An understanding of the wider evolutionary significance of this manipulation must await a fuller documentation of its physiological consequences.

Finally, it has been suggested[1,3,15] that variation in the expression of the V1aR gene, and hence evolutionary changes in vole social behaviour, can be attributed solely to variation in the gene's regulatory DNA sequences. But perhaps we should not be so quick to leap to this conclusion. For instance, mice engineered to include a prairie-vole V1aR gene (plus control sequences) fail to display prairie-vole-like levels of V1aR expression in the ventral pallidum[16]. Similarly, control sequences from the prairie-vole V1aR gene do not yield higher expression levels in rat brain cell lines than do such sequences from montane voles (which are similar to meadow voles)[15]. Gene variation in signalling or regulatory molecules that interact with the V1aR control region are also likely to be important.

Understanding the role of genetic variation in the evolution of any trait requires knowledge of the major genes involved, their distribution among individuals, the distribution of genetically defined individuals in different environments, and the dependence of the trait on the environment for each individual and at each stage of development. This is a tall order, especially for behavioural characteristics. But the research on voles gives us hope that classical comparative studies of natural populations, judiciously coupled with modern molecular and cellular neurobiology, will continue to provide insights into the relationships between genes, brain-cell collectives, ecology and chance in social behaviour. ■

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Quantum physics

Push-button teleportation

H. J. Kimble and S. J. van Enk

Two groups have succeeded in teleporting quantum states between different atoms — a spectacular advance in the quest to achieve quantum computation.

In 1993, Charles Bennett and colleagues described a remarkable protocol for transporting a quantum state from one location to another[1], a protocol that succeeds even when the quantum state is completely unknown at the respective sites. Such quantum teleportation makes use of an extraordinary quantum resource, namely entanglement between two systems. Moreover, it also requires ordinary classical information obtained by performing a joint measurement on the system that carries the quantum state to be teleported and one component of the entangled state (as outlined in Fig. 1). Strangely, neither classical nor quantum channels individually carry any information about the quantum state, leading to the characterization of teleportation as the disembodied transport of quantum states. Initial experimental demonstrations of quantum teleportation, from 1997 onwards, involved the quantum states of beams of light[2–4]. Now, in a landmark advance, two teams have achieved teleportation for the quantum states of massive particles[5,6].

As described on pages 734 and 737 of this issue, Riebe *et al.*[5] and Barrett *et al.*[6] have generated coherent superpositions of two internal states for a single trapped ion (P in Fig. 1), and have teleported these quantum states to a second ion (B), with the help of a third, auxiliary ion (A). The import of these experiments goes well beyond the demonstration of teleportation *per se*, because both schemes incorporate many complex procedures that are required for scalable quantum computing. Indeed, the ion-trap set-up is generally considered one of the most promising implementations for quantum computing, as is once again confirmed by these experiments.

Moreover, quantum teleportation has emerged as an essential operation for diverse tasks in quantum information science. For example, if entangled particles were distributed throughout various sectors of a quantum computer, then quantum teleportation could provide a means for distant quantum bits (or qubits) to interact without the requirement of physical proximity — effectively 'quantum wiring', with desirable scaling properties. In addition, disposable quantum software could be delivered from a remote location using a generalized form of quantum teleportation to enhance the capabilities of rudimentary quantum hardware[7].

Remarkably, the two groups[5,6] have used quite different techniques for achieving teleportation, and yet both reach very similar values of so-called fidelity. Fidelity is a figure of merit that quantifies how well the quantum state that appears in the second ion after teleportation resembles the original quantum state; fidelity is 1 in the ideal case. Both teams report values around 0.75, which exceeds the 'classical' value of 2/3 that can be reached without quantum entanglement. For classical teleportation, the original quantum state is simply measured, and a new quantum state recreated by using only the classical information obtained from the measurement.

Both experiments have thereby reached the milestone of unconditional, or deterministic, teleportation of atomic qubits. The initial quantum state is prepared on demand, then teleported from one ion to another with high efficiency at the push of a button (which in fact triggers a computer-controlled array of complex operations). The teleported state is then available for further experiments. Such bona fide teleportation of quantum bits, following the original proposal of Bennett *et al.*[1], has not been achieved before — not in experiments with polarization states of light, and certainly not for any material system. The only other setting in which deterministic teleportation has been realized is that of continuous quantum variables (roughly, the amplitude and phase of a beam of light)[4].

In terms of the actual physical systems, Riebe *et al.*[5] employ ground and metastable states of trapped calcium ions as qubits; Barrett *et al.*[6] utilize two ground states in the hyperfine structure of beryllium ions. As for the implementation of quantum operations, the two experiments differ in several important aspects. First, crucial elements of both teleportation and quantum computing are joint operations for two qubits that cannot be performed by simply manipulating the qubits separately. Such two-body interactions are required for the creation of entanglement between two ions (step 1 in Fig. 1), and for the implementation of joint or Bell-state measurements (step 3). Riebe *et al.* use a version of the Cirac–Zoller two-qubit gate[8], which relies on the common centre-of-mass motion of the ions. Barrett

