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QUANTUM FEATURE

Superconducting quantum bits

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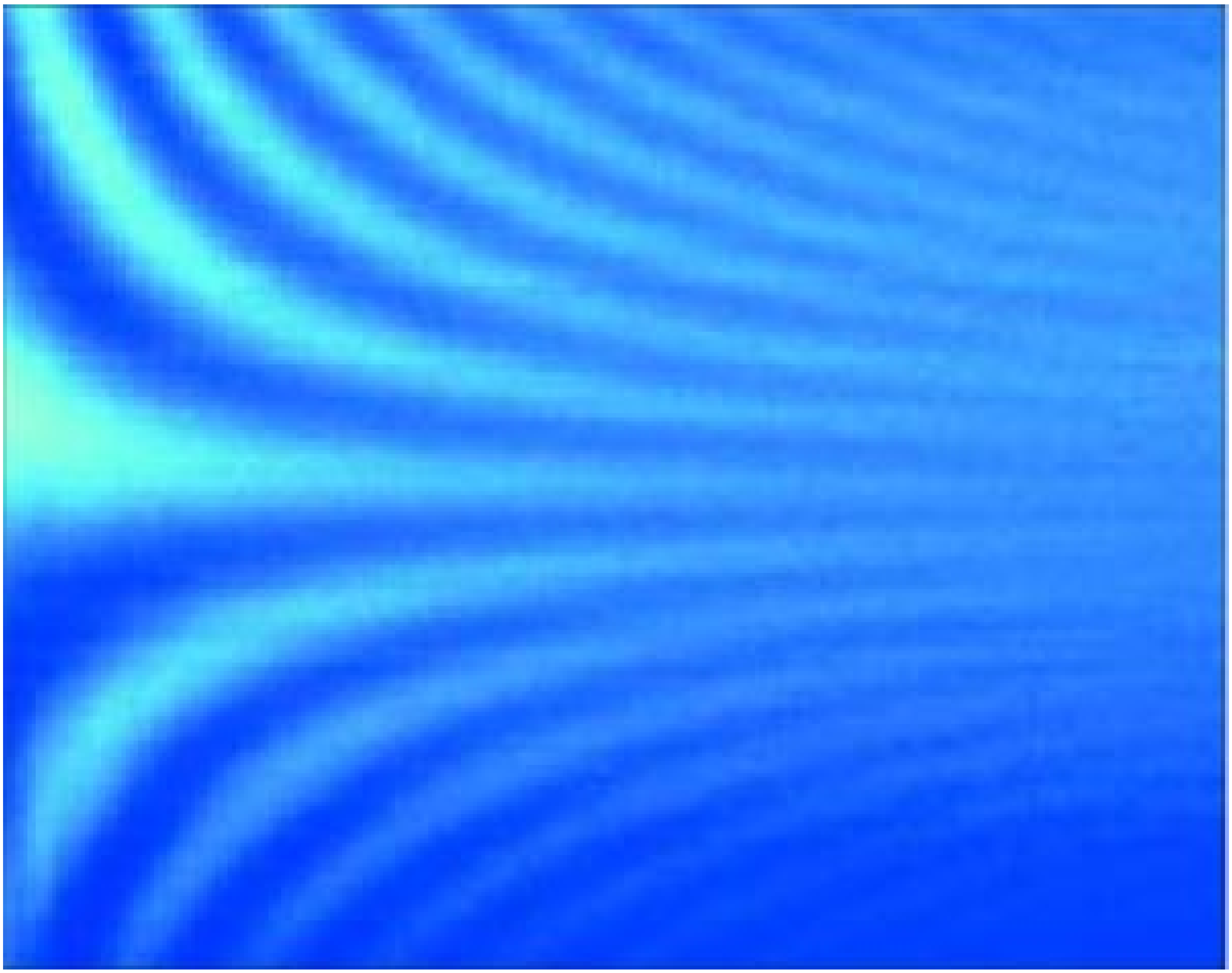
Superconducting devices can be used to explore the boundaries between the quantum and classical worlds, and could also have applications in quantum information



Macroscopic quantum mechanics

The quantum world looks very different to the ordinary world. A quantum particle can, for instance, be in two places simultaneously, while its speed and position cannot both be measured with complete accuracy at the same time. Moreover, if its mass is small enough, a quantum particle can tunnel through energy barriers that its classical counterparts could never cross.

