QUANTUM TELEPORTATION

The science-fiction dream of "beaming" objects from place to place is now a reality—at least for particles of light

by Anton Zeilinger

The scene is a familiar one from science-fiction movies and TV: an intrepid band of explorers enters a special chamber; lights pulse, sound effects warble, and our heroes shimmer out of existence to reappear on the surface of a faraway planet. This is the dream of teleportation—the ability to travel from place to place without having to pass through the tedious intervening miles accompanied by a physical vehicle and airline-food rations. Although the teleportation of large objects or humans still remains a fantasy, quantum teleportation has become a laboratory reality for photons, the individual particles of light.

Quantum teleportation exploits some of the most basic (and peculiar) features of quantum mechanics, a branch of physics invented in the first quarter of the 20th century to explain processes that occur at the level of individual atoms. From the beginning, theorists realized that quantum physics led to a plethora of new phenomena, some of which defy common sense. Technological progress in the final quarter of the 20th century has enabled researchers to conduct many experiments that not only demonstrate fundamental, sometimes bizarre aspects of quantum mechanics but, as in the case of quantum teleportation, apply them to achieve previously inconceivable feats.

In science-fiction stories, teleportation often permits travel that is instantaneous, violating the speed limit set down by Albert Einstein, who concluded from his theory of relativity that nothing can travel faster than light [see "Faster Than Light?" by Raymond Y. Chiao, Paul G. Kwiat and Aephraim M. Steinberg; Scientific American, August 1993]. Teleportation is also less cumbersome than the more ordinary means of space travel. It is said that Gene Roddenberry, the creator of *Star Trek*, conceived of the "transporter beam" as a way to save the expense of simulating landings and takeoffs on strange planets.

The procedure for teleportation in science fiction varies from story to story but generally goes as follows: A device scans the original object to extract all the information needed to describe it. A transmitter sends the information to the receiving station, where it is used to obtain an exact replica of the original. In some cases, the material that made up the original is also transported to the receiving station, perhaps as "energy" of some kind; in other cases, the replica is made of atoms and molecules that were already present at the receiving station.

Quantum mechanics seems to make such a teleportation scheme impossible in principle. Heisenberg's uncertainty principle rules that one cannot know both the precise position of an object and its momentum at the same time. Thus, one cannot perform a perfect scan of the object to be teleported; the location or velocity of every atom and electron would be subject to errors. Heisenberg's uncertainty principle also applies to other pairs of quantities, making it impossible to measure the exact, total quantum state of any object with certainty. Yet such measurements would be necessary to obtain all the information needed to describe the original exactly. (In *Star Trek* the "Heisenberg Compensator" somehow miraculously overcomes that difficulty.)

A team of physicists overturned this conventional wisdom in 1993, when they discovered a way to use quantum mechanics itself for teleportation. The team—Charles H. Bennett of IBM; Gilles Brassard, Claude Crépeau and Richard Josza of the University of Montreal; Asher Peres of Technion–Israel Institute of Technology; and William K. Wootters of Williams College—found that a peculiar but fundamental feature of quantum mechanics, entanglement, can be used to circumvent the limitations imposed by Heisenberg's uncertainty principle without violating it.

Entanglement

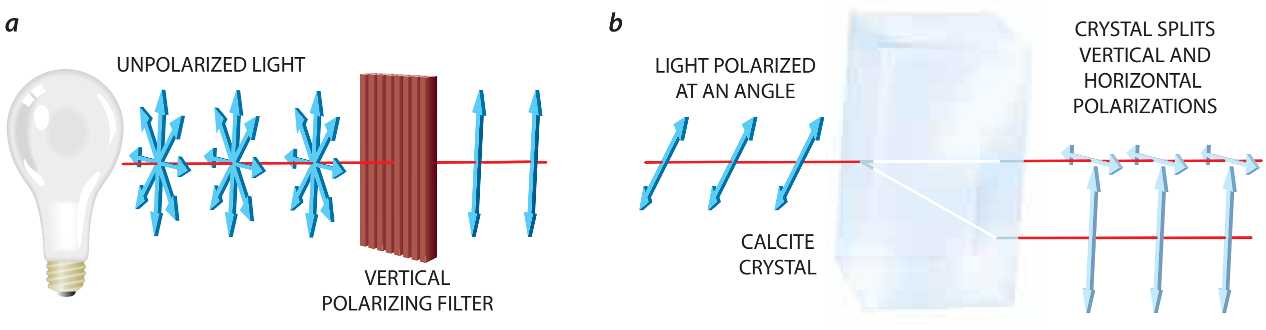
It is the year 2100. A friend who likes to dabble in physics and party tricks has brought you a collection of pairs of dice. He lets you roll them once, one pair at a time. You handle the first pair gingerly, remembering the fiasco with the micro–black hole last Christmas. Finally, you roll the two dice and get double 3. You roll the next pair. Double 6. The next: double 1. They always match.

The dice in this fable are behaving as if

TRAVELERS ARRIVE at Grand Central Station's teleport terminal. Although teleporting large objects, let alone living beings, will never be practical outside of fiction, teleportation of elementary quantum states *has* been demonstrated.

