

What is actually teleported?

Asher Peres*

February 1, 2008

Abstract

There are no “unknown quantum states.” It’s a contradiction in terms. Moreover, Alice and Bob are only inanimate objects. They know nothing. What is teleported instantaneously from one system (Alice) to another system (Bob) is the applicability of the preparer’s knowledge to the state of a particular qubit in these systems. The operation necessitates dual classical and quantum channels. Other examples of dual transmission, including “unspeakable information,” will be presented and discussed. This article also includes a narrative of how I remember that quantum teleportation was conceived.

1 Birthdays

It is a great pleasure to participate in the IBM Symposium honoring the 60th birthday of Charles Bennett. I knew some of Bennett’s works as soon as I became interested in quantum information when I visited John Wheeler in Austin in 1979. However I actually met Charlie only in the summer of 1986, when I spent two months at MIT. We both lived in the house of Tom Toffoli, who also was our host at MIT. Tom had bought a dilapidated house in Howard Street and was busy making it livable. His family had the third floor, I was in the second floor in a tiny apartment that was perfect for me, and Charlie, Theo, and her children were in a larger apartment, also in the second floor. The ground floor had not yet been rebuilt and looked like a construction site.

This time is also the 10th anniversary of quantum teleportation, an article that I had the honor of co-authoring with Charles Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, and William Wootters [1]. I shall discuss only the title of that paper, “Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels” (there is no time for more than the title), and I’ll relate what I remember of how this work was conceived.

*Department of Physics, Technion—Israel Institute of Technology, 32000 Haifa, Israel

I apologize if my memory failed in some cases, or I unwittingly distorted the truth.

In October 1992, Bill Wootters (whom I knew from Austin, where he had been a student), sent me an e-mail saying that he and others in Montreal had found an interesting problem, and he asked for my advice. When things became clearer and we thought of writing a paper with six co-authors, we started arguing on every nuance of the text. All this had to be done by e-mail, because we were then scattered in five different places in four countries and eight time zones. Some of us worked while others were sleeping. Charlie quipped “the Sun never sets on our collaboration” and thereby started an argument who was the king who had said that. First we thought of Charles Quint, but after some research work it turned out that it had been Phillip II.

There were some memorable moments while the text was finalized. One Friday afternoon, Claude sent me an e-mail from Paris: what happens if Alice’s particle, whose state has to be teleported, is itself entangled with another one, far away? Will Bob’s particle become entangled with this other particle, without having ever interacted with it? I was puzzled, but it was time to start the traditional Shabbat diner with my family. As we were eating, I suddenly jumped from my seat, ran to the computer and wrote to Claude “mais oui.” He had invented entanglement swapping!

Charlie did most of the editing. When everything looked fine, I sent him an e-mail with subject: *imprimatur* (the seal of approval of the Great Inquisitor). Charlie submitted the paper to PRL, and wrote to us *alea jacta est*, as if we had crossed the Rubicon. Contrary to expectations, our opus was not rejected by the referees. Later we learnt that one of them was David Mermin who gave a very strong recommendation that it had to be published. It’s only more recently that David deconstructed teleportation, and also dense coding [2].

Not only the contents of the teleportation paper are interesting, but also what is *not* in it. There are no acknowledgments for support by NSF, NASA, DARPA, NRL, and other philanthropic agencies. We never submitted a research proposal, that would have been rejected anyway. There was no time for that.¹ Now, let’s start and analyze the title of the paper.

2 Teleporting

I don’t watch TV and I was suspicious of the term teleportation. In my dictionary [3], I found “theoretical transportation of matter through space by converting it into energy and then reconverting it at the terminal point.” I protested that this was not at all what we had in mind, but Charlie reassured me, saying

¹My last research proposal, about 25 years ago, was rejected by BSF as being a “high risk project.” I asked “Which risk? I am risking to waste my time, what are you risking?” The BSF representative explained that this research might not have the expected results. They wanted to be sure that I’ll write a report with all the answers to the questions I had raised.

that we shall cite Penrose’s book. I threatened that if we cite Penrose, I won’t be a co-author. A few days later, Charlie wrote to me that he wanted to use weak measurements and cite Aharonov and Vaidman. This time, I didn’t fall in the trap.

