QED and experimental advances with superconducting circuits raises many interesting questions, and next we shall discuss some possible themes and areas for future work.

## New regimes of quantum optics

As mentioned above, the relative coupling strength in circuit QED is many orders of magnitude greater than in the better-known versions of cavity QED with real atoms. This means that less-familiar, higher-order effects can have a noticeable influence. One example is the dispersive, or off-resonant, case, in which the qubit and the photon interact without the photon being absorbed. In the 'strong dispersive regime' in circuit QED[26], this interaction, although roughly ten times smaller than the resonant case, is still larger than all sources of decoherence, a situation that has been accessed in only a few experiments with Rydberg atoms[44,45]. Circuit QED couplings can approach the limit where multiphoton effects, which are usually rare, play an important role. Other new phenomena include optical bistability of the cavity, in which the presence of a single atom makes the cavity oscillations strongly anharmonic, and causes the entanglement of multi-photon states. It is also possible to engineer strong photon–photon nonlinearities, based for example on the simultaneous interaction of two cavities with a single qubit.

What is the real limit on the strength of coupling? It should be possible to push coupling strengths beyond the fine-structure limit discussed above for electric fields. For instance, if the current in a transmission line is passed directly through a Josephson junction[53], the relative coupling can be larger than unity ($g > \omega$, where $\omega$ is the transmission frequency of the atom/cavity), so the photon and the qubit cease to be separate entities and the coupling cannot be considered as a perturbation. All these investigations could add significantly to the body of knowledge on the light–matter interaction already gleaned from cavity QED.

## What are the limits of coherence?

Perhaps the greatest outstanding problem with all solid-state implementations of quantum systems is how to minimize decoherence, the inevitable loss of quantum information owing to coupling to undesired degrees of freedom, and secure enough time to allow complex manipulations. In their roughly 10 years of existence, the coherence time of superconducting qubits has increased by a factor of almost 1,000 (from just nanoseconds to a few microseconds), but further improvements will

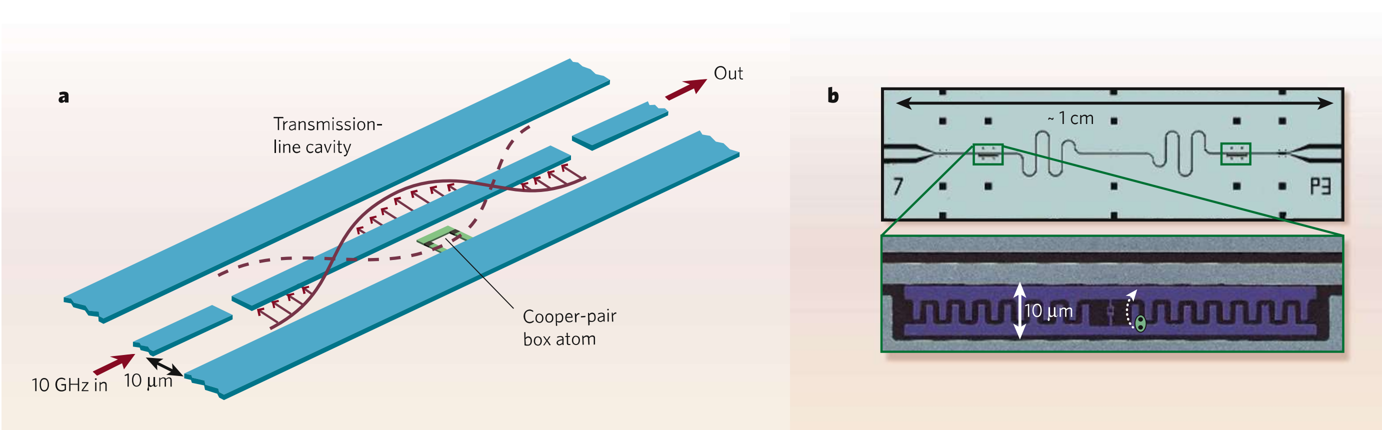



**Figure 2 | Circuit QED devices. a**, Schematic representation (adapted from ref. 22) of the circuit analogue of cavity quantum electrodynamics (QED), where a superconducting qubit (green) interacts with the electric fields (pink) in a transmission line (blue), consisting of a central conductor and two ground planes on either side. The cavity is defined by two gaps (the mirrors) separated by about a wavelength. The cavity and qubit are measured by sending microwave signals down the cable on one side of the cavity and collecting the transmitted microwaves on the output side. **b**, Micrograph of an actual circuit QED device that achieves the strong-coupling limit. It consists of a superconducting niobium transmission line on a sapphire substrate with two qubits (green boxes) on either side. The inset shows one of the superconducting Cooper-pair box charge qubits located at the ends of the cavity where the electric fields are maximal. The qubit has two aluminium 'islands' connected by a small Josephson junction. Changing the state of the qubit corresponds to moving a pair of electrons from the bottom to top (shown schematically).