SPACE CHANNEL/PHILIP SAUNDERS


< Teleport Exit
< Baggage
< Hover Cabs
< Skyway
< Rentals
QUANTUM TRANSPORT ANALYZER
ENTROPIC DECAY
ELECTRON LOCK
DECOHERENCE
PLANCK FACTOR
NEW YORK
QUANTUM
TRANSIT
AUTHORIT



UNPOLARIZED LIGHT consists of photons that are polarized in all directions (*a*). In polarized light the photons' electric-field oscillations (*arrows*) are all aligned. A calcite crystal (*b*) splits a light beam in two, sending photons that are polarized parallel with its axis into one beam and those that are perpendicular into the other. Intermediate angles go into a quantum superposition of both beams. Each such photon can be detected in one beam or the other, with probability depending on the angle. Because probabilities are involved, we cannot measure the unknown polarization of a single photon with certainty.

LAURIE GRACE

they were quantum entangled particles. Each die on its own is random and fair, but its entangled partner somehow always gives the correct matching outcome. Such behavior has been demonstrated and intensively studied with real entangled particles. In typical experiments, pairs of atoms, ions or photons stand in for the dice, and properties such as polarization stand in for the different faces of a die.

Consider the case of two photons whose polarizations are entangled to be random but identical. Beams of light and even individual photons consist of oscillations of electromagnetic fields, and polarization refers to the alignment of the electric field oscillations [*see illustration above*]. Suppose that Alice has one of the entangled photons and Bob has its partner. When Alice measures her photon to see if it is horizontally or vertically polarized, each outcome has a 50 percent chance. Bob's photon has the same probabilities, but the entanglement ensures that he will get exactly the same result as Alice. As soon as Alice gets the result "horizontal," say, she knows that Bob's photon will also be horizontally polarized. Before Alice's measurement the two photons do not have individual polarizations; the entangled state specifies only that a measurement will find that the two polarizations are equal.

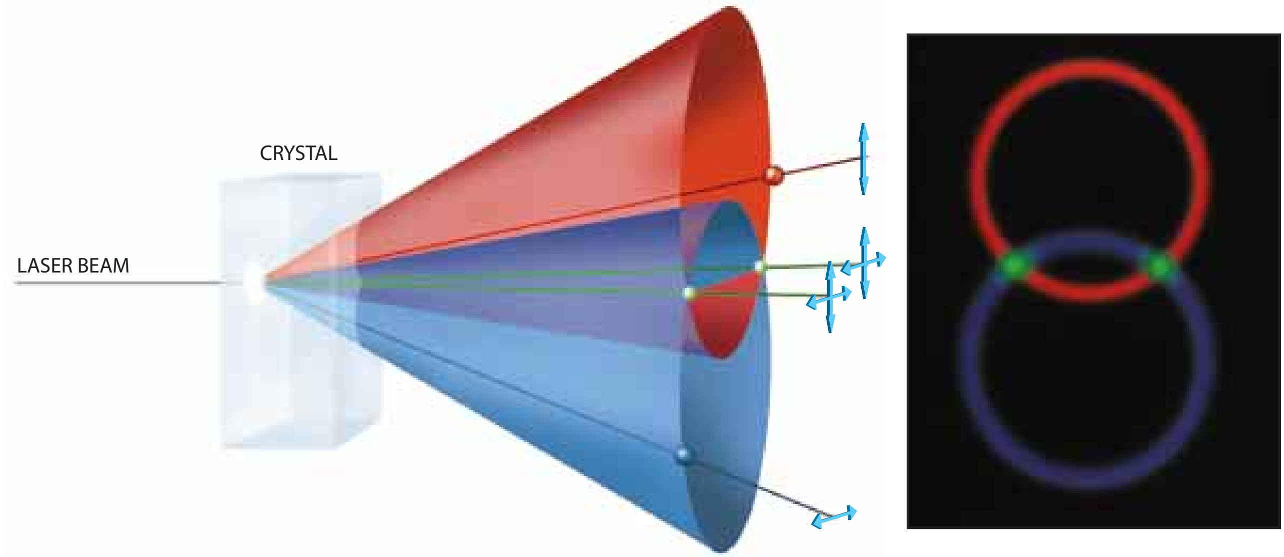
An amazing aspect of this process is that it doesn't matter if Alice and Bob are far away from each other; the process works so long as their photons' entanglement has been preserved. Even if Alice is on Alpha Centauri and Bob on Earth, their results will agree when they compare them. In every case, it is as if Bob's photon is magically influenced by Alice's distant measurement, and vice versa.

You might wonder if we can explain the entanglement by imagining that each particle carries within it some recorded instructions. Perhaps when we entangle the two particles, we synchronize some hidden mechanism within them that determines what results they will give when they are measured. This would explain away the mysterious effect of Alice's measurement on Bob's particle. In the 1960s, however, Irish physicist John Bell proved a theorem that in certain situations any such "hidden variables" explanation of quantum entanglement would have to produce results different from those predicted by standard quantum mechanics. Experiments have confirmed the predictions of quantum mechanics to a very high accuracy.

Austrian physicist Erwin Schrödinger, one of the co-inventors of quantum mechanics, called entanglement "the essential feature" of quantum physics. Entanglement is often called the EPR effect and the particles EPR pairs, after Einstein, Boris Podolsky and Nathan Rosen, who in 1935 analyzed the effects of entanglement acting across large distances. Ein-

PREPARING FOR QUANTUM TELEPORTATION ...