Physicists are comfortable with the use of quantum mechanics to describe atomic and subatomic particles. However, in recent years we have discovered that micron-sized objects that have been produced using standard semiconductor-fabrication techniques – objects that are small on everyday scales but large compared with atoms – can also behave as quantum particles.

These artificial quantum objects might one day be used as "quantum bits" in a quantum computer that could perform certain computational tasks much faster than any classical computing device. Before then, however, these devices will allow us to explore the interface between the quantum and classical worlds, and to study how interactions with external degrees of freedom lead to a gradual disappearance of quantum behaviour.

Quantum information

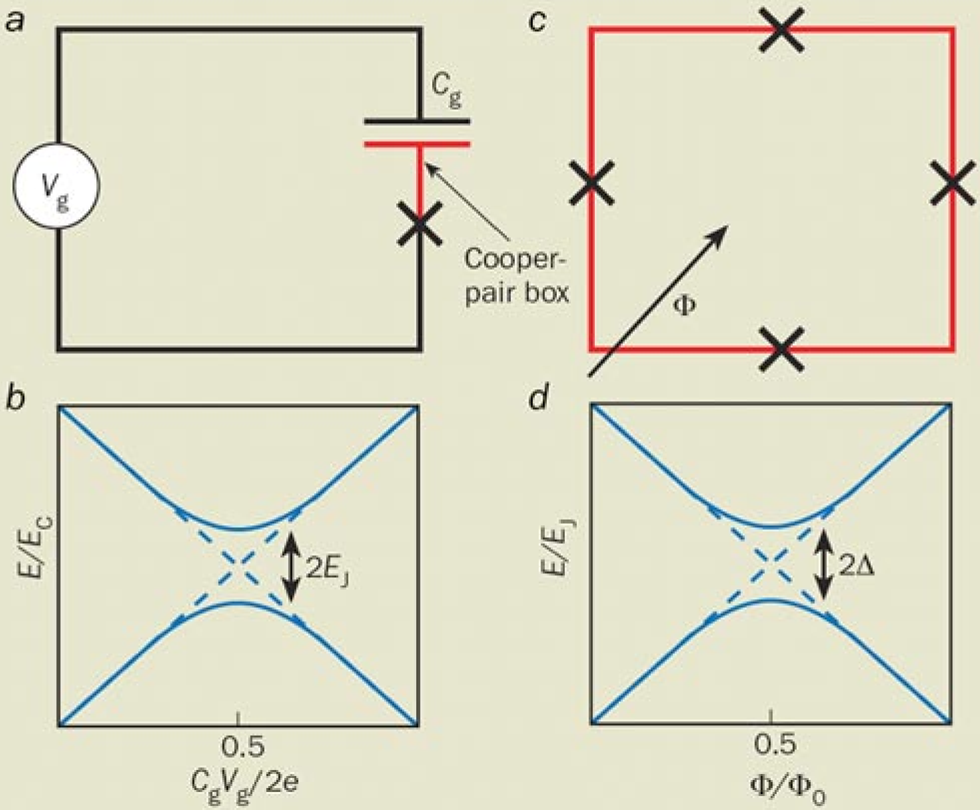
In classical computers information is stored and processed as "bits" that can have one of two possible values: "0" or "1". Quantum bits or "qubits" are different: in addition to "0" and "1" a qubit can also exist in a superposition state, $\alpha|0\rangle + \beta|1\rangle$, in which it can have both values at the same time. However, when a qubit is measured, the result is either "0", with a probability of α^2, or "1", with a probability of β^2.

