The Einstein-Podolsky-Rosen paradox (1935) is reexamined in the light of Shannon’s information theory (1948). The EPR argument did not take into account that the observers’ information was localized, like any other physical object.

I had the privilege of meeting Jim Cushing in 1986, during a conference that Daniel Greenberger had organized in the World Trade Center in New York City [1]. Some time later Cushing sent me a copy of his book [2], where our encounter is related in a footnote:

“I mentioned to Peres that his position appeared to be an instrumentalist one. He replied with no apparent discomfort that others had told him that before. For a physicist’s statement on an instrumentalist interpretation of quantum mechanics, see Peres (1988) [3].”

Jim had asked me that question with the same tone as if he were asking whether I was a cannibal. For a more recent discussion on this subject, see [4].

On the other hand, I never had the privilege of meeting Albert Einstein. He died when I was an undergraduate. I had always been fascinated by Einstein, as any normal Jewish boy would be, and later in my life I even got the impression that I came to know him personally. This is because my PhD thesis advisor was Nathan Rosen, who had been a close collaborator of Einstein. Together they built the Einstein-Rosen bridge in General Relativity [5], and together with Podolsky they formulated the famous EPR paradox [6]. Rosen told me many anecdotes about Einstein and his reactions to various events. (Rosen’s wife Hanna, who was an accomplished pianist, gave piano accompaniment to Einstein who played the violin.)

My first encounter with the EPR paper occurred when I was a graduate student, circa 1958. The subject of my research was gravitational radiation. At that time, I was rather ignorant of quantum theory, having graduated in mechanical and nuclear engineering, not in physics. One day, I came into Rosen’s office, and I found him sorting out his papers. On the ground, there were cartons full of old reprints, with the characteristic green covers of The Physical Review. One of them read: “Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?” The authors were A. Einstein, B. Podolsky, and N. Rosen. I thought that this would be a nice item to have in my collection of reprints, and politely asked:

“Professor Rosen, may I take one of these reprints?”

He looked concerned.

“Ha, how many are left?”

We counted them, which was not difficult: there were two. Then he said, with some hesitation,

“Well, if there are two, you may have one.”

This is how I acquired the last available reprint of the famous article of Einstein, Podolsky, and Rosen.

Let us have a look at that wonderful paper. You will immediately notice that Eqs. (7) and (8) involve entangled wave-functions, and indeed the whole issue is about the physical consequences of such an entanglement. Entangled wave-functions were not new at that time: you can find one, for example, in Eq. (10) of Rosen’s 1931 seminal paper on the ground state of the hydrogen molecule [7], which is probably more famous among chemists than the EPR paper is among physicists.

Some time after that work, Rosen became a post-doc of Einstein at the Institute of Advanced Studies in Princeton. One day, at the traditional 3 o’clock tea, Rosen mentioned to Einstein a fundamental issue of interpretation related to entangled wave-functions. Einstein immediately saw the implications for his long standing disagreement with Bohr. As they discussed the problem, Boris Podolsky joined the conversation, and later proposed to write an article. Einstein acquiesced. When he later saw the text, he disliked the formal approach, but agreed to its publication. Then, as soon as the EPR article appeared, Podolsky released its contents to the New York Times (4 May 1935, page 11) in a way implying that the authors had found that quantum mechanics was faulty. This infuriated Einstein, who after that no longer spoke with Podolsky.

The EPR “paradox” drew immediate attention. Niels Bohr [8] found the reasoning faulty, because it contradicted his complementarity principle. Bell, in his first article on hidden variables and contextuality [9], wrote “the Einstein-Podolsky-Rosen paradox is resolved in the way which Einstein would have liked least.” Actually, the example given by Bell in the proof of his celebrated theorem [10] is based on a much simpler entangled system: two spin- particles in a singlet state [11]. In 1991, David Mermin came to Technion to give the annual Wunsch Lecture. He said that the EPR paper was wrong. After the talk, there was as usual a discussion period. Nathan Rosen politely commented: the paper is not wrong, it makes some assumptions, and then draws the logical con-
conclusions; the assumptions were wrong.

The EPR article was not wrong, but it had been written too early. Some years later, in 1948, Claude Shannon published his theory of information [12] (and it took many more years before the latter was included in the physicist’s toolbox). Shannon was employed by the Bell Telephone Company and his problem was to make communication more efficient. Shannon showed that information could be given a quantitative measure, that he called 

\[ \rho \]

entropy. It was later proved that Shannon’s entropy is fully equivalent to ordinary thermodynamical entropy [13]. Information can be converted to heat and can perform work. Information is not just an abstract notion [14]. It requires a physical carrier, and the latter is (approximately) localized. After all, it was the business of the Bell Telephone Company to transport information from one telephone to another telephone, in a different location.

In the EPR article, the authors complain that “it is possible to assign two different wave functions to ... the second system,” and then, in the penultimate paragraph, they use the word simultaneous no less than four times, a surprising expression for people who knew very well that this term was undefined in the theory of relativity. Let us examine this issue with Bohm’s singlet model. One observer, conventionally called Alice, measures the \( z \)-component of the spin of her particle and find \( +\hbar/2 \). Then she immediately knows that if another distant observer, Bob, measures (or has measured, or will measure) the \( z \)-component of the spin of his particle, the result is certainly \( -\hbar/2 \). One can then ask: when does Bob’s particle acquire the state with \( s_z = -\hbar/2 \)?

This question has two answers. The first answer is that the question is meaningless — this is undoubtedly true. The second answer is that, although the question is meaningless, it has a definite answer: Bob’s particle acquires this state instantaneously. This then raises a new question: in which Lorentz frame is it instantaneous? Here, there is also a definite answer: it is instantaneous in the Lorentz frame that we arbitrarily choose to perform our calculations [15]. Lorentz frames are not material objects: they exist only in our imagination.

When Alice measures her spin, the information she gets is localized at her position, and will remain so until she decides to broadcast it. Absolutely nothing happens at Bob’s location. From Bob’s point of view, all spin directions are equally probable, as can be verified experimentally by repeating the experiment many times with a large number of singlets without taking in consideration Alice’s results. Thus, after each one of her measurements, Alice assigns a definite pure state to Bob’s particle, while from Bob’s point of view the state is completely random (\( \rho \) is proportional to the unit matrix). It is only if and when Alice informs Bob of the result she got (by mail, telephone, radio, or by means of any other material carrier, which is naturally restricted to the speed of light) that Bob realizes that his particle has a definite pure state. Until then, the two observers can legitimately ascribe different quantum states to the same system. For Bob, the state of his particle suddenly changes, not because anything happens to that particle, but because Bob receives information about a distant event. Quantum states are not physical objects: they exist only in our imagination.

In summary, the question raised by EPR “Can quantum-mechanical description of physical reality be considered complete?” has a positive answer. However, reality may be different for different observers.

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