QUANTUM TELEPORTATION OF A PERSON (impossible in practice but a good example to aid the imagination) would begin with the person inside a measurement chamber (*left*) alongside an equal mass of auxiliary material (*green*). The auxiliary matter has previously been quantum-entangled with its counterpart, which is at the faraway receiving station (*right*).



ENTANGLED PHOTON PAIRS are created when a laser beam passes through a crystal such as beta barium borate. The crystal occasionally converts a single ultraviolet photon into two photons of lower energy, one polarized vertically (*on red cone*), one polarized horizontally (*on blue cone*). If the photons happen to travel along the cone intersections (*green*), neither photon has a definite polarization, but their relative polarizations are complementary; they are then entangled. Colorized image (*at right*) is a photograph of down-converted light. Colors do not represent the color of the light.

LAURIE GRACE (*left*); P. G. KWIAT AND M. RECK *Institute for Experimental Physics, University of Vienna (right)*

stein talked of it as "spooky action at a distance." If one tried to explain the results in terms of signals traveling between the photons, the signals would have to travel faster than the speed of light. Naturally, many people have wondered if this effect could be used to transmit information faster than the speed of light.

Unfortunately, the quantum rules make that impossible. Each local measurement on a photon, considered in isolation, produces a completely random result and so can carry no information from the distant location. It tells you nothing more than what the distant measurement result probabilities would be, depending on what was measured there. Nevertheless, we can put entanglement to work in an ingenious way to achieve quantum teleportation.

Putting Entangled Photons to Work

Alice and Bob anticipate that they will want to teleport a photon in the future. In preparation, they share an entangled auxiliary pair of photons, Alice taking photon A and Bob photon B. Instead of measuring them, they each store their photon without disturbing the delicate entangled state [*see upper illustration on next page*].

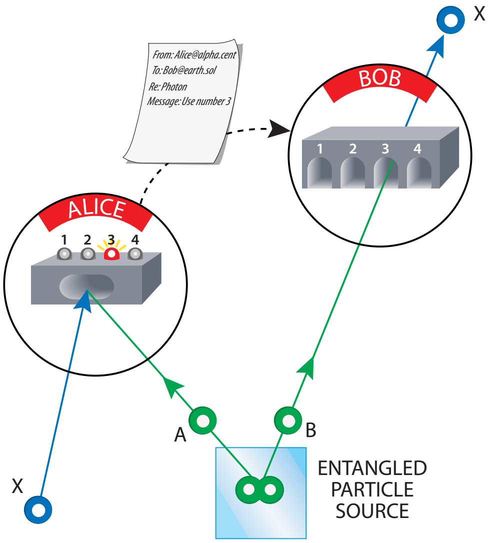
In due course, Alice has a third photon—call it photon X—that she wants to teleport to Bob. She does not know what photon X's state is, but she wants Bob to have a photon with that same polarization. She cannot simply measure the photon's polarization and send Bob the result. In general, her measurement result would not be identical to the photon's original state. This is Heisenberg's uncertainty principle at work.

Instead, to teleport photon X, Alice measures it jointly with photon A, without determining their individual polarizations. She might find, for instance, that their polarizations are "perpendicular" to each other (she still does not know the absolute polarization of either one, however). Technically, the joint measurement

… A QUANTUM MEASUREMENT …

JOINT MEASUREMENT carried out on the auxiliary matter and the person (*left*) changes them to a random quantum state and produces a vast amount of random (but significant) data—two bits per elementary state. By "spooky action at a distance," the measurement also instantly alters the quantum state of the faraway counterpart matter (*right*). MORE>>>

DAVID FIERSTEIN



IDEAL QUANTUM TELEPORTATION relies on Alice, the sender, and Bob, the receiver, sharing a pair of entangled particles A and B (*green*). Alice has a particle that is in an unknown quantum state X (*blue*). Alice performs a Bell-state measurement on particles A and X, producing one of four possible outcomes. She tells Bob about the result by ordinary means. Depending on Alice's result, Bob leaves his particle unaltered (1) or rotates it (2, 3, 4). Either way it ends up a perfect replica of the original particle X.

LAURIE GRACE

of photon A and photon X is called a Bell-state measurement. Alice's measurement produces a subtle effect: it changes Bob's photon to correlate with a combination of her measurement result and the state that photon X originally had. In fact, Bob's photon now carries her photon X's state, either exactly or modified in a simple way.

To complete the teleportation, Alice must send a message to Bob—one that travels by conventional means, such as a telephone call or a note on a scrap of paper. After he receives this message, if necessary Bob can transform his photon B, with the end result that it becomes an exact replica of the original photon X. Which transformation Bob must apply depends on the outcome of Alice's measurement. There are four possibilities, corresponding to four quantum relations between her photons A and X. A typical transformation that Bob must apply to his photon is to alter its polarization by 90 degrees, which he can do by sending it through a crystal with the appropriate optical properties.

Which of the four possible results Alice obtains is completely random and independent of photon X's original state. Bob therefore does not know how to process his photon until he learns the result of Alice's measurement. One can say that Bob's photon instantaneously contains all the information from Alice's original, transported there by quantum mechanics. Yet to know how to read that information, Bob must wait for the classical information, consisting of two bits that can travel no faster than the speed of light.

