Teleportation: from fantasy to fact and back

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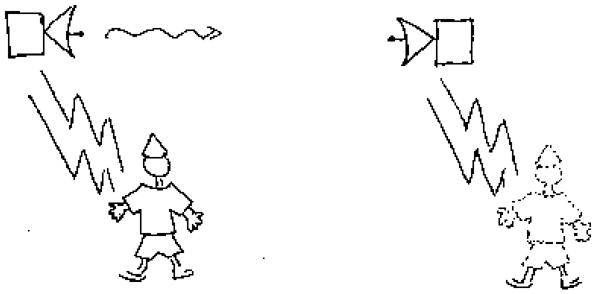
Since a few years, there is a lot of talk about teleportation. And indeed, it has become a reality: researchers have teleported photons, light beams and atoms over distances of up to a few meters. Can this be extended to the type of teleportation we see in the movies, involving people? And if so, when?

First of all, what do we mean with the term "teleportation"? If someone comes up to you saying "Look! I've finally done it: I've discovered how to teleport...," we'd like to be able to decide whether we are even speaking the same language. Now we are all familiar with StarTrek®, so let's take a stab at defining it: *teleportation is some kind of instantaneous "disembodied" transport.*

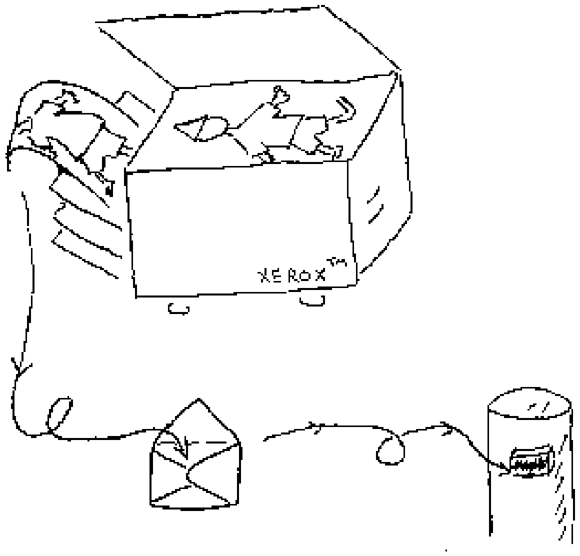
But wait a second! Einstein's theory of relativity — and many decades of experimental evidence back him to the hilt — says that the fastest speed is the speed of light. If we accept this as normative science, then we are going to have to change our definition immediately to: *teleportation is some kind of "disembodied" transport*. This is a little bit better, but we have been rather vague about the "disembodied". Perhaps we should let this figure be our guide to what that might mean:



When you think about this definition for a little while, you realize that we already have lots of examples of teleportation around us every day:

- telephone - transports sound waves as electricity,
- fax - transports an image,
- world wide web - ...

Does this count as teleportation? They are really copying processes. They leave the sound, image, or what-have-you behind, and send the copy shooting across space in some disembodied way. But is this really the definition of teleportation we are looking for? They don't leave a copy of lieutenant Worf behind in our favorite TV program. Or perhaps that's just what they do: they have some machine that measures the positions and momenta and types of atoms throughout the entire person and then sends that information (for example by radio waves) to the place where the body is reconstructed by another machine. Actually, on TV they're also able to recreate the person from the information apparently without a machine to receive it. One thing at a time, please!



What about the original? Well, maybe the machine that measures all those atoms has to slice the person apart to do that. We guess that would be like a photocopy machine with such a hot flash lamp that it vaporizes the original. This wouldn't be a necessary requirement of teleportation, though: as soon as someone worked out how to build a more gentle copying process they could leave the original behind. Would they want to? Would the soul be copied? Would the copy still have to pay taxes if the original were still around? Surely the destruction of the original would raise all sorts of ethical questions! Of course if we could ever learn how to do this we might find new fields of research like "experimental religion." Who knows?

Just how much information are we talking about anyway? The visible human project by the American National Institute of Health requires about 10 Gigabytes (or about ten CD ROMs) to give the full three-dimensional details of a human, down to one millimeter resolution in each direction. If we forget about recognizing atoms and measuring their momenta and just scale that to a resolution of one-atomic length in each direction, that's about 10^{32} bits. This is so much information that even with the best optical fibers conceivable, it would take over one hundred million centuries to transmit all that information (compare this to approximately a hundred centuries of human civilization)! In fact, that is about as long as the universe is old. It would be easier to walk! If we packed all that information into CD ROMs it would fit into a cube almost 1000 kilometers on a side! Enough said?