Such probabilistic behaviour hardly seems to be a good basis for processing information. However, for as long as we can avoid making measurements the quantum system will evolve in a completely deterministic way and, moreover, will maintain its ability to be in two places at the same time and so forth. This ability to remain quantum rather than classical over a period of time is called quantum coherence. Here the word "measurement" refers to events, both intentional and accidental, in which quantum information is transferred out of the quantum system. In the absence of any such measurements the system maintains its quantum coherence.

It is also possible to create a state that is even stranger than a normal quantum state by "entangling" two or more quantum particles. Such an entangled state was demonstrated for the first time with photons in the early 1980s. If the quantum state of one of the entangled particles is changed (e.g. if the polarization of a photon is changed), then the state of the other particle instantly changes in a certain way, even if there is no interaction between them. Quantum computing is based on these three properties of quantum mechanics: superposition, coherence and entanglement (see *Physics World* March 1998 pp33-57).

To be useful a quantum computer will need at least 10,000 qubits. However, it is very difficult to find a technology that combines the necessary level of control over two-level quantum systems with the possibility of mass fabrication. Researchers can routinely create large ensembles of nuclear spins using magnetic resonance techniques, but it is almost impossible to control individual spins.

1 Charge and flux qubits



(*a*) A charge qubit can be made with a circuit in which a Josephson junction (the cross), a capacitor and a voltage gate are connected with superconducting aluminium leads (black lines). The region between the junction and the capacitor forms a "Cooper-pair box" (shown in red). This circuit creates a quantum superposition of the two classical states associated with the presence of zero and one extra Cooper pair in the box. (*b*) In the absence of any quantum effects the energy, E, of the zero state increases as the gate voltage, V_g, increases, while the energy of the one state decreases (dashed lines). This means that both states have the same energy when $V_g = e/C_g$, where C_g is the gate capacitance. However, quantum tunnelling leads to an "avoided crossing" in which the system exists in one of two quantum superposition states (solid lines) that are separated by a gap that is equal to twice the Josephson energy, E_J, which determines the strength of the coupling across the junction. $E_C = 2e^2/C_g$ is the Coulomb charging energy for the capacitor. (*c*) A flux qubit consists of a loop of three Josephson junctions connected with superconducting aluminium leads (red lines) and is subject to an external magnetic flux, Φ. A flux qubit creates a quantum superposition of the two classical states associated with currents circulating clockwise and anticlockwise around the loop. (*d*) The energy-level diagram for a flux qubit is similar to that for a charge qubit, with Δ playing the role of the Josephson energy E_J; $\Phi_0 = h/2e$ is the quantum of magnetic flux in a superconductor.

Figure 1

Single ions and atoms in cavities and traps can be controlled with exquisite precision, but it will be difficult to scale up these techniques to thousands of atoms or ions. Solid-state qubits, on the other hand, have only just been demonstrated, but the microfabrication tools used in the semiconductor industry could provide a route to mass fabrication.

Superconducting qubits

To create a solid-state qubit, like any other kind of qubit, we need to isolate a two-level quantum system. To date, efforts to make solid-state qubits have focused on superconductors and semiconductors. While interesting results have been obtained with two semiconductor approaches – quantum dots and single-donor systems – the superconducting approach is currently the most advanced.

To maintain coherence it is essential to keep electron-electron interactions, and also interactions between electrons and other degrees of freedom (such as phonons in the solid), under control. Superconductors have the advantage in this regard because the electrons condense into Cooper pairs that form a single superfluid. This superfluid is able to move through the metal lattice without any resistance (i.e. without interactions) because it takes a certain amount of energy, known as the energy gap, to break up the Cooper pairs.

In aluminium – a popular material for making superconducting quantum circuits – the energy gap corresponds to a frequency of 90 GHz at a temperature of 20 mK. This gap is an order of magnitude greater than the typical energy difference between the two levels in a superconducting qubit, which means that we can "drive" the qubit without breaking up the Cooper pairs and jeopardizing the quantum coherence of the system.

