PERSPECTIVES: QUANTUM TELEPORTATION

A Tale of Two Cities

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As Samuel Braunstein of the University of Wales puts it, quantum teleportation is the "disembodied transport" of the quantum state of a system from one site to another (*1*). That is, quantum information encoded in the state, rather than matter or energy, is moved from one place to another. Now on page 706 of this issue, a group from the California Institute of Technology (Caltech) reports an experiment that demonstrates the teleportation of the quantum state of a light beam (*2*) with a high degree of confidence. The essential quantum-magical resource that makes teleportation possible is quantum entanglement, a kind of quantum correlation that is more powerful than any classical correlation. With entanglement, quantum systems at separate sites can be manipulated in ways that are impossible classically.

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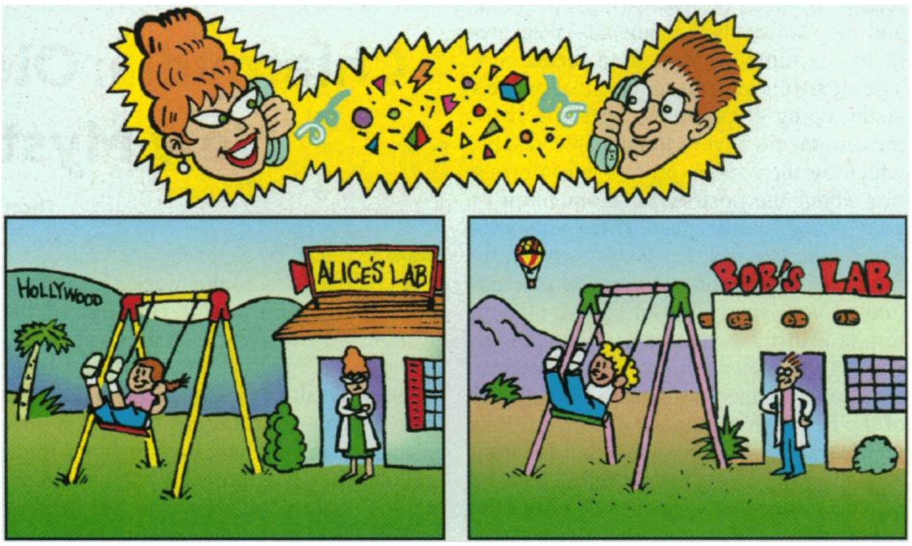
Quantum teleportation was proposed by a team of six scientists in 1993 (*3*). The original proposal focused on teleporting the quantum state of a two-state system, such as the polarization of a photon or a spin-$^1/_2$ particle. Such teleportation has been achieved in the lab by two groups, one at the University of Innsbruck (*4*) and one at the University of Rome ("La Sapienza") (*5*), both of which teleported the polarization state of a photon using entangled photon pairs as the essential resource. The difficulty in these experiments lay in the low efficiency for producing entangled photon pairs and in making entangled measurements on pairs of photons. As a result, there has been some debate about the meaning of these experiments (*6*). Instead of teleporting the state of a two-state system, the Caltech group reports in this issue that they teleported the quantum state of the oscillating electromagnetic fields in a light beam. Lev Vaidman of Tel-Aviv University formulated the essential idea for teleporting the quantum state of an oscillator. Braunstein and Jeff Kimble elaborated Vaidman's idea into the practical form that was implemented at Caltech. The advantages of the Caltech scheme are that the entangled light beams are relatively easy to make and the entangled measurements can be performed by using standard optical elements and high-efficiency photodetection.

To illustrate how the Caltech experiment works, I spin my own "Tale of Two Cities," in which the experiment's electromagnetic-field oscillations are replaced by the less abstract oscillations of a swing. Despite the whimsical nature of the tale, it captures faithfully the salient features of the Caltech experiment. The actors in the teleportation drama are invariably called Alice and Bob, and we're going to place them in Pasadena and Albuquerque. Let's suppose you live in Pasadena, and you and your young daughter like to use the swing set next to Alice's laboratory. One sunny afternoon, after you've set your daughter swinging, Alice suddenly appears and whisks the swing set into her lab. A bit later your daughter (and the swing set) emerge, apparently unharmed, and you see Alice talking on the telephone to her partner, Bob, whose lab in Albuquerque is next to my office. We being old friends, you call me and find that Bob has produced a girl in Albuquerque who is swinging in the same way, that is, with the same amplitude and the same phase, as your daughter was swinging in Pasadena (see figure).

Alice offers to do the same demonstration as many times as you wish, and your daughter being willing, you repeatedly set her swinging in Pasadena and direct me to observe the girl who appears in Albuquerque. After a few experiments with different amplitudes and phases, you come up with the obvious explanation: Alice must be making careful observations of your daughter's swinging and reporting her results to Bob, who sets an Albuquerque girl swinging according to Alice's instructions. You know, however, that Alice's observations are limited by the uncertainty principle of quantum mechanics, which prevents her from determining both the position and momentum of the swing with arbitrary precision. If Alice were making measurements on your daughter's swing, the errors introduced by the uncertainty principle would inevitably lead to subtle differences in the Albuquerque swinger, which could be detected by very precise observation of many repetitions. Confident that you can find these subtle differences, you direct me to make the appropriate measurements, but to your consternation, I report that even at and beyond the measurement limits set by the uncertainty principle, the Albuquerque swinger consistently reproduces the swinging you initiated in Pasadena. Desperate now, you tap the phone line from Alice to Bob to determine just what they're saying to each other. To your astonishment, you discover that Alice is transmitting utter gibberish to Bob, which varies randomly from trial to trial and which has no correlation with the swinging state that you prepared. Completely mystified, you conclude that Alice and Bob are hiding something and that whatever that something is, it's pretty mysterious.