"But what about the uncertainty principle" we hear you ask, "can you really measure things that accurately?" Well, quantum mechanics tells us that the precision with which we can measure position and momentum of any particle are limited by a very simple formula:

$$\begin{array}{rl} & \text{uncertainty in position} \\ \times & \text{uncertainty in momentum} \\ \gtrsim & \text{Planck's constant.} \end{array}$$

If we measure each atom to within a typical atomic size, the velocities will be uncertain by about 300 meters per second (if the particle weighs as much as a Hydrogen atom, say). This sounds fast, but it's not so bad. The ordinary jiggling of our atoms due to us being at room temperature is more than three times larger. In other words, the uncertainty principle doesn't appear to be too restrictive in terms of how well we can measure those atoms. Of course, that's not all. What about the "quantum state" of those atoms? Does it matter what energy levels they are all in? Do the chemical reactions need to have this information to work once we reassemble the atoms to make a person?

We don't believe that this is true, and neither do a number of other scientists we've asked. But that's hardly a definitive answer. What tends to convince people that the detailed quantum state is not important to get right, is that people routinely go to hospitals for NMR (nuclear magnetic resonance) and ESR (electron spin resonance) scans to see inside them. These scans mix up the quantum states of at least some large number of atoms and nuclei of the people being scanned — usually in their brain! — yet it doesn't seem to disturb their feeling of who they are, or even upset their appetites! (We should note that there are some eminent physicists and mathematicians, like Eugene Wigner, Roger Penrose and others who are not convinced and hold that consciousness requires quantum mechanics to be fully understood.) Thus here again the quantum nature of our atoms and molecules doesn't appear to rule out the copying method for teleportation. The sheer amount of information involved is still mind boggling, though. Perhaps we should start with something smaller, like a subatomic particle.

When we want to teleport something like an electron, everything we have talked about so far changes: the amount of information we have to transport is actually rather small, but suddenly we do have to worry about the uncertainty principle. For example, we cannot find out with arbitrarily high precision in which direction the spinning axis of the electron is oriented, and whether the electron is spinning clockwise or counter-clockwise. This is called the “spin state” of the electron. This lack of precision rules out any teleportation scheme based on measuring, sending and recreating an atomic-scale system. It would violate the uncertainty principle and fundamental laws of quantum mechanics themselves. In fact, this prohibition against copying has itself been risen to the status of a law and is called the no-cloning principle. Notwithstanding this strong prohibition it turns out that we can *still* perfectly teleport the spin state of our electron, and this is where it really gets weird.

To see how we can get around no-cloning. Let’s recall what teleportation should look like: A sender, whom we will call Alice, is given an electron in a spin state that is unknown to her. After “doing something” to the electron (we will talk about that in a minute), she contacts the receiver, whom we will call Bob, to teleport the electron. Alice can tell Bob anything she wants, but can only use a conventional communication channel, like radio or the telephone or even email. It is then Bob’s job to put the spin state of the original electron onto one in his laboratory (he doesn’t need to recreate the matter itself, just the information content!).

But there doesn’t seem to be anything special about Bob here. Anybody could tap the communication channel that Alice is using, and simply apply the same recreation protocol that Bob is using. They too could create a copy of the state in their own lab. But as we have already argued, this would violate no-cloning. So if it really were to work, there would have to be something singling out Bob as the unique receiver. That special something is shared between himself and Alice and it is called quantum entanglement.

Entanglement is a property of two or more quantum particles, like electrons. So let’s think about the entanglement between two electrons: suppose that they always have opposite spin. In other words, whenever the spin state of one electron in any given direction is clockwise, its partner must be spinning counter-clockwise in the same direction. When this is true for all possible spinning axes, the two electrons are called entangled. In fact, there are many kinds of entanglement, but this is the type we’re interested in for now.

So we have three electrons: Alice’s electron whose spin we want to teleport, and a second electron sitting right next to it in her lab. This second electron has an entangled partner that is waiting in Bob’s lab. In principle, there is no limit to how far his lab is away. It might even be in another galaxy!

Now, what is this special “something” that Alice does to her electron? We somehow have to connect the initial electron with Bob’s electron, and we can accomplish that by creating *new* entanglement between the two electrons at Alice’s site. When we *measure* this new entanglement between the two electrons, we actually force them to have opposite spin states. However, the electron that was part of the quantum channel already had a spin state opposite to Bob’s electron, so now the remote electron must be spinning in the same direction as the initial electron.

Hang on! Something is not quite right here. . . , we did not use the radio, the telephone or even email! Without such classical communication, teleportation is instantaneous, and this is forbidden by Einstein’s laws. How can this be resolved?