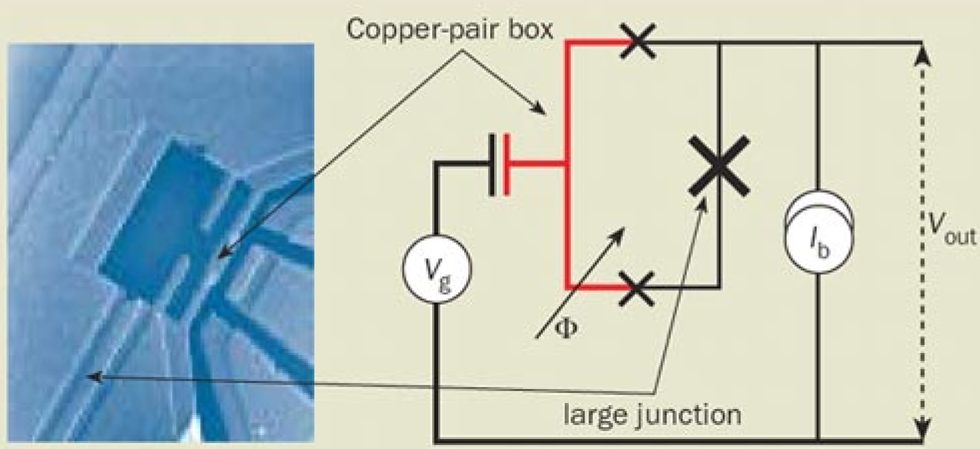
The behaviour of the electron superfluid is completely determined by a single quantum wavefunction. The amplitude of this wavefunction determines the number of Cooper pairs, while the value of the phase is related to the supercurrent and any magnetic field that is present. The amplitude and phase of the wavefunction are conjugate variables – that is, they are related by an uncertainty principle that means we cannot measure both of their values with arbitrary precision at the same time. The two primary types of superconducting qubit, the charge qubit and the flux qubit, are directly related to these two variables: charge qubits are associated with the amplitude, while flux qubits are related to the phase.

A key component in most superconducting qubits is a device called a Josephson junction. This consists of a thin layer of aluminium oxide, which is an insulator, sandwiched between two superconducting layers of aluminium, which becomes a superconductor when cooled below 1.2 K. The insulating layer is so thin (a few nanometres) that Cooper pairs can tunnel through it and couple the superconducting wavefunctions on either side of the barrier. Most of the circuits for superconducting qubits built so far consist of Josephson junctions and other components like capacitors connected by superconducting leads made of aluminium.

Different types of qubits

Two energies are important when designing a superconducting qubit. The Josephson energy, E_J, is a measure of the strength of the coupling across the junction, while the Coulomb charging energy, E_C, is the energy needed to increase the charge on the junction by 2*e*. The junction is essentially a capacitor with $E_C = 4e^2/2C$, where *e* is the charge of the electron and *C* is the capacitance.

2 The quantronium



A scanning electron micrograph (left) and circuit diagram of the quantronium developed at CEA Saclay. In this circuit the single Josephson junction in a charge qubit is replaced by two small junctions in parallel that are connected to a larger junction to form a closed loop. Again the Cooper-pair box is shown in red. However, the superposition now occurs between two counter-rotating currents in the loop, which is observed by measuring the current, I_b, through the large junction. The system is controlled by a voltage V_g and a magnetic flux Φ.

Figure 2

If E_C is larger than E_J, the circuit tends to fix the numbers of Cooper pairs. However, tunnelling through the junction can lead to transitions between states containing different numbers of Cooper pairs. This combination creates the charge qubit.

On the other hand, if E_J is larger than E_C, the requirement that the total phase difference around a closed loop in the circuit must be a multiple of 2π dominates, and the circuit can be used as a flux qubit. With the proper choice of parameters, transitions between phase states – e.g. from 0 to 2π – are possible.

