# The fastest way from A to B

Tony Sudbery

**Quantum teleportation is a way of transferring the state of one particle to a second, effectively teleporting the initial particle. This technique has only existed as a thought experiment — until now.**

Quantum teleportation has been achieved in the laboratory, by teams headed by Anton Zeilinger in Vienna (who report on page 575 of this issue[1]) and Francesco De Martini in Rome[2] (in a paper submitted to *Physical Review Letters*). This fancifully named process, devised four years ago by Charles Bennett *et al.*[3,4], is a way to transfer quantum information about an object instantaneously to a distant object, using 'entanglement' — a mysterious connection between separated objects, which Einstein, Podolsky and Rosen pointed out was a feature of quantum mechanics. Einstein *et al.* found entanglement unbelievable, but thanks to John Bell and the experiments inspired by his work, it is now well established. It is also accepted that entanglement cannot be used to transfer readable information instantaneously, which would violate the principles of relativity. Indeed, what Bennett *et al.* showed is that the full information needed to reconstruct the state of an object can be divided into two parts, quantum and classical. The former can be transmitted instantaneously, but it cannot be used without the latter, which can only be transmitted by conventional means at the speed of light or slower.

The communication channel for teleportation consists of a pair of entangled particles, one held by the sender, Alice, and one by the receiver, Bob. Let us call these 'handset' particles. The entanglement is like an invisible cat's cradle connecting them, and it is delicate — the particles must be well isolated from their environments to remain in a coherent entangled state. A third party, Carol, gives Alice another particle whose state, constituting the message, is to be communicated to Bob. Alice cannot simply read the message and transmit the information by a conventional channel, because quantum mechanics decrees that the full information is not accessible on a single reading, and the process of reading will change some of the information unpredictably. Instead she measures a joint property of the message particle and her handset. This still leaves her with incomplete information about the message and causes an uncontrollable change in the particles. But because of the entanglement, it simultaneously causes a related change in Bob's handset particle. This is the quantum part of the information. The classical part is the result of Alice's measurement, which she must communicate by a classical channel. It tells Bob what operation he must perform on his handset to complete the transformation and make it into a perfect copy of the message.

The practical difficulty lies in measuring the joint property of the message particle and Alice's handset particle. How can the two be held together during the measurement? The two experiments find different ways around this. In Zeilinger and colleagues' experiment (Fig. 1), Alice's handset particle and Carol's message particle are directed at the joint measurement apparatus independently, with no guarantee that they will arrive together. Only in the rare cases that they coincide is the joint measurement made and the teleportation successful. De Martini's experiment (Fig. 2) has a much higher proportion of successes, but demonstrates a slightly different kind of teleportation, suggested by Sandu Popescu[2]. In this, the message particle and Alice's handset, instead of being two separate particles, are two aspects of a single particle, namely the polarization and direction of motion of a photon. These enter in the theory just like two separate particles, and they can be used just as well to demonstrate teleportation. The only difference is that Carol must inscribe her message on Alice's handset instead of giving it to her on a separate particle. ▶

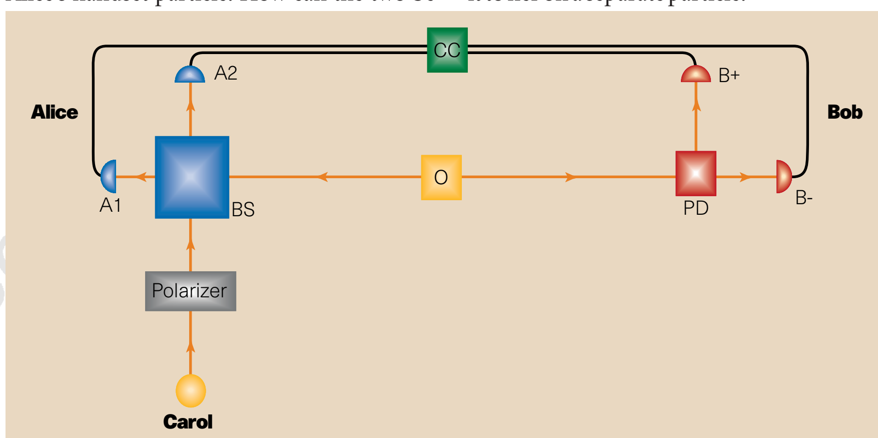


Figure 1 **The teleportation experiment of Zeilinger and colleagues[1]. O is the source of an entangled pair of photons; BS is Alice's beamsplitter with detectors A1 and A2 at its output ports; PD is Bob's polarization detector (with output B+ corresponding to the polarization of Carol's message particle). A coincidence counter (CC) registers triple coincidences between A1, A2 and B+, but not A1, A2 and B–. Carol's message particle has effectively been teleported to Bob's polarization detector.**