be necessary. It is not yet clear whether materials, circuit designs or other, unknown factors will ultimately be the limiting factor.

Three-dimensional dielectric[55,56] and superconducting microwave resonators[57] that can store photons for about a second or more already exist. But for the miniaturized, on-chip cavities used for circuit QED, demonstrated photon lifetimes are only about ten times longer than those of a qubit, perhaps tens of microseconds. Because superconducting qubits are actually rather similar to electrical resonators (with the extra ingredient of nonlinearity provided by a Josephson junction), making the lifetime of an on-chip, linear cavity effectively infinite can be viewed as a necessary, but not sufficient, step for making truly robust qubits. Indeed, this quest may teach us how to make better junctions and qubits[58]. If cavity lifetimes continue to exceed those of qubits, they might serve a useful role[29] as a 'quantum memory', where quantum information could be stored as photon superpositions. Because cavities can inherit a nonlinearity from coupling with a qubit, it may be useful to ask what the optimal amount of nonlinearity should be, and to imagine 'photonic qubits' in which energy is shared between linear and nonlinear elements in order to optimize coherence.

## Wiring up elemental quantum objects

We have so far confined ourselves to discussing the circuit QED interaction of superconducting qubits. There are, however, a large variety of elemental quantum objects with microwave transitions, which could in principle be coupled via transmission lines (Fig. 4). Qubits made from fundamental systems such as atoms or spins offer certain advantages, including perfect reproducibility (identical atoms have identical spectra) and longer coherence times, although they can be more difficult to integrate together. These include electric-dipole-coupled systems such as atoms and molecules, or magnetic dipoles such as nuclear and electron spins, which each have their own advantages and disadvantages. They will all interact with the electric or magnetic fields of a photon if placed appropriately inside a cavity, but some will interact more strongly, and others will tend to have longer coherence times. Several approaches for building 'hybrid' quantum systems with both macroscopic, artificial components and microscopic, individual particle elements have been proposed recently[59–61].

What would make the most ideal 'atom' in a circuit QED or a quantum device? There are various trade-offs, which can be viewed by arranging the systems in a rough hierarchy based on the 'size', or transition moment. In general terms, the larger the size, the higher the vacuum Rabi frequency, and the more rapidly the qubits can communicate via the cavity. But the coherence times of these systems tend to vary inversely, and what counts is the number of operations possible, which is essentially the ratio of coupling and decoherence rates. At one end of the spectrum are Rydberg atoms and superconducting qubits, which have micrometre-scale electric dipoles that can match the size of a typical superconducting cavity and approach the fine-structure limit with vacuum Rabi frequencies of hundreds of megahertz, although these have coherence times on the order of microseconds[9] to milliseconds[60]. In the middle are polar molecules, which are small compared with the cavity and would have correspondingly slower coupling rates, but their coherence times could be more than 1,000 times longer. At the other extreme are spins, which can have lifetimes of seconds but have coupling rates of around a hertz, which is probably too small to be practical. In many cases, ensembles of particles could be used to increase the coupling strength, but at the expense of losing nonlinearity.

Experimental efforts with these hybrid systems are now under way in several laboratories[62,63]. Another approach to communicating quantum information around a chip is to actually transport the qubits themselves. This is already being done for trapped ions based on microfabricated traps[62,64]. As well as being an approach to engineering quantum processors, all this work may lead to new ways to cool and manipulate quantum objects, and perhaps even to new kinds of spectroscopy and precision measurements. Manipulating rotational or hyperfine microwave transitions in atoms and molecules can influence the electronic transitions at optical wavelengths, which are accessible simultaneously. This might eventually lead to the possibility of transferring quantum information from a chip to an optical fibre. Such a quantum interconnect is a highly desirable feature for quantum repeaters and communication.