The charge qubit consists of a small volume of superconductor, known as a Cooper-pair box, that is connected to a weak Josephson junction and driven with a gate voltage, V_g, through a capacitor. If $V_g = e/C_g$, where C_g is the capacitance of the gate, then the classical states in which there are zero (|0>) and one (|1>) extra Cooper pairs in the box have the same energy (see figure 1*a*).

However, quantum tunnelling through the Josephson junction results in the formation of two new quantum states: one is a symmetric superposition of the classical zero and one states (|0> + |1>), while the other is an antisymmetric superposition (|0> - |1>). These new quantum states differ in energy by $2E_J$, and this superposition forms the basis of the charge qubit (see figure 1*b*). By applying time-varying signals to the voltage gate it is possible to control the dynamics of the system.

A typical flux qubit is made by joining three Josephson junctions with superconducting leads to form a closed loop and using an applied magnetic field (perpendicular to the loop) to drive the circuit by controlling the phase (see figure 1*c*). The junctions are needed to provide a “weak spot” where transitions between different phase states can take place. A flux qubit could be made with just one or two junctions, but the use of three allows the behaviour of the circuit to be fine-tuned more easily.

When the magnetic flux through the loop, Φ, is equal to half the quantum of magnetic flux in a superconductor, the state with a zero phase difference around the loop ($|0\rangle$) has the same energy as the state with a 2π phase difference ($|1\rangle$). One of these states corresponds to a current circulating around the loop in the clockwise direction, while the other state corresponds to a current moving in the opposite direction. As happens with the charge qubit, two new quantum superposition states are formed, and again the difference in energy between the states is equal to the tunnelling strength, which depends on a number of parameters (see figure 1*d*).

There is also a third type of superconducting qubit, usually known as a phase qubit. This employs a single Josephson junction and the two levels are defined by quantum oscillations of the phase difference between the electrodes of the junction.

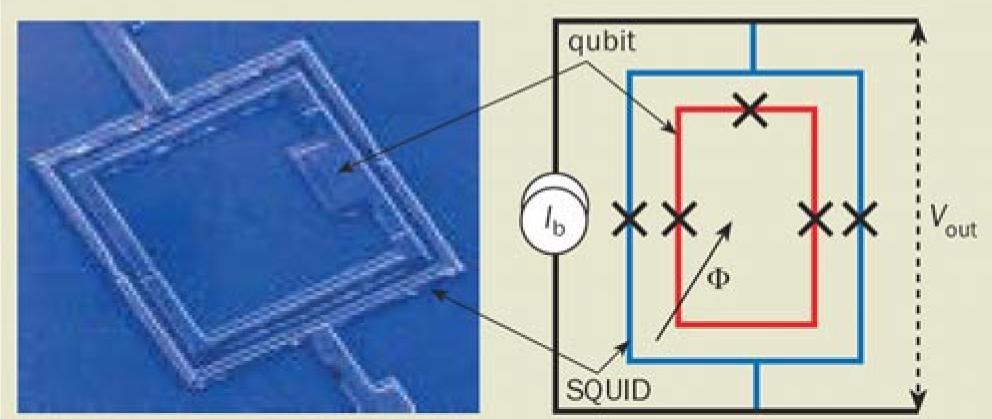
One problem with superconducting qubits is that there are always more than two levels in the system. There can, for instance, be two or three extra Cooper pairs in the box in a charge qubit, or there can be a 4π or 6π phase difference in a flux qubit. However, with careful design the energy difference between the two “good” levels and the other “bad” levels can be made large enough to prevent quantum information leaking out of the qubit.

But there are more serious limitations. An isolated qubit may be very coherent, but this coherence can be destroyed by the connections with the outside (classical) world that are needed to control and measure the qubit. In our experiments we design the connecting circuit to optimize coherence. In principle, driving a circuit is easier than measuring it because signal sources tend to be strong, while the qubit signal is usually very weak. Strong coupling makes measurement easier, but it is also detrimental to quantum coherence. Therefore the experimentalist, guided by theory, has to make their own choices.