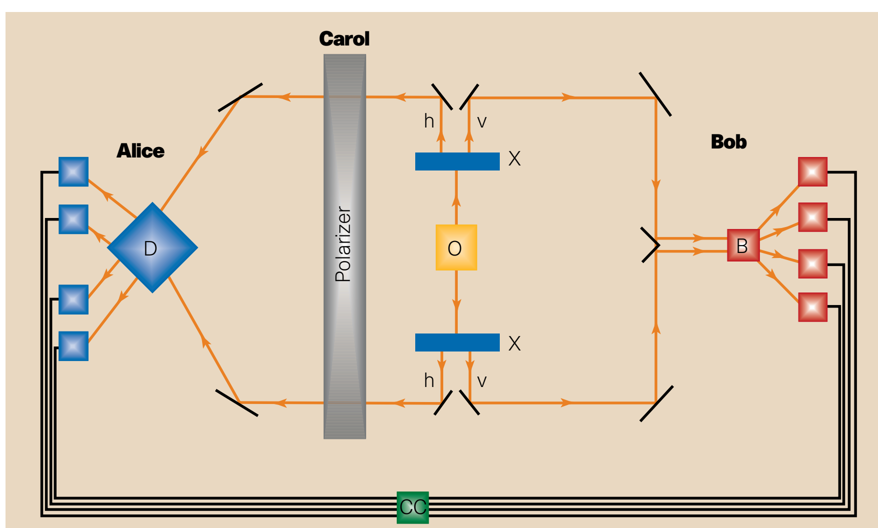


Figure 2 **The experiment of De Martini and colleagues[2]. Calcite crystals (X) separate horizontally and vertically polarized photons. Bob's switch (B) sends his photon to four detectors, each corresponding to one outcome of Alice's detector (D); and the counter (CC) detects coincidences between the two.**

In the experiment of Zeilinger and colleagues, pairs of entangled photons are created by a process called parametric down-conversion, in which a single photon is converted into two plane-polarized photons with perpendicular planes of polarization. These are pairs of handset particles, so one is sent to Alice, the other to Bob. Independently, a photon of the same frequency is put in a known state of polarization and sent to Alice to be the message particle. Alice has a beamsplitter, a device that can receive light in two entry ports and direct it to either of two exit ports. Her joint measurement on the two particles she receives consists of directing them to the two entrance ports of her beamsplitter and seeing how they emerge. This has the desired effect on the particles (and therefore on Bob's handset particle) if they arrive simultaneously. The particles were detected by Zeilinger and colleagues if they emerged from different output ports of the beamsplitter with opposite polarizations, which is one of the four possible outcomes. In those cases, Bob's handset particle was found to acquire the state of the message particle, and the particle had thus been teleported.

De Martini's group proceeds differently. They first convert the correlation between the polarizations of the entangled pair to a correlation between their paths in space. Each handset particle can travel by two different routes to its recipient Alice or Bob, and if one takes the high road, the other takes the low road. This frees the polarization aspect of Alice's photon to be the message. On its way, it is put in a chosen state of either plane or elliptical polarization — this is Carol inscribing her message. At Alice's end, both routes lead the photon to a device that measures various combinations of the polarization of the photon and its path of travel. Meanwhile, Bob's photon goes to a detector with four possible settings, each corresponding to one result of Alice's measurement: for a particular setting, the detector fires if the operation called for by the corresponding result of Alice's measurement would put the photon in the polarization state inscribed by Carol. Thus if teleportation has been successful, Bob's detector will fire every time the corresponding result is obtained by Alice — as was observed.

Quantum teleportation is a striking application of the holistic nature of the physical world revealed by quantum mechanics. It is expected to have uses in quantum computers, which will, in theory, be much faster than classical computers at solving certain problems. It can be used to transmit information reliably in noisy situations where messages would otherwise be degraded, and to transfer information from fleeting or hard-to-control carriers, such as photons, to particles more suitable for permanent storage, such as trapped ions. And it is bound to feature in the continuing discussions about realism, locality and whether there really is what Einstein called "spooky action at a distance". □

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1. Bouwmeester, D. *et al. Nature* **390,** 575–579 (1997).
2. Boschi, D., Branca, S., De Martini, F., Hardy, L. & Popescu, S. *Phys. Rev. Lett.* (submitted).
3. Bennett, C. H. *et al. Phys. Rev. Lett.* **70,** 1895–1899 (1993).
4. Sudbery, T. *Nature* **362,** 586–587 (1993).

