

What is actually teleported?

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There are no “unknown quantum states.” The phrase is self-contradictory. 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 of the state of a particular qubit in the systems. The operation necessitates the use of dual classical and quantum channels. Other examples of dual transmission, including “unspeakable information,” are presented and discussed. This paper also includes a narrative of my recollections of how quantum teleportation was conceived.

Landmarks

It was a great pleasure to participate in the May 2003 symposium at the IBM Thomas J. Watson Research Center honoring the sixtieth birthday of Charles Bennett. I learned of Charlie’s work when I became interested in quantum information upon visiting John Wheeler at the University of Texas at Austin in 1979. However, I actually met Charlie in the summer of 1986, when I spent two months at MIT. We both lived in the house of Tom Toffoli, who was also our host at MIT. Tom had bought a dilapidated house on Howard Street and was busy making it livable. His family occupied the third floor; I was on the second floor in a tiny apartment that was perfect for me. Charlie, Theo, and her children were in a larger apartment, also on the second floor. The ground floor had not yet been rebuilt and looked like a construction site.

The symposium also marked the tenth anniversary of the discovery of quantum teleportation, described in the paper that I had the honor of coauthoring with Charles Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, and William Wootters [1]. I shall discuss only the title of the paper, “Teleporting an Unknown Quantum State via Dual Classical and Einstein–Podolsky–Rosen Channels,” and relate what I recall of the conception of the work. I apologize if my recollections are imperfect or if I have unwittingly distorted any aspect of the story.

In October 1992, Bill Wootters (whom I knew from The University of Texas at Austin, where he had been a student) sent me an e-mail note indicating that he and others at the University of 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 coauthors, 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 about which king had said that. First we thought it might have been Charles Quint, but after some research work we learned that it was Philip II of Spain.

There were some memorable moments while the text was finalized. One Friday afternoon, Claude Crépeau sent me an e-mail note 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 dinner 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 reinvented entanglement swapping [2]!

Charlie did most of the editing. When everything looked fine, I sent him an e-mail note with a subject designation of *imprimatur* (the seal of approval of the Great Inquisitor). Charlie submitted the paper to *Physical Review Letters* (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 learned that one of them was David Mermin, who gave a very strong recommendation that it be published. It is only more recently that David has deconstructed teleportation, and also dense coding [3].

Not only are the contents of the teleportation paper interesting, but also what is *not* in it. There are no

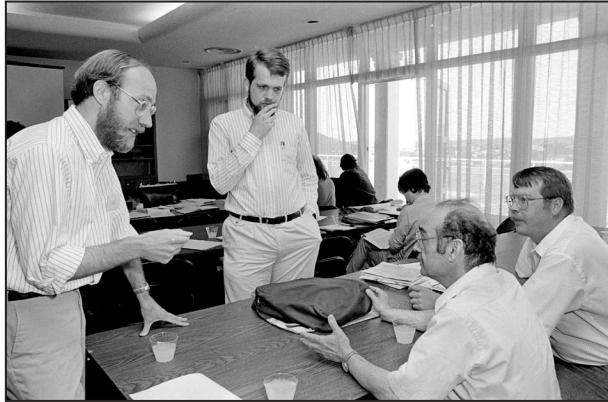


Figure 1

Informal discussion at the 1989 SFI Workshop on Complexity, Entropy, and Physics of Information. From left to right: William Wootters (Williams College, Massachusetts), Benjamin Schumacher (Kenyon College, Ohio), Asher Peres (Technion, Israel), and Warner Miller (Kirtland Air Force Base, New Mexico). Photograph by Cary Herz: © 1989, reproduced with permission.

acknowledgments for support by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Defense Advanced Research Projects Agency (DARPA), the Naval Research Laboratory (NRL), or other research support agencies. We never submitted a research proposal: It would have been rejected anyway. There was no time for that.¹ Next, let's start to analyze the title of the paper.

Teleporting

I don't watch television and was suspicious of the term *teleportation*. In my dictionary [4] I found the definition, "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 that we would cite Roger Penrose's 1989 book, *The Emperor's New Mind* [5]. I threatened that if we cited it, I would not be a coauthor. A few days later, Charlie wrote to me that he wanted to use weak measurements and cite a paper by Aharonov and Vaidman. This time, I didn't fall into the trap. Actually, we could have cited another paper by those authors [6], which introduced the use of *dense coding*. However, the presentation of this technique was so bizarre

¹ My last research proposal, about 25 years ago, was rejected by the United States-Israel Binational Science Foundation (BSF) as being a "high-risk project." I asked: Which risk? I am risking the wasting of 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 would write a report with all the answers to the questions I had raised.

that the paper was not noticed then by the small quantum information community.