How to make a charge qubit

The first superconducting qubit to demonstrate its potential was the charge qubit. In a groundbreaking experiment in 1999, Yasunobu Nakamura and co-workers at NEC in Japan made a charge qubit that consisted of a small Josephson junction and an aluminium box for the Cooper pairs.

3 Making measurements on a flux qubit



A scanning electron micrograph (left) and circuit diagram of a flux qubit at Delft. The current circulating in the qubit (shown in red) is measured using a superconducting quantum interference device (SQUID). This device, which is shown in blue, is a loop that contains two more Josephson junctions.

Figure 3

The NEC team started with the gate voltage below e/C_g, which meant that the box was in the “zero” state. The box actually contained millions of Cooper pairs in the zero state, which is electrically neutral, while the “one” state contains an extra Cooper pair. Next the researchers suddenly increased the voltage to e/C_g to create the state that is a superposition of these two basic charge states. Since the initial state of the system, the zero state, was not one of the new eigenstates, the system oscillated between the two superposition states with a frequency of $2E_J/h$, where h is Planck’s constant (see Nakamura *et al.* in Further reading).

After a certain time the gate voltage was reduced again, and the system was projected back into one of the two basic charge states. By adding a small additional junction to the box it was possible to determine if the system ended up in the zero or one state, because a single non-superconducting electron escaped though this junction every time the system ended up in the one state. The readout signal was a current that depended on the relative weighting of the zero and one states. By performing the experiment many times, Nakamura and co-workers were able to show that the probability of the system returning to the zero or one state oscillated as the length of the voltage pulse increased.

The NEC group recently expanded this type of experiment to two coupled charge qubits, and was able to demonstrate the basic two-qubit quantum operations (see Yamamoto *et al.* in Further reading). Unfortunately, these types of qubits and the technique used to measure them cannot be easily scaled up, and the readout process limits the length of time over which quantum operations can be performed. Moreover, the purity of the charge qubit is severely limited by random fluctuations of charged defects in or near the barriers of the junctions.

However, it is possible to scale up the qubit designs based on charge states, as Daniel Estève, Michel Devoret and colleagues at the CEA laboratory in Saclay near Paris demonstrated in 2002. They developed an ingenious type of qubit, which they called the quantronium, with a readout that is completely different to that used by the NEC team.

In the quantronium the Josephson junction of the Cooper-pair box is split into two small parallel junctions (see figure 2 and Vion *et al.* in Further reading). Calculations show that when there is no extra charge in the box, there is a small clockwise current in the loop formed by the two junctions; and when there is one extra charge in the box, the current is anticlockwise. This means that the current can be measured, rather than the charge, and the device can therefore be described as a charge qubit with a phase readout.

To make measurements the Saclay team arranged its circuit so that the circulating current passed through a third, larger Josephson junction. The two qubit states can be distinguished by measuring the maximum current through this junction when there is no applied voltage. The Saclay team then irradiated the quantronium with microwave photons at a frequency that matched the energy difference between the two qubit states. Estève, Devoret (who is now at Yale) and co-workers confirmed that the microwaves drove what are known as Rabi oscillations between the two states at a frequency that was proportional to the amplitude of the microwave signal.

They also used magnetic-resonance techniques to determine the characteristic times for decoherence and to find “magic points” – values of the gate voltage and the flux in the current loop for which the coherence was significantly stronger. The Saclay team is now studying two-qubit systems.