**Learning and memory**

# Never fear, LTP is hear

**Robert C. Malenka and Roger A. Nicoll**

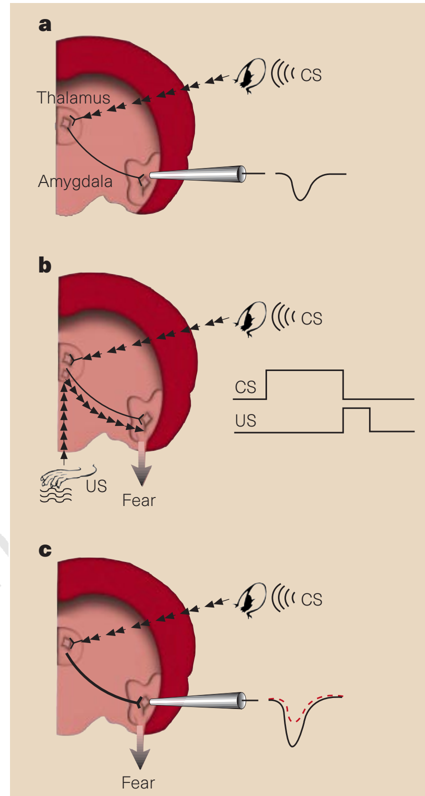


Figure 1 **Experiment by Rogan *et al.*[2] to show the link between long-term potentiation and memory, using a fear-conditioning response. The authors monitored changes in the extracellular potential in the lateral amygdala of an animal while it was trained to respond to a conditioned stimulus (CS), which was an audible tone, and/or an unconditioned stimulus (US; a foot shock).** a, **Pre-training. The sound waves (the CS) go into the ear, and this information goes to the thalamus and then to the amygdala, where a response is recorded.** b, **During training. The US is given just after the CS, and this causes 'fear'.** c, **After training. The CS now causes a larger response in the amygdala, and alone also elicits fear. The pathway from the thalamus to the amygdala is thicker, because this is the path that has presumably been strengthened during the training. (Dashed lines represent neural pathways that are either not illustrated or not known.) In a complementary study, McKernan and Shinnick-Gallagher[3] have shown *in vitro* that fear conditioning causes an increase in strength at the synapses that process the CS in the lateral amygdala.**

Synaptic transmission is the main mechanism by which neurons communicate, and an attractive hypothesis is that learning occurs, and memories are encoded, by activity-dependent changes in synaptic strength. With the discovery of hippocampal long-term potentiation (LTP), and the ability to study its mechanisms in experimentally accessible *in vitro* preparations, neurobiologists seemed to be on the verge of solving one of the more fascinating problems in neurobiology — the molecular basis for memory. But some reports have raised a nagging doubt as to whether LTP-like phenomena are actually used in the behaving animal during learning[1]. Now, complementary papers by Rogan *et al.*[2] and McKernan and Shinnick-Gallagher[3] (pages 604 and 607 of this issue) lay this doubt to rest. They show that fear conditioning, which is a form of pavlovian (classical) conditioning, indeed causes an increase in synaptic strength in the appropriate neural circuit.

Why has it been so difficult to make a connection between LTP and memory? Most studies have concentrated on the hippocampus, because this medial temporal lobe structure was the first one shown to be part of the brain's memory system[4]. Moreover, LTP was first described in the hippocampus[5], and it is most easily studied in this structure. However, the exact functions of the hippocampus remain unclear and the hippocampal-dependent tasks that are often used in behavioural studies are complex. Thus, the exact information carried by the hippocampal synapses and circuits that are (presumably) modified during learning and memory is unknown. Combining sophisticated molecular genetic and electrophysiological techniques in the behaving animal has been a step in the right direction[6]. But the demonstration of an increase in hippocampal synaptic strength (that is, LTP) during learning has remained elusive.

Enter fear conditioning, which has many attractive features for studying the neural mechanisms of memory. During fear conditioning, a neutral conditioned stimulus (the CS; for example, a tone) is followed by an unconditioned stimulus (the US; for example, a foot shock) which routinely elicits a