We had other semantic problems. I proposed to write that the quantum state was disembodied and reincarnated. This was found unacceptable. Later, when a newsman asked me whether it was possible to teleport not only the body but also the soul, I answered “only the soul.” Even that is a gross oversimplification.

3 Unknown quantum state

The notion “quantum state” encapsulates what is *known* of the preparation of a system [4]. An unknown quantum state is a contradiction in terms, an oxymoron, just as a “research proposal.” Enrico Fermi said that when there is no surprise, it’s not research.

Anyway, Alice and Bob are not real people. They are inanimate objects. I have seen an optical bench with a label ALICE near a piece of hardware, and BOB near another one. The hardware knows nothing. What is teleported instantaneously from one system (Alice) to another system (Bob) is the applicability of the preparer’s knowledge to the state of a particular qubit in these systems [5]. The preparer whose knowledge is teleported is a real person with a PhD in physics. His name is Chris.

The next item in the title are the dual classical and EPR channels. The text we submitted said “EPR” and the APS editorial office automatically expanded this acronym into “electron paramagnetic resonance.” Somebody caught the error and restored the dignity of Einstein, Podolsky and Rosen.² Dual classical and quantum channels still are an open problem, and I’ll keep them for the end.

4 Quantum archaeology

“The discovery of quantum teleportation grew out of an attempt to identify what other resource, besides actually being in the same place, would enable Alice and Bob to make an optimal measurement of the Peres-Wootters states.” [6] In 1980, during my second visit to John Wheeler at Austin, I shared an office with Bill Wootters who had just submitted his Ph.D. thesis “The acquisition of information from quantum measurements.” In that thesis, there were two observers, the ancestors of Alice and Bob, who used polarized photons to communicate quantum information. Soon after that, I read a fascinating article “Unforgeable Subway Tokens” [7] that I had found during a bibliographic search of Charlie’s works, because I was interested in the thermodynamics of information.

²This does not always happen. See Phys. Rev. A **64**, 042310 (2001), line 12 of text.

Figure 1: sfi.jpg will be supplied separately

In 1989, the Santa Fe Institute organized a workshop on complexity, entropy, and the physics of information. Bill was there on sabbatical leave, and I stayed an extra couple of weeks in order to work with him. We discussed the following problem: given two quantum systems in the same state, can we acquire more information by a joint measurement on both, than by separate measurements on each one, assisted by classical communication (the acronym LOCC didn't exist yet). My intuition was that a joint measurement would in some cases be more efficient, and Bill's intuition was the opposite. I proposed a few simple examples, for which Bill showed that his opinion was correct. As I had to leave SFI, we decided to continue by using bitnet.

5 BITNET

Before e-mail, there was BITNET (“because it’s time net”) a service that was provided gratis by IBM for a few years. IBM is not a philanthropic institution. The strategy was similar to that of drug pushers who offer free cocaine to children. After the kids are hooked, they need the drug and pay dearly for it. The difference is that when IBM discontinued bitnet, it was replaced by another free service, Internet (I don’t know who actually pays for that).

I learnt of bitnet in 1985, when Murray Peshkin at ANL wanted to communicate with me and asked Harry Lipkin at Weizmann what was my address. Harry explained to me the theory, and soon after that Murray sent me a first message: “Welcome to the brave new world of bitnet!” Likewise I taught the magic to Bill and welcomed him in the brave new world. All this was quite primitive by today’s standards, with a 1200 baud modem. After a few other unsuccessful attempts to prove to Bill that joint measurements could be more efficient, I proposed trine states,³ with the property that

$$\langle\psi_1, \psi_2\rangle\langle\psi_2, \psi_3\rangle\langle\psi_3, \psi_1\rangle = -\frac{1}{8}.$$

This is the most negative number that can be obtained with any three states. For example, photons linearly polarized $2\pi/3$ apart, or spin- $\frac{1}{2}$ particles polarized

³A trine is an astrological configuration where three planets make angles of 120° . The word trine was introduced by Charlie, because I disliked Mercedes and no one would take Mitsubishi.

$4\pi/3$ apart, form a trine (note that fermions have to be rotated by 4π to return to the original state). This was a lucky guess. It was recently proved [8] that a trine measurement has the largest entanglement cost of all POVMs.