## Making a complex quantum state

Through its ability to use photons to communicate between several qubits, circuit QED

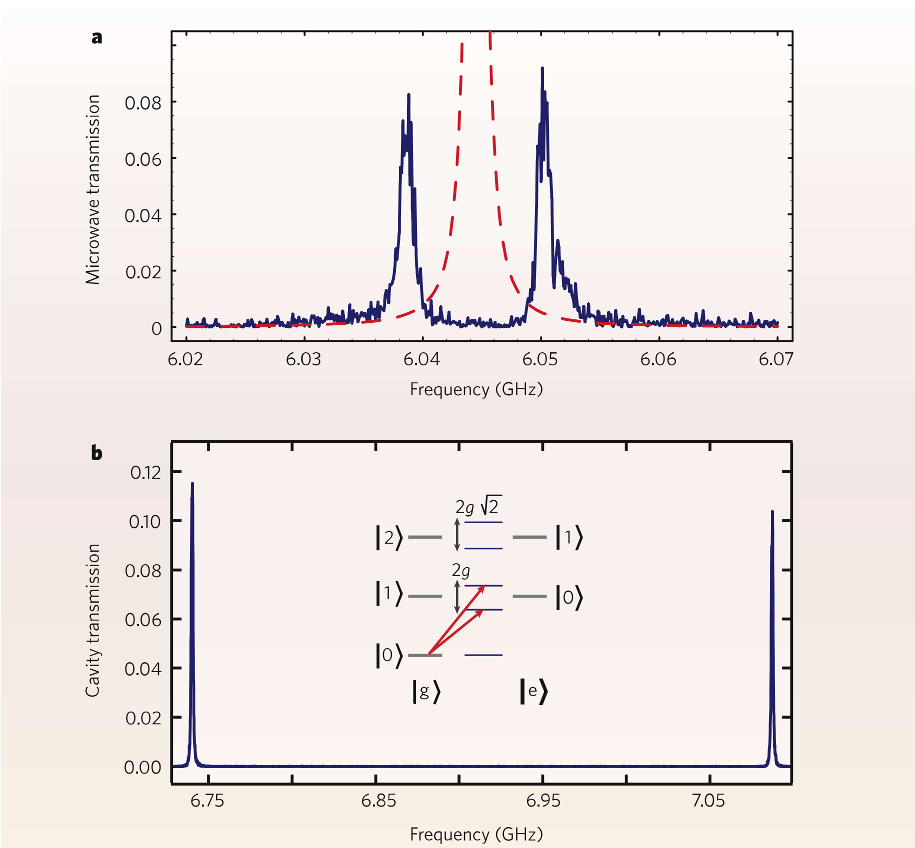



**Figure 3 | Vacuum Rabi splitting.** Observation of strong coupling and the fine-structure limit in a circuit. **a**, Measurement of the microwave transmission of a cavity like that in Fig. 2b (adapted from ref. 23). The appearance of two peaks in the transmission, as a result of vacuum Rabi splitting, indicates strong coupling. Without the qubit, a single transmission peak (dashed line) is observed. With the qubit tuned to match the cavity frequency, the qubit–cavity interaction mixes together the photon and qubit states, and the new eigenstates of the system are coherent superpositions that are symmetric and antisymmetric combinations of atom and photon. The decay rates of these half-atom/half-photon superposition states is the average of the photon and atom decay rate, $(g+\kappa)/2$. Strong coupling is observed by starting with the system in its lowest energy state (with no photons and the atom in the ground state) and measuring the presence of two peaks separated by $2g\sim 12$ MHz about the original cavity resonance. This splitting of the cavity resonance is akin to observing vacuum Rabi oscillations in the frequency domain. **b**, A more recent experimental result, showing a separation of the vacuum Rabi peaks by about $2g/2\pi = 350$ MHz, in which $g/\omega \sim 2.5\%$; the cavity decay rate is $\kappa/2\pi \sim 800$ kHz and the qubit decay rate is $\gamma/2\pi \sim 200$ kHz. This experiment approaches the fine-structure limit (see Box 2) for the maximal value of an electric dipole coupling.