Skeptics might complain that the only thing teleported is the photon's polarization state or, more generally, its quantum state, not the photon "itself." But because a photon's quantum state is its defining characteristic, teleporting its state is completely equivalent to teleporting the particle [*see box on page 57*].

Note that quantum teleportation does not result in two copies of photon X. Classical information can be copied any number of times, but perfect copying of quantum information is impossible, a result known as the no-cloning theorem, which was proved by Wootters and Wojciech H. Zurek of Los Alamos National Laboratory in 1982. (If we could clone a quantum state, we could use the clones to violate Heisenberg's principle.) Alice's measurement actually entangles her photon A with photon X, and photon X loses all memory, one might say, of its original state. As a member of an entangled pair, it has no individual polarization state. Thus, the original state of photon X disappears from Alice's domain.

Circumventing Heisenberg

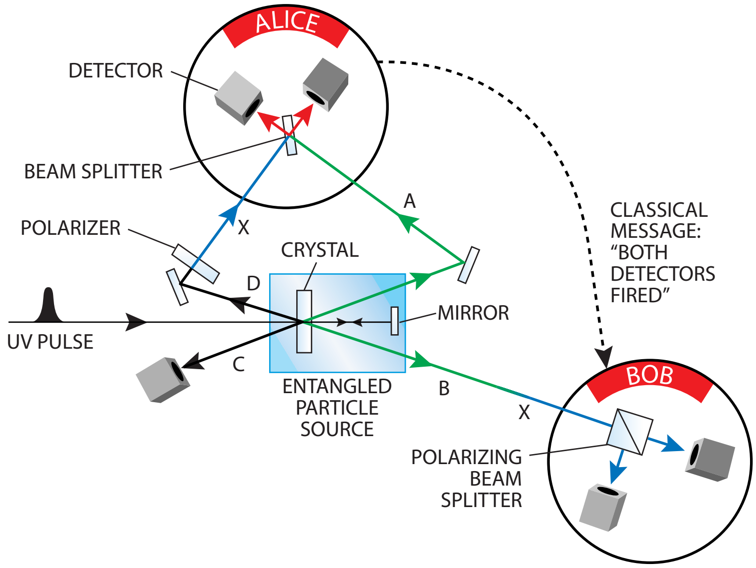
Furthermore, photon X's state has been transferred to Bob with neither Alice nor Bob learning anything about what the state is. Alice's measurement result, being entirely random, tells them nothing about the state. This is how the process circumvents Heisenberg's principle, which stops us from determining the complete quantum state of a particle but does not preclude teleporting the complete state so long as we do not try to see what the state is!

Also, the teleported quantum information does not travel materially from Alice to Bob. All that travels materially is the message about Alice's measurement result, which tells Bob how to process his photon but carries no information about photon X's state itself.

In one out of four cases, Alice is lucky with her measurement, and Bob's photon immediately becomes an identical

... TRANSMISSION OF RANDOM DATA ...

MEASUREMENT DATA must be sent to the distant receiving station by conventional means. This process is limited by the speed of light, making it impossible to teleport the person faster than the speed of light.



INNSBRUCK EXPERIMENT begins with a short pulse of ultraviolet laser light. Traveling left to right through a crystal, this pulse produces the entangled pair of photons A and B, which travel to Alice and Bob, respectively. Reflected back through the crystal, the pulse creates two more photons, C and D. A polarizer prepares photon D in a specific state, X. Photon C is detected, confirming that photon X has been sent to Alice. Alice combines photons A and X with a beam splitter [*see illustration on next page*]. If she detects one photon in each detector (as occurs at most 25 percent of the time), she notifies Bob, who uses a polarizing beam splitter to verify that his photon has acquired X's polarization, thus demonstrating successful teleportation.

LAURIE GRACE

replica of Alice's original. It might seem as if information has traveled instantly from Alice to Bob, beating Einstein's speed limit. Yet this strange feature cannot be used to send information, because Bob has no way of knowing that his photon is already an identical replica. Only when he learns the result of Alice's Bell-state measurement, transmitted to him via classical means, can he exploit the information in the teleported quantum state. Suppose he tries to guess in which cases teleportation was instantly successful. He will be wrong 75 percent of the time, and he will not know which guesses were correct. If he uses the photons based on such guesses, the results will be the same as if he had taken a beam of photons with random polarizations. In this way, Einstein's relativity prevails; even the spooky instantaneous action at a distance of quantum mechanics fails to send usable information faster than the speed of light.

It would seem that the theoretical proposal described above laid out a clear blueprint for building a teleporter; on the contrary, it presented a great experimental challenge. Producing entangled pairs of photons has become routine in physics experiments in the past decade, but carrying out a Bell-state measurement on two independent photons had never been done before.

Building a Teleporter

A powerful way to produce entangled pairs of photons is spontaneous parametric down-conversion: a single photon passing through a special crystal sometimes generates two new photons that are entangled so that they will show opposite polarization when measured [*see top illustration on page 53*].

A much more difficult problem is to entangle two independent photons that already exist, as must occur during the operation of a Bell-state analyzer. This means that the two photons (A and X) somehow have to lose their private features. In 1997 my group (Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl and Harald Weinfurter), then at the University of Innsbruck, applied a solution to this problem in our teleportation experiment [*see illustration at left*].