With a pair of identical trine states, it was impossible to match the mutual information obtainable from a joint measurement by means of a small number of LOCC steps, and Bill devised a “ping-pong” method with a sequence of POVMs, converging to some optimum. These were long and difficult calculations. Bill used a MacIntosh with PASCAL. I had an IBM PS/2 with FORTRAN. When our results agreed, we were pretty sure that there was no numerical error. The optimal mutual information that we could obtain in this way was less than that of a joint measurement. On 15 February 1990, we submitted our paper [9] and naturally ran into trouble with the referees. The typical reaction was: it may be correct, but why is this interesting? As I tried to explain the paper to one of my colleagues at Technion, he quipped with a grimace “it’s only engineering.” Our paper was thus rejected by PRL and I had to convince a reluctant Bill to appeal to the Editorial Board. Our appeal was adjudicated by Tony Leggett and our opus finally appeared on 4 March 1991.

6 Meeting all the teleporters

In October 1992, there was in Dallas a meeting on physics and computation. I introduced Bill Wootters to Charlie, and told him of our work. Charlie already knew it. He pulled a copy from his briefcase, and told us that he was showing it to everybody. Later he introduced me to Gilles Brassard and we immediately were friends, as we could speak French. I also met for the first time Richard Jozsa, who was at that time in Montreal, and Claude Crépeau who was then based in Paris. Gilles invited Bill to give a seminar at Université de Montréal. Everybody but me was there. After the seminar, there was a discussion in Gilles’s office and the question was raised what other resource would enable Alice and Bob, far away from each other, to make an optimal measurement of the trine states. After everyone returned home, Bill sent me a bitnet. I already told the rest of the story.

In June 1993, there was the first Torino workshop on quantum information. Today, there are hundreds of participants in quantum information conferences, but at that time we were only a small number of addicts (Fig. 2). The two gentlemen with bizarre dresses are the most important people: one of them collects money for ISI (Institute for Information Interchange, in Torino) and the other one spends that money and organizes meetings. Everyone in that picture is still active in the field, except Mai-Mai Lam who chose a different career, a real loss for the quantum information community.

Figure 2: The first Torino workshop on quantum information. From left to right, first row: Massimo Palma, Claude Crépeau, Gilles Brassard, Charles Bennett, Bruno Huttner, Umesh Vazirani, David Deutsch; second row: Mai-Mai Lam, Artur Ekert, André Berthiaume, Wojtek Zurek, Asher Peres, Neil Gershenfeld, Bill Wootters, Mario Rasetti, Roger Penrose; third row: Ben Schumacher, Carl Caves, Juan-Pablo Paz, Günter Mahler, Andy Albrecht, Richard Jozsa, Norman Margolus, Giuseppe Castagnoli.

Figure 3: sc-vie.jpg will be supplied separately

7 Group picture

The weather in Villa Gualino was wonderful. Claude lent his camera to André Berthiaume who took a group picture of the six teleporters. When Claude returned to Paris, he arranged to have an article on quantum teleportation appear in the popular scientific magazine *Science et Vie* [10]. The following month, I was a few days in Tournai and bought the journal in a newstand, but not before I checked that my picture was indeed in it. The newstand owner was flabbergasted.

Our next group picture, with exactly the same configuration, was taken twice in Cambridge (UK) in July 1999. Not far from us, there was a big cat, and Charlie later manipulated the photos so that the cat (whom he called *teleportus*) appeared distorted in the first picture, but properly Pauli rotated in the second one. The true name of the cat was Sam [11].

8 Dual classical and quantum channels

Dual classical and quantum channels have a long history in quantum information theory. In the classic BB84 protocol [12], each successful attempt of Alice and

Figure 4: Cambridge double picture to be supplied by Charlie

Bob to produce a random *secret* bit shared by both of them costs one qubit and two public bits of classical information. In the teleportation protocol [1], the remote preparation of one qubit requires one EPR pair, one local qubit, and two bits of public information.

Dual channels are also needed for “unspeakable” quantum information, namely information that cannot be represented by a sequence of discrete symbols. For example, Alice wants to indicate to Bob a direction in space. If they have a common coordinate system to which they can refer, or if they can create one by observing distant fixed stars, Alice simply communicates to Bob the components of a unit vector \mathbf{n} along that direction, or its spherical coordinates θ and ϕ . But if no common coordinate system has been established, all she can do is to send a real physical object, such as a gyroscope, whose orientation is deemed stable.

