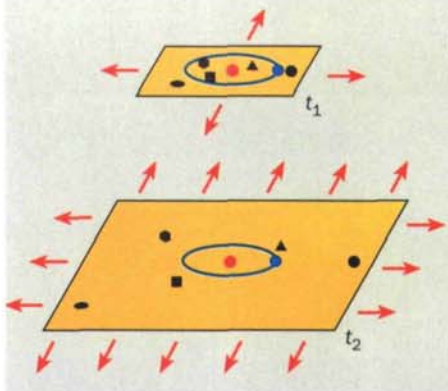
mass inside the vacuole and the mass density of the universe. If we use the mass of the Sun and the current measurement of the mass density of the universe, for instance, the vacuole radius would be around one-thousandth the size of the entire galaxy. This would clearly be unsatisfactory as the vacuole would then include many other stars within the galaxy. Another serious problem arises from the fact that the model is unstable, and depends crucially on the unrealistic assumption of spherical symmetry, as we have proved recently (*Phys. Rev. Lett.* 1997 **78** 2284; *Phys. Rev. D* 1998 **57** 3389).

Following Einstein and Straus, subsequent attempts to improve the cosmic-expansion models focused on the study of particle trajectories inside the expanding universe. The results showed that the expansion *may* affect the path of the particles. (In our analogy, if the orbits expanded at the same rate as the universe they would be like circles painted on the elastic sheet.) The problem lies in determining how much the system feels the expansion and whether there can be different effects depending on the kind of system involved. This is where Bonnor's results are illuminating. He studied the influence of the cosmic expansion on a system of two oppositely charged particles bound by their electromagnetic attraction. His aim was to determine how much the hydrogen atom is affected by the expansion.

The problem is relevant because the electromagnetic interaction is responsible for holding the structure of extended bodies together (as long as they are not too big). Studying the influence of the cosmic expansion on the hydrogen atom should therefore indicate whether extended bodies participate in the expansion or not.

Admittedly, the system analysed here is a simplified model because Bonnor studies the hydrogen atom as if it were a classical object. Nevertheless the analysis is consistent. The electron is treated as a particle moving in the electric field created by the proton, while the electromagnetic radiation emitted by the system is neglected, a reasonable assumption to make as the hydrogen atom is stable.



Atoms in the expanding universe. A stretched elastic sheet can be used to describe how the universe expands from a time, t_1, to a later time, t_2. The objects are fixed on the sheet and move apart as the sheet expands, although their size does not change. A hydrogen atom is represented by an electron (blue) orbiting around a proton (red). Bonnor's results imply that this orbit has remained practically unchanged throughout the history of the universe.

The proton moves in the same way as the average matter in the universe and its electric field is obtained by solving the Maxwell equations in the expanding universe. Bonnor assumes that the electron initially moves in a circular orbit, and then calculates the first-order correction to its trajectory caused by the moving proton using a perturbative method.

The effect of the expanding universe is estimated by evaluating how the radius of the electron's trajectory changes in the time it takes to revolve once around the proton. This quantity is then compared with the distance an uncharged particle would move in the same time interval. Given the size of the hydrogen atom and the current age of the universe, the calculation shows that the change in radius of the electron orbit is 10^{-67} times smaller than the change for an uncharged particle. In other words, the hydrogen atom remains practically unaffected by the cosmic expansion.

The results, however, raise other questions. Is the effect also negligible in other epochs of the universe, for instance? The answer is that the relative change of the electron orbit decreases with the square of the age of the universe, so that the maximum effect would be seen in the early universe.

Even during the epoch of atom formation, when the universe was approximately 300 000 years old, the relative change of the electron orbit was just 3×10^{-59}, which is still insignificant.

One could even ask how the size of a hydrogen atom has changed over the whole history of the universe? Clearly, this problem cannot be solved fully by using the perturbation method, which is only reliable when the electron makes one loop around the proton. Nevertheless, a naïve computation using Bonnor's results shows that the variation from the time of atom formation to the present day is 10^{-59} times the current size of the hydrogen atom. In other words, the size of this atom has remained practically the same throughout the history of the universe.

In our opinion, Bonnor's result deserves attention and is certainly thought provoking. If the result is extrapolated to other atoms and to molecules, we can conclude that the cosmic expansion does not affect human-scale objects like laboratories and our bodies, or even Brooklyn!