In our experiment, a brief pulse of ultraviolet light from a laser passes through a crystal and creates the entangled photons A and B. One travels to Alice, and the other goes to Bob. A mirror reflects the ultraviolet pulse back through the crystal again, where it may create another pair of photons, C and D. (These will also be entangled, but we don't use their entanglement.) Photon C goes to a detector, which alerts us that its partner D is available to be teleported. Photon D passes through a polarizer, which we can orient in any conceivable way. The

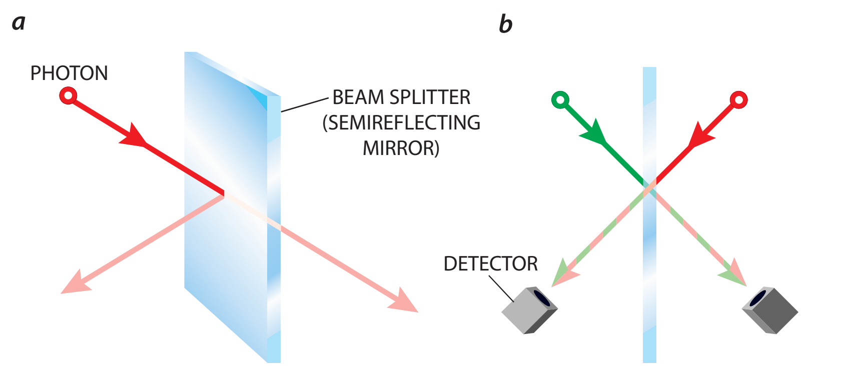
… RECONSTRUCTION OF THE TRAVELER

RECEIVER RE-CREATES THE TRAVELER, exact down to the quantum state of every atom and molecule, by adjusting the counterpart matter's state according to the random measurement data sent from the scanning station.

DAVID FIERSTEIN

resulting polarized photon is our photon X, the one to be teleported, and travels on to Alice. Once it passes through the polarizer, X is an independent photon, no longer entangled. And although *we* know its polarization because of how we set the polarizer, Alice does not. We reuse the same ultraviolet pulse in this way to ensure that Alice has photons A and X at the same time.

Now we arrive at the problem of performing the Bell-state measurement. To do this, Alice combines her two photons (A and X) using a semireflecting mirror, a device that reflects half of the incident light. An individual photon has a 50–50 chance of passing through or being reflected. In quantum terms, the photon goes into a superposition of these two possibilities [*see illustration at right*].



BEAM SPLITTER, or semireflecting mirror (*a*), reflects half the light that hits it and transmits the other half. An individual photon has a 50–50 chance of reflection or transmission. If two identical photons strike the beam splitter at the same time, one from each side (*b*), the reflected and transmitted parts interfere, and the photons lose their individual identities. We will detect one photon in each detector 25 percent of the time, and it is then impossible to say if both photons were reflected or both were transmitted. Only the relative property—that they went to different detectors—is measured.

LAURIE GRACE

Now suppose that two photons strike the mirror from opposite sides, with their paths aligned so that the reflected path of one photon lies along the transmitted path of the other, and vice versa. A detector waits at the end of each path. Ordinarily the two photons would be reflected independently, and there would be a 50 percent chance of them arriving in separate detectors. If the photons are indistinguishable and arrive at the mirror at the same instant, however, quantum interference takes place: some possibilities cancel out and do not occur, whereas others reinforce and occur more often. When the photons interfere, they have only a 25 percent likelihood of ending up in separate detectors. Furthermore, when that occurs it corresponds to detecting one of the four possible Bell states of the two photons—the case that we called "lucky" earlier. The other 75 percent of the time the two photons both end up in one detector, which corresponds to the other three Bell states but does not discriminate among them.

When Alice simultaneously detects one photon in each detector, Bob's photon instantly becomes a replica of Alice's original photon X. We verified that this teleportation occurred by showing that Bob's photon had the polarization that we imposed on photon X. Our experiment was not perfect, but the correct polarization was detected 80 percent of the time (random photons would achieve 50 percent). We demonstrated the procedure with a variety of polarizations: vertical, horizontal, linear at 45 degrees and even a nonlinear kind of polarization called circular polarization.

The most difficult aspect of our Bell-state analyzer is making photons A and X indistinguishable. Even the timing of when the photons arrive could be used to identify which photon is which, so it is important to "erase" the time information carried by the particles. In our experiment, we used a clever trick first suggested by Marek Zukowski of the University of Gdansk: we send the photons through very narrow bandwidth wavelength filters. This process makes the wavelength of the photons very precise, and by Heisenberg's uncertainty relation it smears out the photons in time.

A mind-boggling case arises when the teleported photon was itself entangled with another and thus did not have its own individual polarization. In 1998 my Innsbruck group demonstrated this scenario by giving Alice photon D without polarizing it, so that it was still entangled with photon C. We showed that when the teleportation succeeded, Bob's photon B ended up entangled with C. Thus, the *entanglement* with C had been transmitted from A to B.

Piggyback States

Our experiment clearly demonstrated teleportation, but it had a low rate of success. Because we could identify just one Bell state, we could teleport Alice's photon only 25 percent of the time—the occasions when that state occurred. No complete Bell-state analyzer exists for independent photons or for any two independently created quantum particles, so at present there is no experimentally proven way to improve our scheme's efficiency to 100 percent.

