QUANTUM INFORMATION

A gem of a quantum teleporter

Diamond-based quantum teleportation works every time

By **Mete Atatüre**[1] and **John J. L. Morton**[2]

The television series "Star Trek" owes its longevity to the fact that when Captain Kirk was in danger on the surface of a planet, his chief engineer, Montgomery Scott, could teleport him back to the Enterprise each and every time, not just once every thousand episodes. The quantum-mechanical realization of teleportation—where a quantum state can be teleported to a distant location—has taken a while to reach this level of reliability. On page 532 of this issue, Pfaff *et al.* (*1*) report on the first deterministic and unconditional quantum teleportation using matter-based systems.

Quantum teleportation addresses the basic question of how to transmit information about the state of a quantum system without sending the physical system itself. It is the quantum equivalent of the fax machine. Heisenberg's uncertainty principle states that it is impossible to obtain all of the information about a quantum system by measuring it and equally impossible to make an accurate copy. However, this task is not hopeless. In 1993, Bennett *et al.* (*2*) devised a method based on quantum entanglement and a basic classical communication channel, by which a quantum state could cease to exist in one location and then reappear at another. In this protocol, two parties ("Alice" and "Bob") each possess a quantum bit (or qubit), having first established quantum entanglement between them—more or less the way Einstein, Podolsky, and Rosen (*3*) first described nonlocal quantum correlations.

Alice then has a quantum system in some unknown state $|\phi\rangle$ that she would like to send to Bob. She first interacts this system with her qubit and then measures both. At this point, the state $|\phi\rangle$ is neither with Alice nor with Bob. Bob's qubit is one simple transformation away from becoming $|\phi\rangle$, but Alice must tell Bob the result of her measurements (using a classical channel; a phone line would do) for Bob to know what this transformation needs to be. As Bennett *et al.* observed, "The net result of teleportation is completely prosaic: the removal of $|\phi\rangle$ from Alice's hands and its appearance in Bob's hands a suitable time later." So, the quantum fax machine shreds the input state as it sends it.

Implementing this protocol in practice is challenging, because it requires bringing together a number of elements of the quantum practitioner's toolbox—creating entanglement, storing quantum states, and feeding forward the results of Alice's measurement to determine operations applied on Bob's system. Proof-of-concept demonstrations were performed by three different groups of researchers based on single photons and squeezed light (*4–6*). Without the resources to allow Alice and Bob to store quantum-correlated light (this requires a quantum memory, which is still under development), such methods enable state teleportation only in an a posteriori probabilistic manner or require a continuously running bright optical link between Alice and Bob. Nevertheless, teleportation using photons has been demonstrated over distances of almost 150 km (*7*). Space (e.g., satellite links) is the next, if not final, frontier.

The problem with probabilistic teleportation. Previous demonstrations of quantum teleportation between matter-based systems were probabilistic, leading to mostly unsuccessful attempts and therefore corrupting the final teleported state. The approach of Pfaff *et al.* verifies entanglement before performing the teleportation steps, so every attempt is successful in the end

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Demonstrating quantum teleportation with matter systems is arguably even more intriguing, because light already does a good job of transmitting quantum states without any help from physicists. The obvious way for Alice and Bob to possess entangled matter qubits is to entangle two qubits through local interactions and then separate them, giving one each to Alice and Bob. Performing such a separation of qubits within their lifetime is challenging in practice. A more elegant scheme is to entangle remote qubits by causing each to emit a photon that is correlated with its state and then interfering those two photons and measuring them (*8*).

This act can project the two matter qubits into an entangled state, even though they never interacted directly. However, practical implementations of this are not deterministic and have a very low probability of success (see the figure). Remote entanglement has been performed with both trapped ions and cavity-coupled atoms separated by a few meters, enabling quantum teleportation between them (*9*, *10*). Currently, atoms in cavities are the state-of-the-art and can clock 10 successful teleportation events per second, based on 10,000 attempts per second. The "post-selected" data answers the question "when Alice and Bob did share entanglement, were they able to teleport their state?"

The next step is to be able to wait until entanglement is successfully created and only then attempt teleportation—the quantum equivalent of waiting for a dial tone. Entangled qubits must be stored long enough to verify their entanglement before commencing the teleportation protocol. Pfaff *et al.* have turned this approach into reality using the spins of impurity atoms in diamond. Diamond impurities, such as the negatively charged nitrogen vacancy (NV), are nature's cost-effective trapped ions. Strong confinement of electrons by an impurity atom automatically provides discrete energy levels for preparation, control, and measurement of the electronic spin qubit. Essential properties of the NV center in diamond include long spin coherence lifetimes (approaching 1 s), optical transitions that allow readout of the spin state and spin-photon entanglement, and a neighborhood of nuclear spins interacting with the NV electron spin that form a small quantum register.