Solid start for solid-state quantum bits

From **Caspar van der Wal** and **Leo Kouwenhoven** in the Department of Applied Sciences, Delft University of Technology, The Netherlands

Quantum computers have the potential to solve certain problems much faster than any classical computer. For instance, present-day computers would take longer than the age of the universe to factorize a 1000-bit number. A quantum computer could do it in a few seconds. These theoretical possibilities have stimulated a large amount of experimental research on the various technologies that might be used to actually build a quantum computer. Yasunoba Nakamura and colleagues at the NEC Fundamental Research Laboratories in Tsukuba and the Japan Science and Technology Corporation in Kawaguchi recently demonstrated for the first time some of the techniques that would be needed to build a computer using a solid-state device (Y Nakamura, Yu A Pashkin and J S Tsai 1999 *Nature* **398** 786).

In classical computation, information is stored as "bits" that can have one of two values, for example zero or one. A quantum bit, however, can be both zero and one at the same time. It is the ability of quantum particles to be in two quantum states at the same time that makes it possible for quantum computers to greatly outperform classical computers, at least in theory. Many of these ideas were discussed in the special issue of *Physics World* on quantum information published in March 1998.

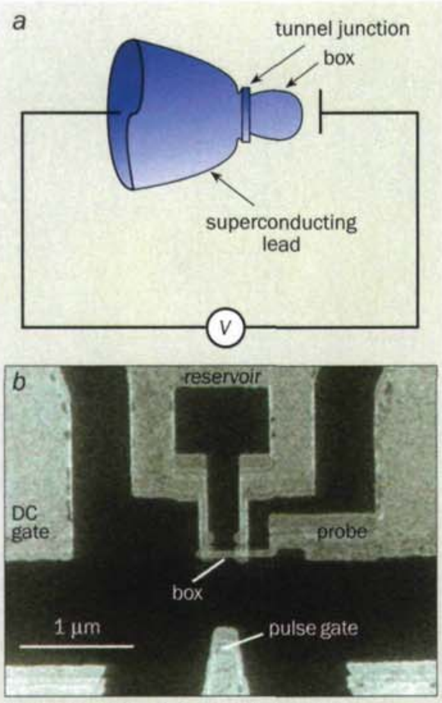
Single and coupled quantum bits or "qubits" have already been demonstrated with trapped ions, photons inside cavities and in nuclear magnetic resonance (NMR) experiments on molecules. These types of experiment have been used to study the dynamics of quantum systems for many years. In these systems the timescale for quantum coherence – essentially the length of time the system can stay in a well defined "superposition" of quantum states before relaxing into a single state – can be as long as a few seconds. The NEC team demonstrated control over the quantum state of a two-level system in a solid-state device by observing quantum-mechanical oscillations of charge in a small superconducting circuit under the influence of electric pulses.

However, a practical processor would require the integration of a large number of qubit elements, meaning that large amounts of equipment would be required for the ion trap, photon cavity and NMR experiments mentioned above to be performed. It would be more practical if semiconductor technology could be used to integrate the qubit element within a solid, as happens in conventional computer chips. Several solid-state systems that could, in principle, lead to integrated quantum circuits have already been proposed. These ideas include NMR on regularly arranged impurities in a solid-state substrate (*Nature* 1998 **393** 133), single-electron charge or spin states in semiconductor quantum dots (*Phys. Rev.* 1998 **A57** 120) and charge or flux states in superconducting circuits (*Nature* 1999 **398** 305).

All these systems would have the advantage of great flexibility in design, easy access for control signals and the possibility of integrating a large number of elements in a small area. There is, however, a trade-off between control and long coherence times in quantum systems. The price for easy control and dense integration is that the quantum states are also extremely vulnerable to all sorts of noise sources in the solid-state environment.

One major source of noise in these experiments is external noise. Nakamura and colleagues isolated their superconducting circuit in a microwave-tight copper box inside a dilution refrigerator at 30 millikelvin, with extensive shielding and filtering. The experimental challenge is to prepare the input state, to read the output state, and to have controlled state evolution in between using a microwave pulse. Nakamura and colleagues were able to feed the pulses through the low-temperature shield without allowing any noise to enter.