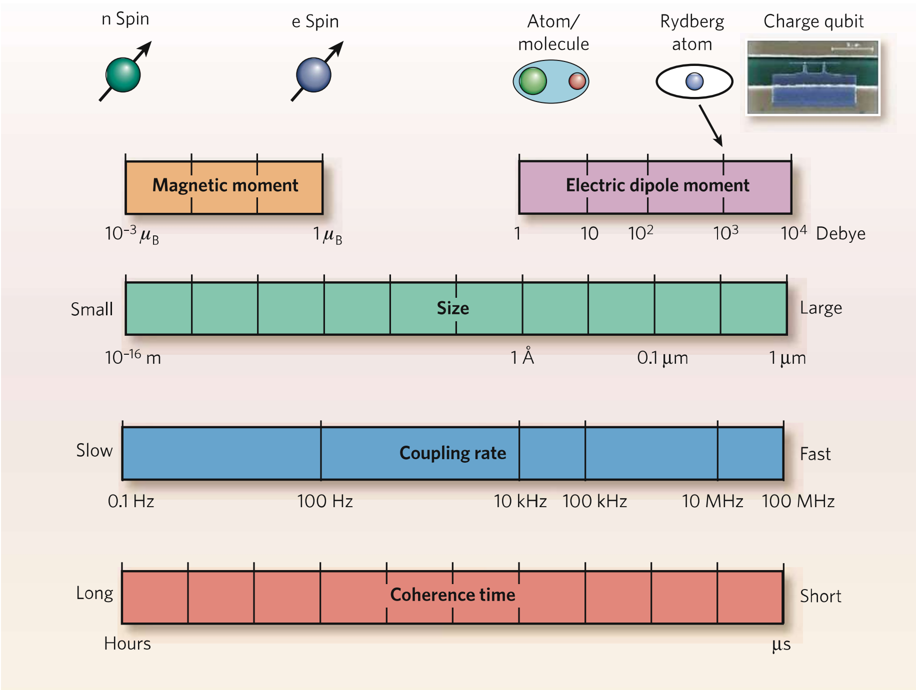



**Figure 4 | Wiring up quantum systems.** Besides a Cooper-pair box, many other quantum systems have microwave transitions that could be coupled to photons in a transmission line. What is important for quantum computation is the number of operations that can be performed, so the longer lifetimes of smaller particles can partly offset the weaker couplings. For a line with transverse dimensions on the order of a micrometre, the electrical field strengths for a single 5-GHz photon are $E_0 \sim 1.4\,\mathrm{V\,m^{-1}}$ (see Box 2), and the corresponding vacuum Rabi coupling rate is $g/2\pi \sim 10$ kHz for a 1-debye dipole moment. Magnetic dipoles such as spins could also couple to the corresponding magnetic fields, $B_0 \sim 0.1$ milligauss, with vacuum Rabi rates of about $g/2\pi \sim 100$ Hz per Bohr magneton. Quantum systems can be compared according to their electric or magnetic dipole moments (or the magnitude of the emitter strength, top bars), the required transverse size of a cavity to reach maximal coupling (second bar), their coupling rates (third bar) to a technologically feasible (1 µm) cavity, and the expected lifetimes of coherent superpositions (bottom bar). Which quantum system is optimal depends on many details, including the ease of trapping or fabricating in a cavity, and on the many factors in the qubit environment that can affect the coherence times.

may help to bring about more complex quantum systems with superconducting circuits. The next step could be to demonstrate multiparticle entanglement and develop simple schemes for quantum error correction.

Some of the most beautiful investigations of quantum optics have shown that the most counterintuitive properties of quantum mechanics, such as entanglement, nonlocality and the measurement problem, are real. What might we learn by extending these tests to engineered, macroscopic systems?

To build even a small quantum information device, we will need unprecedented control over matter at the quantum level. Is the often-cited factoring of large numbers the only, or indeed the most interesting, way to exploit such an amazing capability? It is possible that quantum computers of this sort will simply prove too difficult to build. So finding short-term applications for smaller quantum machines that justify the effort may be crucial to the future of these endeavours.

A final point is that, during a large-scale quantum computation, the device will need to occupy devilishly complex quantum states, which we have little experience with so far. We may find that there is a fundamental principle, which we haven't discovered yet, that prevents their existence. Such a possibility might even mark the end of the road for quantum computing — but provide a new beginning for basic science. ■

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