We had other semantic problems: I proposed stating that the quantum state was disembodied and reincarnated. This was found to be 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 was a gross oversimplification.

Unknown quantum state

The notion of a quantum state encapsulates what is *known* of the preparation of a system [7]. An unknown quantum state is self-contradictory, an oxymoron, just as is 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 of the state of a particular qubit in these systems [8]. The preparer whose knowledge is teleported is Chris, a real person.

The next portion of the title pertains to the dual classical and EPR channels. The text we submitted contained the acronym "EPR," which was expanded by PRL into "electron paramagnetic resonance." Somebody caught the error and restored the dignity of Einstein, Podolsky, and Rosen.² Dual classical and quantum channels continue to be an open problem. I'll discuss them later.

Quantum archaeology

As indicated by Charlie, "the discovery of quantum teleportation, incidentally, 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" [9]. In 1980, during my second visit to John Wheeler at the University of Texas 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 paper by Charlie entitled "Unforgeable Subway Tokens" [10] that I had found during a bibliographic search of his work, because I was interested in the thermodynamics of information.

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



Figure 2

The first Torino Workshop on Quantum Information (June 1993). 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. Courtesy of the Institute for Scientific Interchange, Torino, Italy.

In 1989, the Santa Fe Institute (SFI) organized a workshop on complexity, entropy, and the physics of information (**Figure 1**). 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 (local operation and classical communication) did not yet exist.] 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. After I left the SFI, we continued to communicate by BITNET (Because It's Time Network), a predecessor of today's Internet. I learned of the existence of BITNET in 1985, when Murray Peshkin at the Argonne National Laboratory wanted to communicate with me and asked Harry Lipkin at the Weizmann Institute for my electronic address. With Harry's help, I was able to receive my first electronic message from Murray: "Welcome to the brave new world of bitnet!" Likewise, I taught the magic to Bill and welcomed him

to 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 $4\pi/3$ 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 [11] that a trine measurement has the largest entanglement cost of all positive operator valued measures (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

³ A trine is an astrological configuration in which three planets make angles of 120° . The word *trine* was introduced by Charlie.

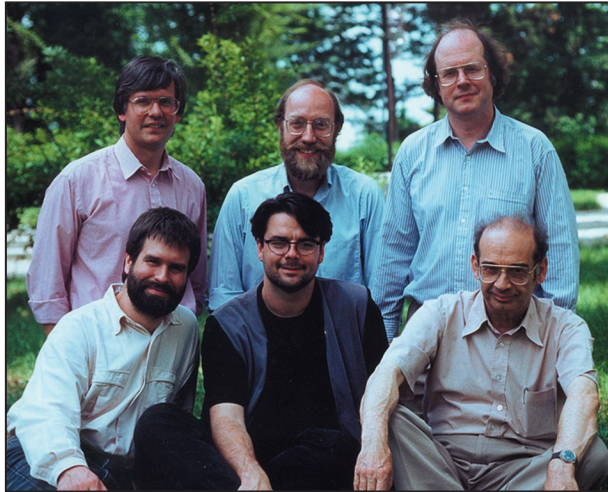


Figure 3

The six “fathers” of the 1989 paper on quantum teleportation at the 1993 Torino Workshop on Quantum Information. Clockwise from upper left: Richard Jozsa (Université de Montréal), William Wootters (Williams College, Massachusetts), Charles Bennett (IBM, Yorktown Heights, New York), Asher Peres (Technion, Israel), Claude Crépeau (Laboratoire d’Informatique de l’École Normale Supérieure, Paris), and Gilles Brassard (University of Montreal). Photograph by André Berthiaume, reproduced with permission.

and difficult calculations. Bill used a Macintosh** PC with PASCAL software. I had an IBM PS/2* and used 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 February 15, 1990, we submitted a paper [12] on the work, and naturally ran into trouble with the referees. The typical reaction was this: It may be correct, but why is it 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 its editorial board. Our appeal was adjudicated by Tony Leggett at the University of Illinois, and our opus finally appeared on March 4, 1991.

Meeting all the teleporters

In October 1992, there was a meeting in Dallas on physics and computation. I informed Charlie of my work with Bill Wootters; he was already aware of it. He pulled a copy from his briefcase and told me that he was showing it to everybody. Later he introduced me to Gilles Brassard, and we immediately became friends, since 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 the Université de Montréal. Although I wasn’t there (Richard, Charlie, and Claude were), I was told that during the question period after the talk, Charlie asked whether the two participants could achieve the optimal result if they shared an EPR pair. The discussion continued in Gilles’s office. The problem was 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 e-mailed me about the problem. I’ve already told the rest of the story.