In addition to external noise, the quantum coherence of a solid-state qubit can be destroyed by interactions with internal degrees of freedom in the sample. For instance, in two-level systems built with semiconductor quantum dots, even spontaneous emission due to the vacuum fluctuations in the phonon environment can lead to a loss of coherence (*Science* 1998 **282** 932). Superconducting systems might have an advantage in this area because the presence of the "superconducting gap" means there are no low-energy excitations. The electrons in a superconductor are bound together in so-called Cooper pairs, which all share the same quantum-mechanical wavefunction. The qubit therefore involves a macroscopically large number of Cooper pairs. Theory predicts that such macroscopic quantum states are much more robust with respect to noise than two-level systems occupied by just one or two electrons.



(*a*) The quantum charge oscillation was demonstrated with a micro-fabricated superconducting device. A small superconducting electrode (the box) is connected to a large superconducting reservoir via a tunnel junction. The capacitance of the box is so small that it requires a significant amount of energy to add a single Cooper pair to the box. The voltage source is used to control the number of Cooper pairs in the box, and the charge on the box oscillates when a fast voltage pulse is applied. (*b*) A scanning electron micrograph of the device. The box is connected to the reservoir via two tunnel junctions in parallel. An additional electrode probes the state of the system.

Nakamura's device consists of a small superconducting electrode connected to a large superconducting lead via a thin insulating oxide layer (see figure). This connection forms a tunnel junction that is about 1 nm thick. The lead is made of aluminium, which becomes superconducting below 1 K. The electrode is essentially a 700 × 50 × 15 nm aluminium "box" that contains about 10^8 electrons. The capacitance of this box is so small that the energy of the total system (i.e. the lead plus the box) changes by a noticeable amount if even just one Cooper pair tunnels through the junction. It is therefore significant whether an extra Cooper pair is located in the box or in the lead. These two charge states can be used to represent a zero and one state, respectively.

However, this is a quantum system and the location of a Cooper pair is not well defined. This means that the probability of finding an extra Cooper pair in the box is non-zero, as is the probability of finding the extra pair in the lead. This coherent superposition of the zero and one states could therefore form the basis of a quantum logic gate. When a voltage pulse is applied to the box, the probabilities for the charge states oscillate in time, typically with microwave frequencies. This technique was used in the new experiments to control the quantum state of the device. By applying extremely short electrical pulses, Nakamura and coworkers were able to resolve this quantum-mechanically coherent oscillation in time. They found that the oscillation stays coherent for up to a few nanoseconds. (The pulses were between one-tenth and a few nanoseconds in duration).

This impressive state-of-the-art control is, however, only a first small step towards a solid-state quantum computer. Even in the most optimistic scenario it will take decades of research to build a circuit of solid-state qubits that will remain coherent long enough – a few microseconds – for meaningful computation. However, the route to long coherence times is interesting in its own right as it directly touches on the fundamentals of quantum mechanics. For many physicists this fundamental issue is probably more of a motivation for research than the prospect of realizing a quantum computer.

Fermions go it alone

From **Thierry Martin** in the Centre de Physique Théorique, Université de la Méditerranée, Marseille, France

In quantum mechanics it is possible to pack an arbitrary number of bosons into the same quantum state. The maximum occupancy for fermions, however, is one. Back in 1956 two British scientists, Hanbury Brown and Twiss, conducted a classic experiment that showed that photons, a type of boson, have a tendency to bunch into clusters. Their experiment comprised two light sources and two detectors set up to measure the light that was transmitted and reflected by a beam splitter at the centre of the experimental configuration (see figure *a*). The bunching was observed by measuring the intensity correlation between the two coherent beams of light as a function of time. Hanbury Brown and Twiss measured the likelihood of observing a fluctuation in one detector at a particular time when a signal was detected at an earlier time in the other detector. The positive correlation they found was consistent with the bunching property of bosons.

But what would happen in an analogue of the Hanbury Brown and Twiss experiment if fermions were used instead of bosons? As more than one fermion cannot occupy the same quantum state, we should expect to see an anticorrelation between the particle intensities measured at the two detectors. But to detect such a negative correlation requires the incoming stream of electrons to have most of its quantum states fully occupied. The outlook for such an experiment therefore looked pessimistic at the time of Hanbury Brown and Twiss, as it was impossible to achieve high-density electron beams before the advent of fabricated micron-sized devices.