Working with flux qubits

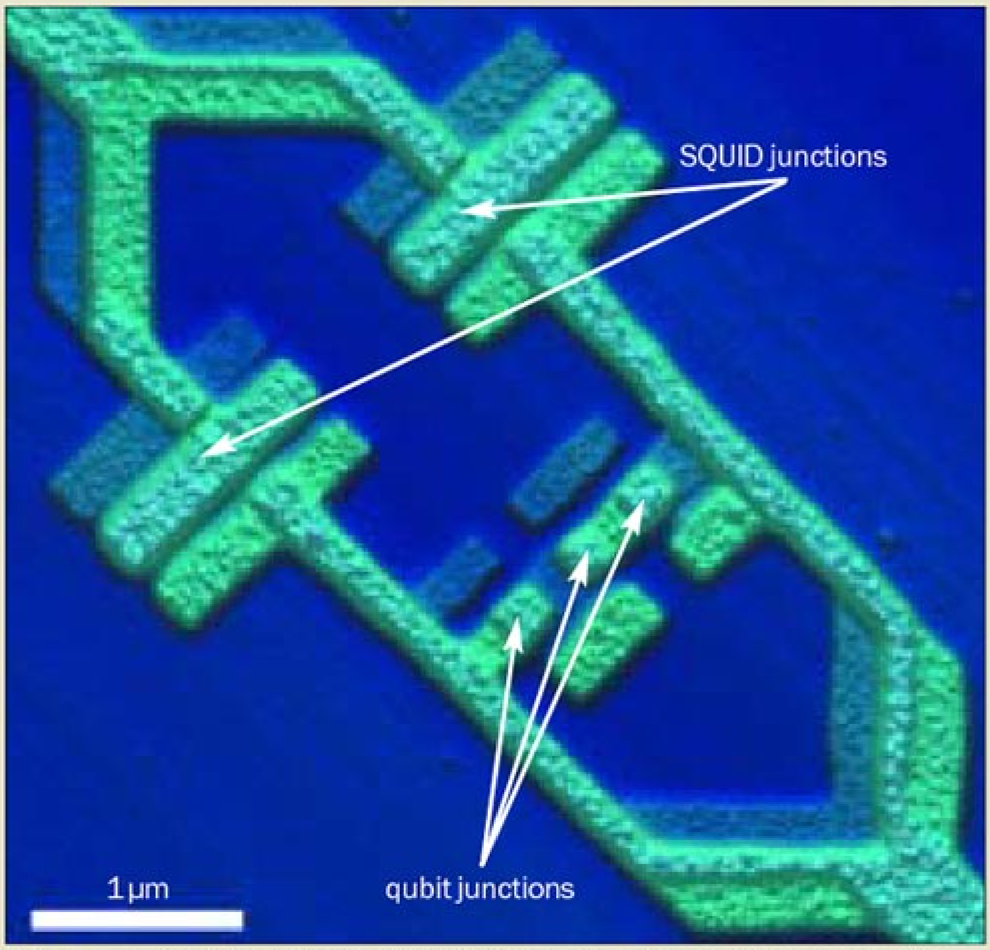
Our group at Delft in the Netherlands, in collaboration with Terry Orlando and colleagues at the Massachusetts Institute of Technology in the US, has focused on the flux qubit because the magnetic noise in practical circuits is much smaller than the electrical noise generated by defects. We use the standard flux-qubit circuit – three Josephson junctions connected by superconducting aluminium leads – with a magnetic flux, Φ, that is equal to about half the quantum of magnetic flux in a superconductor, $\Phi_0/2 = h/4e$. The two basic states are a clockwise current in the loop (the zero state) and an anticlockwise current (the one state).

Measurements are made with a superconducting quantum interference device (SQUID). This device, which consists of two Josephson junctions in parallel, is the most sensitive magnetic-flux detector known. Moreover, SQUIDs can be fabricated with the same tools that are used to make the qubits themselves (see figures 3 and 4).