Pfaff *et al.* have harnessed each of these capabilities into one quantum teleportation protocol that follows the original

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[1] Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK. [2] London Centre for Nanotechnology, University College London, London WC1H 0AH, UK. E-mail: ma424@cam.ac.uk; jjl.morton@ucl.ac.uk

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proposal almost verbatim. They used two cryogenically cooled NV centers (belonging to Alice and Bob, respectively) separated by 3 m and defined a nitrogen spin near Alice's NV center to be the input qubit. As in the case of the atomic counterparts, the remote entanglement is formed probabilistically (with a rather modest rate of once every 250 s) and heralded by a successful measurement outcome of interfering photons from the two NVs (*11*). The heralding places the two NV electron spins into an entangled singlet state that lasts as long as the electronic spin coherence time (a few milliseconds, with the help of active error protection known as dynamical decoupling) (*12*). This time is sufficient for Alice to couple the nearby nitrogen spin qubit with her half of the entangled pair, measure both spins through optical readout, and then feed forward this information to determine the operation to be performed on Bob's qubit. In contrast to previous demonstrations, this work distinguished all four of the different measurement outcomes of Alice's qubits in a single shot, a prerequisite for the success rate to exceed 50%. Bringing all of these elements together, Pfaff *et al.* demonstrated deterministic quantum teleportation between distant matter qubits.

As usual with cutting-edge research, there is sufficient room for improvement. The actual teleportation fidelity was 86%, caused by the combined effect of practical imperfections at each stage. The initial step of generating entangled spins is the current bottleneck on the operation bandwidth of 1/250 Hz. Better photon collection efficiency, possibly through optical cavities, could result in this step being reduced to milliseconds. Another area of focus is improving the millisecond storage time scale of the initial singlet state, perhaps using nuclear spins on both sites as the storage qubits, so that there is time for entangling a larger number of qubits in a concatenated computation protocol. With some if not all of these improvements, a fundamentally secure and feasible quantum communications network with diamond-based quantum nodes is within reach. ■

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EVOLUTION

An epigenetic window into the past?

DNA damage in ancient genomes may provide insight into past regulatory changes in humans and other species

By **Ludovic Orlando** *and* **Eske Willerslev**

Over the past 30 years, ancient DNA has helped to track past population dynamics, environmental changes, and historical epidemics. Studies of ancient genomes have provided insights into the evolution of humans (*1*, *2*) and other mammals (*3*). Going beyond sequences, epigenetic changes, such as methylation patterns, can also be detected in ancient genomes (*4*, *5*). This epigenetic information has the potential to elucidate regulatory changes underlying species divergence and population adaptation.

Epigenetic information regulates the accessibility of chromatin to transcription factors and thereby coordinates gene expression. Consequently, epigenetic changes influence various biological processes, including cell differentiation, aging, and cancer (*6*). Cytosine methylation (^{m}C), one of the best-known epigenetic markers, is often associated with gene silencing and is generally found at CpG dinucleotide sites in vertebrate genomes (*6*). The best method for reconstructing high-resolution methylation maps is bisulphite sequencing, which converts unmethylated cytosines into uracils (U) and therefore CpG sites into UpG sites. At ^{m}CpG sites, where methylation precludes bisulphite conversion, no mutation is observed. Applied to 26,000-year-old bison bones, this method revealed methylation patterns at four candidate loci (*7*). However, bisulphite conversion is associated with severe DNA degradation and is thus poorly suited for ancient DNA, which is only available in trace amounts.

DNA conversion reactions similar to those caused by bisulfite treatment take place naturally after an organism dies. The most common such reaction mostly occurs at single-stranded overhangs, converting CpG into UpG sites and ^{m}CpG into TpG sites. Current approaches for reconstructing ancient methylation maps exploit this pattern by disabling the sequencing of UpGs on high-throughput platforms (*4*, *5*). The location of CpG→TpG mutations in the genome reveals places where cytosines were methylated (*8*) (see the figure).

Pedersen *et al.* have applied this approach to the genome sequence of a 4000-year-old paleo-Eskimo (called Inuk), revealing methylation patterns closely matching those from modern hair (*4*). The DNA had been extracted from hair. Thus, methylation data could help to identify the source of ancient DNA molecules and rule out contamination from modern human DNA, a major problem in past studies. The methylation state at clock CpG sites, where methylation levels change with age in a predictable manner (*9*), revealed that Inuk probably died in his fifties. The methylation map was then used to attempt to predict gene expression in Inuk's hair. Genes coding for key hair proteins appeared to be highly expressed, and predicted levels of gene expression were significantly correlated with transcription levels in living hair follicles.

> ***These studies provide hope that it may be possible to identify the epigenetic contribution to past evolutionary transitions.***

Using a similar approach, Gokhman *et al.* have shown that the bone methylation maps from two archaic hominins that lived 50,000 to 130,000 years ago in the Altai mountains strongly resemble those from human osteoblast cells (*5*), except for ~2000 regions where at least one archaic hominin showed differential methylation. These regions include the *HOXD* cluster, a key regulator of limb development. If confirmed for more individuals, these findings could identify key regulatory sites that contribute to the anatomical differences between modern humans and archaic hominins.

Centre for GeoGenetics, Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, 1350K Copenhagen, Denmark. E-mail: lorlando@snm.ku.dk