In 1994 a way to circumvent this problem was proposed by Sandu Popescu, then at the University of Cambridge. He suggested that the state to be teleported could be a quantum state riding piggyback on Alice's auxiliary photon A. Francesco De Martini's group at the University of Rome I "La Sapienza" successfully demonstrated this scheme in 1997. The auxiliary pair of photons was entangled according to the photons' locations: photon A was split, as by a beam splitter, and sent to two different parts of Alice's apparatus, with the two alternatives linked by entanglement to a similar splitting of Bob's photon B. The state to be teleported was also carried by Alice's photon A—its polarization state. With both roles played by one photon, detecting all four possible Bell states becomes a standard single-particle measurement: detect Alice's photon in one of two possible locations with one of two possible polarizations. The drawback of the scheme is that if Alice were given a separate unknown state X to be teleported she would somehow have to transfer the state onto the polarization of her photon A, which no one knows how to do in practice.

Polarization of a photon, the feature employed by the Innsbruck and the Rome experiments, is a discrete quantity, in that any polarization state can be expressed as a superposition of just two discrete states, such as vertical and horizontal polarization. The electromagnetic field associated with light also has continuous features that amount to superpositions of an infinite number of basic states. For example, a light beam can be "squeezed," meaning that one of its properties is made extremely precise or noise-free, at the expense of greater randomness in another property (à la Heisenberg). In 1998 Jeffrey Kimble's group at the California Institute of Technology teleported such a squeezed state from one beam of light to another, thus demonstrating teleportation of a continuous feature.

Remarkable as all these experiments are, they are a far cry from quantum teleportation of large objects. There are two essential problems: First, one needs an entangled pair of the same kind of objects. Second, the object to be teleported and the entangled pairs must be sufficiently isolated from the environment. If any information leaks to or from the environment through stray interactions, the objects' quantum states degrade, a process called decoherence. It is hard to imagine how we could achieve such extreme isolation for a large piece of equipment, let alone a living creature that breathes air and radiates heat. But who knows how fast development might go in the future?

Certainly we could use existing technology to teleport elementary states, like those of the photons in our experiment, across distances of a few kilometers and maybe even up to satellites. The technology to teleport states of individual atoms is at hand today: the group led by Serge Haroche at the École Normale Supérieure in Paris has demonstrated entanglement of atoms. The entanglement of molecules and then their teleportation may reasonably be expected within the next decade. What happens beyond that is anybody's guess.

A more important application of teleportation might very well be in the field of quantum computation, where the ordinary notion of bits (0's and 1's) is generalized to quantum bits, or qubits, which can exist as superpositions and entanglements of 0's and 1's. Teleportation could be used to transfer quantum information between quantum processors. Quantum teleporters can also serve as basic components used to build a quantum computer [*see box on page 59*]. The cartoon on the next page illustrates an intriguing situation in which a combination of teleportation and quantum computation could occasionally yield an advantage, almost as if one had received the teleported information instantly instead of having to wait for it to arrive by normal means.

Quantum mechanics is probably one of the profoundest theories ever discovered. The problems that it poses for our everyday intuition about the world led

SKEPTICS CORNER

THE AUTHOR ANSWERS COMMON TELEPORTATION QUESTIONS

Isn't it an exaggeration to call this teleportation? After all, it is only a quantum state that is teleported, not an actual object. This question raises the deeper philosophical one of what we mean by identity. How do we know that an object—say, the car we find in our garage in the morning—is the same one we saw a while ago? When it has all the right features and properties. Quantum physics reinforces this point: particles of the same type in the same quantum state are indistinguishable even in principle. If one could carefully swap all the iron atoms in the car with those from a lump of ore and reproduce the atoms' states exactly, the end result would be identical, at the deepest level, to the original car. Identity cannot mean more than this: being the same in all properties.

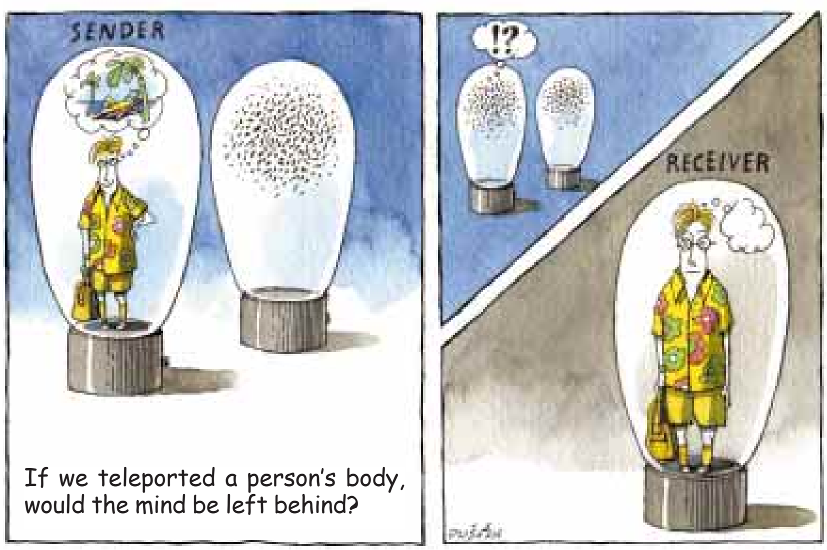
Isn't it more like "quantum faxing"? Faxing produces a copy that is easy to tell apart from the original, whereas a teleported object is indistinguishable even in principle. Moreover, in quantum teleportation the original must be destroyed.