As we said earlier, there are many kinds of entanglement, and the measurement Alice performed can actually give her *four* different outcomes. Every outcome corresponds to a slightly different type of entanglement, which corresponds to a different type of correlation between the entangled spins. Since she has no way of predicting the measurement result, she has to correct for it at the remote electron. Which means: she has to send the outcome to Bob's lab, where the remote electron is sitting! For that, she uses a conventional communication channel — and in those, the information cannot move faster than the speed of light. Depending on this measurement result, Bob will rotate or flip the electron in a particular way to make the spin axis parallel to the original, and Bob's electron now has the same spin state as Alice's. This is quantum teleportation [1].

What exactly happened here? And what happened to the original electron? According to the no-cloning law, the spin state of the original electron must be destroyed, right? Indeed, by forcing it to become entangled with the electron of the quantum channel, we lost the original spin state. The spin state therefore truly disappears on one end, and it reappears at the remote end with perfect precision!

Another question is: what happened to the information of the spin state when it was teleported? The measurement outcome that we sent to the destination is totally random, so it does not contain any information about the spin state. Somehow, the information appears in Bob's electron instantaneously, but it must be made accessible by the transmission of Alice's measurement result.

The weirdest thing of all is perhaps that nobody needs to know the original spin state of the electron. When the initial electron is itself entangled to a fourth electron, it becomes meaningless to talk about its individual spin state. But the teleportation still works, and afterwards the fourth electron is entangled to Bob's remote electron! We call this *entanglement swapping*, because we start with two entangled pairs of electrons (1,2) and (3,4), and we end up with two entangled electrons (1,4) that have never even seen each other.

You might think this is truly science fiction, but amazingly people have actually done this in the lab. Instead of the spin state of the electron, they used polarization states of photons [2, 3, 4, 5], the quantum state of a light beam [6], and the spin state of a whole atom [7]. In most of these experiments the distance over which the quantum system was teleported was only about one meter (and only nanometers in one case [7]), however, using an optical fiber to share the entanglement, one group managed to perform quantum teleportation over *two kilometers* [4].

Of course, the aim of these experiments is not directed towards the eventual teleportation of people at all. In fact, all this research was carried out in the context of the development of a whole new technology that hopes to take advantage of the weirdness of quantum mechanics. Such technologies include quantum computers, which can do some calculations far more efficiently than the fastest conventional computer ever could. They also include quantum communication which can allow provably secure communication no matter how advanced the technology of an eavesdropper.

Fine, but it's fun to speculate. So let's do just that. Suppose we wanted to simply build a fancy big three-dimensional fax machine which could scan and transmit people to where-ever a receiving machine could rebuild them. We already argued that the best known communication channels would be woefully inadequate to transfer the apparently huge amount of information involved. But technology improves at an incredible rate. Will the limitations to our communication bandwidth always be a barrier to such a feat?

Let's build our speculations on those of others. Back in 1965 Gordon Moore predicted that the complexity and processing power of computer chips would double every 12 to 18 months. Considering that this was shortly after the invention of the transistor it's an amazing prediction. Even more amazing because the semiconductor industry has used this prediction as a roadmap for developing and introducing new technology. This increase in capacity to process information doesn't quite generalize to improved communication bandwidth, which doesn't improve at quite this rate, but let's take this figure as a benchmark for our speculations.

At this rate of doubling, to have a communication channel which could transfer the huge amounts of information we mentioned would take about another 100 years. But don't expect anything before then unless totally new physics is involved. And all this is a 'shortest' time estimate. It's much more likely we'll be stuck to conventional travel, due to the demise of Moore's law. And then we'd never be able to teleport.

In fact, Moore's law is not expected to last beyond about 2017 when transistors would have shrunk to a size where their switching would be controlled by individual electrons. But maybe we can extend its reach. After all, our computer chips are still primarily two-dimensional. If we could deal with the heating problem (say by devising near reversible computer logic gates) we could conceive of building chips with as much complexity in the third dimension as they currently have in those of the silicon substrate. Even without finding a way of shrinking transistors to be smaller than atoms this could give Moore's law room for another 50 years expansion beyond its predicted end. However, this would still leave us way short of our bandwidth goal!

Maybe we don't really need to transmit all the information about a person. What about some sort of intelligent compression routine? Unfortunately, this routine would have to be really good, offering compression factors of millions of billions (not simply a factor of 10, which we might get when we compress with 'zip'). It could be that future biology will help us understand how much information is really important. However, would you want to have your brain compressed? (Actually, compression might not hurt too much, since most people tend to use only 10% of their brain power anyway. . .)

Perhaps the likes of Wigner and Penrose will turn out to be right after all, in that the quantum state is crucial for successful teleportation of a person. But that's OK, because quantum teleportation tells us how to teleport all that quantum stuff without violating any fundamental laws. Of course, to find out who's right, it looks like we'll have no choice but to wait and see. . .

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Professor Braunstein’s most cited work on quantum teleportation was chosen among the ‘top ten [scientific] breakthroughs’ of 1998 by the journal Science.

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