At this point Alice decides she's had enough fun at your expense. She steps out



Entangled swings. The oscillations of a girl swinging in Pasadena are duplicated in Albuquerque, after Alice in Pasadena calls her partner Bob in Albuquerque. Investigation shows that the obvious explanation violates the uncertainty principle, but Alice explains that the duplication is accomplished by quantum teleportation.

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of her lab to confess that she and Bob are using quantum teleportation to transport the quantum state of the swing, and she generously offers to explain how teleportation works. For each experiment, she and Bob use a pair of swings, one at her lab and one at his, which are prepared in advance in the sort of entangled quantum state introduced by Einstein, Podolsky, and Rosen (EPR) in their classic 1935 paper (*7*). In the EPR state, both swings have completely uncertain positions and momenta, but their positions and momenta are correlated in a specific way. If Alice measures the position of her swing, she can predict with certainty that Bob's swing has the same position; likewise, if she measures momentum, she can predict that Bob's swing has the opposite momentum.

Alice uses entanglement in one other way. When she brings your swing into the lab, she makes two entangled measurements involving your swing and her swing from the EPR pair. She measures the difference between the two swings' positions and the sum of their momenta—measurements permitted by quantum mechanics. The position and momentum of Alice's swing being completely uncertain, these measurements have unpredictable results, which by themselves provide no information about the position or momentum of your swing. Yet because of the entanglement, Alice knows that Bob's swing from the EPR pair has the position and momentum of your swing, offset by the random results of her measurements. She communicates the measurement results to Bob, who applies suitable forces to his member of the EPR pair to remove the offsets, thus reconstructing in his swing the quantum state that your swing had initially.

The Caltech experiment teleported the coherent-state oscillations of the electromagnetic fields in a light beam, the big difference from the tale being that the two cities were in the same room at Caltech. An optical parametric oscillator (OPO) generated the entangled light beams, one of which was sent to Alice and one to Bob. Although the perfect correlations of an EPR state are an unattainable limit, the "squeezed states" generated by the OPO had sufficient entanglement to do the job. Alice made her two entangled measurements by first combining, at a 50/50 beam splitter, her output from the OPO with the coherent state to be teleported and then making homodyne measurements on the two outputs of the beam splitter. Bob corrected the state of his output from the OPO by using Alice's measurement results to modulate the amplitude and phase of a strong laser beam, which he combined with his output from the OPO at a highly asymmetric beam splitter. Certification of successful teleportation came from demonstrating that the teleported state matched the input coherent state better than the uncertainty principle would allow if Alice measured the coherent-state input and sent the results to Bob.

The uncertainty-principle limits on measuring and duplicating a quantum state are a special case of the more general restriction that quantum mechanics does not allow one to distinguish and identify nonorthogonal quantum states. This quantum-mechanical limitation, long thought to prohibit teleportation, turns out to be an essential feature of the entanglement-based teleportation procedure. The information Alice transmits to Bob provides no information about the teleported state.

This two-faced character of quantum mechanics seems to be a common theme in the emerging field of quantum information science. Although the huge amount of information stored in the state of a quantum system is inaccessible, it can be used in quantum cryptography and quantum computation. The apparently restrictive features of quantum mechanics turn out on closer examination to allow quantum systems to perform information-processing tasks that would be impossible in a classical world. Quantum teleportation of two-state systems or harmonic oscillators is a first step in developing an array of techniques for processing and thus taking advantage of the power of quantum information.

References

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PERSPECTIVES: GENOME SEQUENCING

Chlamydia: Old Ideas Crushed, New Mysteries Bared

Thomas Hatch

The report by Stephens and colleagues on page 754 of this week's issue summarizes the major findings of the *Chlamydia trachomatis* genome sequencing project, funded by the National Institutes of Health (*1*). Unlike other bacteria whose genome sequences have been published, chlamydia have an obligatory intracellular life-style, growing only within the cells of eukaryotic organisms. Its genome sequence reveals how chlamydiae have adapted to this nutrient-rich yet potentially hostile environment. As an additional benefit, the sequence provides a powerful tool for chlamydial research, which has been hampered by the difficulty of propagating large numbers of organisms and by the lack of a functional system for genetic transformation.

Chlamydia trachomatis is the agent of trachoma (still a major cause of blindness in Asia and Africa) and is the most common bacterial sexually transmitted disease in the United States. *Chlamydia pneumoniae*, which is also being sequenced as part of the ongoing Chlamydia Genome Project, is a common cause of a usually mild, community-acquired pneumonia. This organism, however, can spread from the respiratory tract into other parts of the body and has been detected in up to 70% of atheromatous lesions in blood vessels (*2*). Although exactly how *C. pneumoniae* contributes to the pathogenesis of atherosclerosis remains unknown, prophylactic antibiotic trials are planned for individuals at high-risk for coronary disease (*3*).

The roughly 1 million–base pair sequence has revealed surprises, as much by what was found as what was not found. For years chlamydiae were thought to lack key enzymes and cellular machinery for generating ATP, instead sequestering host nucleoside triphosphates by translocation mechanisms (*4*). The new sequence does reveal two potential ATP/ADP translocases, but it also identifies genes that may allow chlamydiae to generate at least minimal amounts of ATP on its own.

A long-standing paradox has been the inhibition of chlamydial cell division by penicillin in the apparent absence of the principal penicillin target, peptidoglycan (*5*). The peptidoglycan deficiency is thought to be compensated by a unique disulfide–cross-linked, supramolecular protein complex in the cell wall, which provides the structural stability normally afforded by peptidoglycan (*6*). The se-

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