Can we really hope to teleport a complicated object? There are many severe obstacles. First, the object has to be in a pure quantum state, and such states are very fragile. Photons don't interact with air much, so our experiments can be done in the open, but experiments with atoms and larger objects must be done in a vacuum to avoid collisions with gas molecules. Also, the larger an object becomes, the easier it is to disturb its quantum state. A tiny lump of matter would be disturbed even by thermal radiation from the walls of the apparatus. This is why we do not routinely see quantum effects in our everyday world.

Quantum interference, an easier effect to produce than entanglement or teleportation, has been demonstrated with buckyballs, spheres made of 60 carbon atoms. Such work will proceed to larger objects, perhaps even small viruses, but don't hold your breath for it to be repeated with full-size soccer balls!

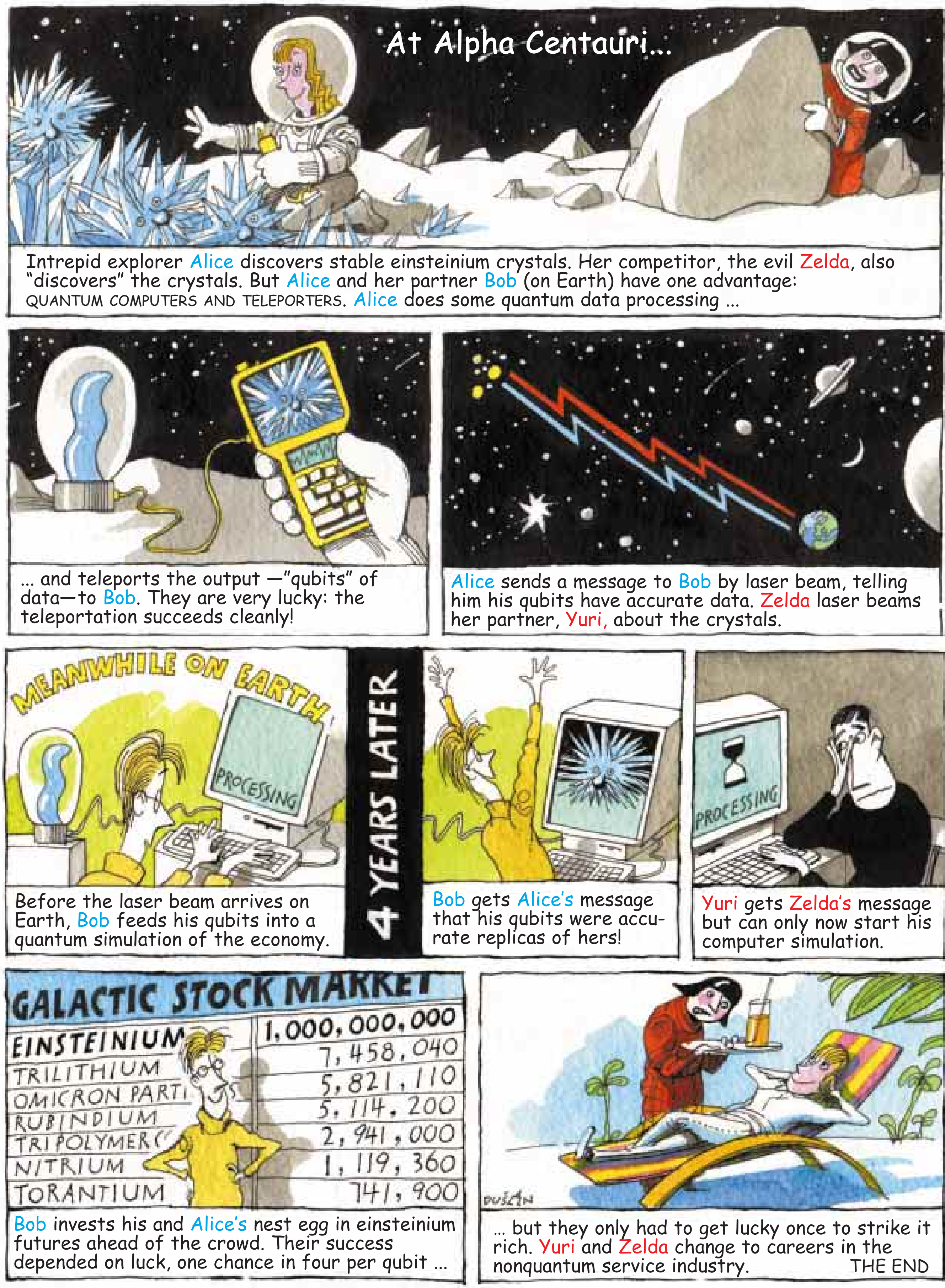
Another problem is the Bell-state measurement. What would it mean to do a Bell-state measurement of a virus consisting of, say, 10^7 atoms? How would we extract the 10^8 bits of information that such a measurement would generate? For an object of just a few grams the numbers become impossible: 10^{24} bits of data.