The first Torino, Italy, workshop on quantum information was held in June 1993. Today, there are hundreds of participants in quantum information conferences, but at that time we were only a small number of adherents (**Figure 2**). The two gentlemen with neat suits are the most important people: One of them collects money for ISI (the 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 for Mai-Mai Lam, who chose a different career—a real loss for the quantum information community.

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 (**Figure 3**). When Claude returned to Paris, he arranged to have an article on quantum teleportation appear in the popular scientific magazine *Science et Vie* [13]. The article contained a picture entitled “Les pères de la téléportation.”⁴ The following month, I spent a few days in Tournai and bought a copy of the magazine at a newsstand, but not before checking to see that my picture was indeed in it. The newsstand owner was flabbergasted.

Our next group picture, with exactly the same configuration, was taken twice in Cambridge (UK) in July 1999 (**Figure 4**). Not far from us there was a big cat, and Charlie later manipulated the picture so that the cat (whom he called the *teleportus*) appeared distorted in the first picture, but properly Pauli-rotated in the second one.

A third group picture, in the same canonical positions, was taken during the IBM symposium celebrating Charlie’s sixtieth birthday (**Figure 5**).

Dual classical and quantum channels

Dual classical and quantum channels have a long history in quantum information theory. In the classic BB84

*Trademark or registered trademark of International Business Machines Corporation.

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⁴ The French word *pères* (pronounced “pair”) means *fathers*. My name does not contain the accent grave.



Figure 4

The same group of authors, together again in 1999, in Cambridge, UK. They are shown witnessing the application of their technique to a small furry animal. In the photograph on the left, the teleportedus has not yet undergone the final corrective Pauli transformation. Photographic trickery by Charles Bennett, reproduced with permission.

protocol [14], each successful attempt by Alice and 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, suppose that Alice wants to indicate a direction in space to Bob. 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 having a 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 [15]. The experimenter’s



Figure 5

The authors convene once more, in 2003, at the Charles Bennett 60th Birthday Symposium at the IBM Thomas J. Watson Research Center in Yorktown Heights, New York. Photograph by Charles Bennett, reproduced with permission.

aim, minimizing the mean square error, is the same as maximizing fidelity.

Massar and Popescu [16] assumed that Alice sent N particles having parallel spins, polarized along $\mathbf{n}$, and

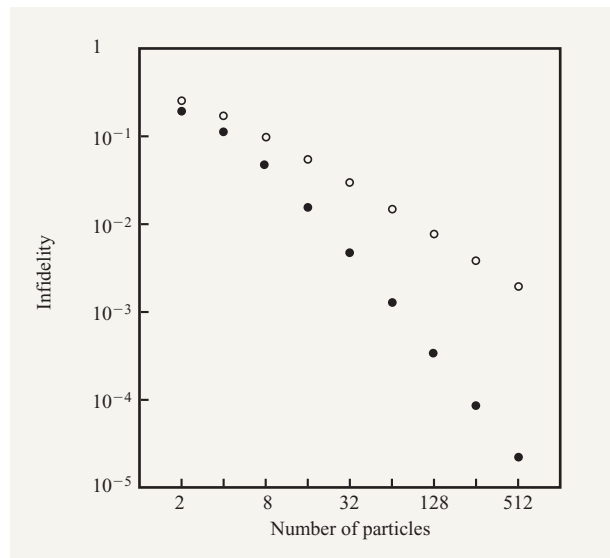


Figure 6

Transmission of a direction by N spins. Open circles are the results of Massar and Popescu [16], closed circles are those of Peres and Scudo [15].

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 [17]. This better result also required, of course, the transmission of a classical bit, to indicate which spin was parallel and which one opposite to **n**. This raised the question of what was the most efficient signal state for N spins: How quickly does F approach 1? Peres and Scudo [15] and a Barcelona group [18] showed that the optimal result was a quadratic approach, as illustrated in **Figure 6**. 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 labeling these N spins, requiring the transmission of about $N \log_2 N$ classical bits.

EPR vs. quantum teleportation

In the EPR-Bohm scenario [19], 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 *instantaneously* knows the corresponding component of Bob's spin [20], namely Bob's result if he measures (whether before or after Alice does) 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 designated as 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 the left-hand part of Figure 4. But then the process would not have been called teleportation and attracted so much attention. . .

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Received April 29, 2003; accepted for publication June 2, 2003

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