In the quantum world, the role of the gyroscope is played by a system with large angular momentum. The fidelity of the transmission is usually defined as

$$F = \langle \cos^2(\chi/2) \rangle = (1 + \langle \cos \chi \rangle)/2,$$

where χ is the angle between the true \mathbf{n} and the direction indicated by Bob’s measurement. The physical meaning of F is that the *infidelity* $1 - F = \langle \sin^2(\chi/2) \rangle$ is the mean square error of the measurement [13]. The experimenter’s aim, minimizing the mean square error, is the same as maximizing fidelity.

Massar and Popescu [14] took N parallel spins, polarized along \mathbf{n} , and showed that $1 - F = 1/(N + 2)$. It then came as a surprise that for $N = 2$, parallel spins were not the optimal signal, and a slightly higher fidelity resulted from the use of opposite spins [15]. This better result also required, of course, the transmission of a classical bit, to tell which spin was parallel and which one opposite to \mathbf{n} . This raised the question what was the most efficient signal state for N spins. How quickly will F tend to 1? Peres and Scudo [13] and a Barcelona group [16] showed that the optimal result was a quadratic approach, as illustrated in Fig. 5. This, however necessitates that the N spins be distinguishable (for example, a proton, an electron, and so on). Then there are $N!$ possible ways of labelling these N spins, requiring the transmission of about $N \log_2 N$ classical bits.

Figure 5: Transmission of a direction by N spins. Open circles are the results of Massar and Popescu [14], closed circles are those of Peres and Scudo [13].

9 EPR vs quantum teleportation

In the EPR-Bohm scenario [17], Alice and Bob share a pair of spin- $\frac{1}{2}$ particles in a singlet state. Alice measures a component of her spin, and then she knows *instantaneously* the corresponding component of Bob's spin [18], namely Bob's result if he measures (has measured, will measure) the same component of his spin. However, Alice cannot choose the result she obtains.

In the teleportation scenario, Chris chooses the state of the qubit he prepares near the apparatus called ALICE. He also prepares an EPR pair and places the two entangled spins with ALICE and BOB, far away from each other. Then ALICE is used to measure the two spins in her location so that Chris knows which one of the four possible results was obtained; and then Chris *immediately* knows the state of the spin located at BOB.

The scenario could stop here. There is no compelling reason to transmit the two classical bits to BOB, if we are satisfied with a rotated *teleportus* as in Fig. 4a. But then the process would not have been called teleportation and attracted so much attention ...

References

- [1] C. H. Bennett *et al.*, Phys. Rev. Letters, **70**, 1895 (1993).
- [2] N. D. Mermin, Phys. Rev. A **65**, 012320 (2002); *ibid.* **66**, 032308 (2002).
- [3] *Webster's New World Dictionary of the American Language* (Collins, New York, 1974).
- [4] A. Peres, Am. J. Phys. **52**, 644 (1984).
- [5] C. A. Fuchs and A. Peres, Physics Today **53** (3) 70 (2000).
- [6] C. H. Bennett *et al.*, Phys. Rev. A **59**, 1070 (1999).
- [7] C. H. Bennett *et al.*, *Advances in Cryptology* (Proceedings of Crypto-82, Plenum, New York, 1983) p. 267.

- [8] R. Jozsa *et al.*, quant-ph/0303167.
- [9] A. Peres and W. K. Wootters, Phys. Rev. Lett. **66**, 1119 (1991).
- [10] H. Guillemot, Science et Vie, no. **910**, 40 (1993).
- [11] Lei Poo, private communication (1999).
- [12] C.H. Bennett and G. Brassard, in *Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, Bangalore, India* (IEEE, New York, 1984) p. 175.
- [13] A. Peres and P. F. Scudo, Phys. Rev. Lett. **86**, 4106 (2001).
- [14] S. Massar and S. Popescu, Phys. Rev. Lett. **74**, 1259 (1995).
- [15] N. Gisin and S. Popescu, Phys. Rev. Lett. **83**, 432 (1999).
- [16] E. Bagan, M. Baig, A. Brey, R. Muñoz-Tapia, and R. Tarrach, Phys. Rev. A **63**, 052309 (2001).
- [17] D. Bohm, *Quantum Theory* (Prentice-Hall, New York, 1951) p. 614.
- [18] A. Peres, Phys. Rev. A **61**, 022117 (2000).