The currents in the qubits are carried by a billion Cooper pairs, and quantum tunnelling involves reversing the directions of all these particles simultaneously. Five years ago many physicists doubted if quantum tunnelling could take place in a piece of metal with dimensions of several microns. In 2000, however, experiments by Jonathan Friedman and co-workers at Stony Brook in the US and by Casper van der Wal and colleagues in Delft showed that it is possible to create a quantum superposition of distinct macroscopic states in which all the Cooper pairs are travelling in both the clockwise and anticlockwise directions at the same time (see *Physics World* August 2000 pp23-24).

In these experiments the absorption of microwave radiation by the circuit was measured as a function of frequency and applied flux. From these spectroscopic data it was clear that the qubit did not have two states of equal energy, but opposite current, at $\Phi \sim h/4e$, as would be the case if there were no quantum superposition or tunnelling. Rather, the data showed that two new symmetric and antisymmetric superposition states had been formed.

4 Flux qubit



This image of a flux qubit plus SQUID system was obtained with an atomic force microscope at Delft. The qubit is formed by the small loop bottom right, and the three Josephson junctions are indicated by arrows. The SQUID is the larger loop and contains two Josephson junctions. As the SQUID and qubit loops share a large fraction of their circumference, they are tightly coupled. A technique called shadow-evaporation was used to make the circuit.

Figure 4

We went on to demonstrate Rabi oscillations and recently we performed the first spectroscopic measurements on two coupled flux qubits. Again we were able to measure energy differences as a function of the applied magnetic flux. Meanwhile John Martinis and co-workers at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, have performed comparable experiments with a single-junction phase qubit. The NIST team found that decoherence in this system is mostly caused by defects in the junction barrier.

The longest decoherence times – which measure how long the system remains coherent – observed to date are between 500 ns and 4 μs, although the most important factor is the number of quantum operations that can be performed before the coherence disappears. Since a pulsed operation can be as short as about 1 ns, it should be possible, in principle, to perform hundreds or thousands of operations, although a practical quantum computer would need to be capable of performing 100,000 controlled operations.

If a superconducting qubit is well designed, then decoherence is mostly caused by materials problems such as defects, rather than the influence of the external (classical) circuit. Efforts have now began at Delft and the University of California at Santa Barbara, to where Martinis has recently moved, to use epitaxial techniques to make Josephson junctions with fewer defects.

Earlier this year Robert Schoelkopf and colleagues at Yale University in the US and, independently, Irinel Chiorescu and co-workers at Delft demonstrated coherent coupling between a qubit and a harmonic oscillator, and showed that a single photon could be transferred from the qubit to the oscillator. The ability to combine photon-based quantum communication over long distances with quantum computers built with superconducting qubits is an exciting prospect for the future of quantum information.

What next?

Superconducting qubits are not yet ideal building blocks for the quantum computers of the future. The quantum oscillations observed in experiments so far have amplitudes that are, at best, about half of what they should be. We cannot tell whether this is due to problems with the qubits or to inadequate measurements, and we have to work hard on improving both aspects.

We also need to increase decoherence times, in particular by using improved fabrication techniques to reduce the number of defects in tunnel barriers. This is not going to be easy or happen quickly. Improved fabrication techniques are also needed to improve the yield and quality of samples, which will speed up research. There is also a need for better ways to couple qubits with each other, and also with the outside world, and for new ways to switch this coupling on and off. We can expect progress in this area in the next year or two.

Progress in fabrication technology and coupling techniques will also benefit basic research. Physicists will, for instance, continue to use superconducting circuits to test fundamental aspects of quantum theory, such as entanglement and the boundary between the quantum and classical worlds.

It remains to be seen if superconducting qubits can be controlled as accurately as those based on trapped atoms or magnetic resonance, or if quantum computers built from superconducting qubits can be scaled up successfully. In theory these things are possible but it will take at least 20 years to build a real quantum computer.

It is unlikely that the superconducting quantum information processor of 2024 will have the layout that we would design now, or use the algorithms for quantum error correction or factorization that have been proposed to date. Indeed, solid-state quantum bits are as different from transistors as lasers are from light bulbs. We still have to learn how to use them and what to use them for.

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