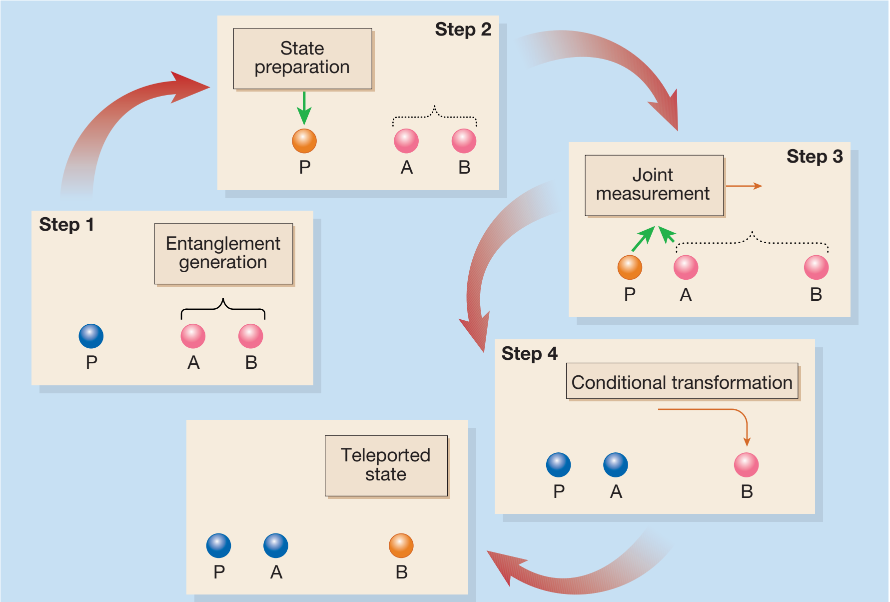

Figure 1 **Quantum teleportation, step by step. Although the details of their experiments differ, Riebe *et al.*[5] and Barrett *et al.*[6] have followed the protocol suggested by Bennett *et al.*[1] to achieve deterministic teleportation of a quantum state between trapped ions. First, an entangled state of ions A and B is generated, then the state to be teleported — a coherent superposition of internal states — is created in a third ion, P. The third step is a joint measurement of P and A, with the result sent to the location of ion B, where it is used to transform the state of ion B (step 4). The state created for P has then been teleported to B.**

et al. adopt a recently developed geometric method to perform two-qubit gating[9].

A second difference concerns how the authors addressed individual ions for manipulating quantum states, including projective measurements. Riebe *et al.* are able to address any specified target ion using tightly focused laser beams and have developed a technique to 'hide' the remaining ions from the target ion's fluorescence by changing their internal states so that they are insensitive to the fluorescent light. Barrett *et al.* have developed the capability to move groups of ions selectively to separate zones in a segmented trap, thereby isolating any target ion while still maintaining entanglement within the system.

The details of implementation aside, these two experiments represent a magnificent confluence of experimental advances, ranging from precision spectroscopy and laser cooling to new capabilities for controlled two-body interactions. The techniques developed and employed by these groups will no doubt prove important in the quest to build large-scale quantum computers based on trapped ions. Indeed, the fact that such diverse procedures performed so superbly in two separate laboratories attests to the flexibility and great potential of ion trapping for processing quantum information. ■

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Atmospheric chemistry

Fire and ice

Small air bubbles, trapped in glaciers and ice caps, have been a priceless source of information about the history of Earth's atmosphere: the record now goes back some 800,000 years. But, for a gas to be preserved in this frozen archive of atmospheric history, it must be chemically inert, and so there can be no direct record of the short-lived species, such as ozone (O_3) and the hydroxy radical (OH), that drive the key chemical processes in the atmosphere.

Writing in the *Journal of Geophysical Research* (doi:10.1029/2003JD004218; 2004), Becky Alexander *et al.* suggest that a little-known peculiarity of isotope chemistry, known as 'mass-independent fractionation', may offer a glimpse into the history of vegetation burning and its effects on oxidation reactions in the atmosphere.

The fractionation of isotopes that occurs during most chemical and physical processes is usually proportional to the mass difference between the isotopes. But a few reactions, notably the formation of ozone, also lead to isotope fractionations that are not proportional to the isotope mass. The resulting anomaly in the isotopic composition of atmospheric ozone is passed on to the sulphate and nitrate formed from aqueous-phase reactions between O_3 and SO_2 and NO_x respectively. Other processes that lead to sulphate and nitrate, such as gas-phase reactions involving the hydroxy radical, do not show this anomaly.

As a result, we can tell the relative contributions of liquid-phase oxidation by O_3 and gas-phase oxidation by OH from the isotopic composition of sulphate and nitrate trapped in the layers of ancient ice in Greenland and Antarctica. Alexander *et al.* have identified a large isotope anomaly in Greenland ice that dates from the period 1830–1900, and it turns out to correlate perfectly with indicators of biomass burning — formate and ammonium — in the same ice layers. They propose that this anomaly is the consequence of elevated levels of ozone that stemmed from air pollution from the fires that the pioneers used to clear North America for agriculture in the nineteenth century.

These data cannot yield quantitative conclusions about the amounts of oxidants in the pre-industrial atmosphere. They can, however, serve as constraints for models that integrate information about the emissions that are associated with different types of land use and their reactions in the atmosphere. Such models are used for analysing and predicting the human impact on atmospheric composition. In the tropics, high concentrations of water vapour and solar ultraviolet radiation combine to produce the

highest OH concentrations worldwide, making this area the most important region for atmospheric oxidation. So, for further understanding of those processes, we might want to look with added urgency for isotopic clues in the few and rapidly vanishing ice caps on mountains in the tropics (pictured, Mount Huascarán in Peru, in 1978). **Meinrat O. Andreae**

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