Would teleporting a person require quantum accuracy? Being in the same quantum state does not seem necessary for being the same person. We change our states all the time and remain the same people—at least as far as we can tell! Conversely, identical twins or biological clones are not "the same people," because they have different memories. Does Heisenberg uncertainty prevent us from replicating a person precisely enough for her to think she was the same as the original? Who knows. It is intriguing, however, that the quantum no-cloning theorem prohibits us from making a perfect replica of a person.



DUSAN PETRICIC

THE QUANTUM ADVENTURES OF ALICE & BOB



DUSAN PETRICIC

Einstein to criticize quantum mechanics very strongly. He insisted that physics should be an attempt to grasp a reality that exists independently of its observation. Yet he realized that we run into deep problems when we try to assign such an independent physical reality to the individual members of an entangled pair. His great counterpart, Danish physicist Niels Bohr, insisted that one has to take into account the whole system—in the case of an entangled pair, the arrangement of both particles together. Einstein's desideratum, the independent real state of each particle, is devoid of meaning for an entangled quantum system.

Quantum teleportation is a direct descendant of the scenarios debated by Einstein and Bohr. When we analyze the experiment, we would run into all kinds of problems if we asked ourselves what the properties of the individual particles *really* are when they are entangled. We have to analyze carefully what it means to "have" a polarization. We cannot escape the conclusion that all we can talk about are certain experimental results obtained by measurements. In our polarization measurement, a click of the detector lets us construct a picture in our mind in which the photon actually "had" a certain polarization at the time of measurement. Yet we must always remember that this is just a made-up story. It is valid only if we talk about that specific experiment, and we should be cautious in using it in other situations.

Indeed, following Bohr, I would argue that we can understand quantum mechanics if we realize that science is not describing how nature *is* but rather expresses what we can *say* about nature. This is where the current value of fundamental experiments such as teleportation lies: in helping us to reach a deeper understanding of our mysterious quantum world. SA

QUANTUM COMPUTERS

Perhaps the most realistic application of quantum teleportation outside of pure physics research is in the field of quantum computation. A conventional digital computer works with bits, which take definite values of 0 or 1, but a quantum computer uses quantum bits, or qubits [see "Quantum Computing with Molecules," by Neil Gershenfeld and Isaac L. Chuang; SCIENTIFIC AMERICAN, June 1998]. Qubits can be in quantum superpositions of 0 and 1 just as a photon can be in a superposition of horizontal and vertical polarization. Indeed, in sending a single photon, the basic quantum teleporter transmits a single qubit of quantum information.

Superpositions of numbers may seem strange, but as the late Rolf Landauer of IBM put it, "When we were little kids learning to count on our very sticky classical fingers, we didn't know about quantum mechanics and superposition. We gained the wrong intuition. We thought that information was classical. We thought that we could hold up three fingers, then four. We didn't realize that there could be a superposition of both."

A quantum computer can work on a superposition of many different inputs at once. For example, it could run an algorithm simultaneously on one million inputs, using only as many qubits as a conventional computer would need bits to run the algorithm once on a single input. Theorists have proved that algorithms running on quantum computers can solve certain problems faster (that is, in fewer computational steps) than any known algorithm running on a classical computer can. The problems include finding items in a database and factoring large numbers, which is of great interest for breaking secret codes.

So far only the most rudimentary elements of quantum computers have been built: logic gates that can process one or two qubits. The realization of even a small-scale quantum computer is still far away. A key problem is transferring quantum data reliably between different logic gates or processors, whether within a single quantum computer or across quantum networks. Quantum teleportation is one solution.

In addition, Daniel Gottesman of Microsoft and Isaac L. Chuang of IBM recently proved that a general-purpose quantum computer can be built out of three basic components: entangled particles, quantum teleporters and gates that operate on a single qubit at a time. This result provides a systematic way to construct two-qubit gates. The trick of building a two-qubit gate from a teleporter is to teleport two qubits from the gate's input to its output, using carefully modified entangled pairs. The entangled pairs are modified in just such a way that the gate's output receives the appropriately processed qubits. Performing quantum logic on two unknown qubits is thus reduced to the tasks of preparing specific predefined entangled states and teleporting. Admittedly, the complete Bell-state measurement needed to teleport with 100 percent success is itself a type of two-qubit processing. *—A.Z.*

LAURIE GRACE

The Author

ANTON ZEILINGER is at the Institute for Experimental Physics at the University of Vienna, having teleported there in 1999 after nine years at the University of Innsbruck. He considers himself very fortunate to have the privilege of working on exactly the mysteries and paradoxes of quantum mechanics that drew him into physics nearly 40 years ago. In his little free time, Zeilinger interacts with classical music and with jazz, loves to ski, and collects antique maps.

Further Information

QUANTUM INFORMATION AND COMPUTATION. Charles H. Bennett in *Physics Today,* Vol. 48, No. 10, pages 24–31; October 1995.

EXPERIMENTAL QUANTUM TELEPORTATION. D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter and A. Zeilinger in *Nature,* Vol. 390, pages 575–579; December 11, 1997.

QUANTUM INFORMATION. Special issue of *Physics World,* Vol. 11, No. 3; March 1998.

QUANTUM THEORY: WEIRD AND WONDERFUL. A. J. Leggett in *Physics World,* Vol. 12, No. 12, pages 73–77; December 1999.

More about quantum teleportation and related physics experiments is available at www.quantum.at on the World Wide Web.