Quantum Entanglement: epistemological overview

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Abstract

In this paper, we will introduce a brief history of Quantum Entanglement (QE) with reference to important works: 1) Jaeger (Jaeger 2010) and 2) Emerson (Emerson, 2009).

1 Non-locality: background

Quantum Mechanics has posed philosophical problems from its beginnings. Main discussions deals with the notion of quantum state. Some philosophers of science argue that quantum states represent potential, not reality. but, quantum nonlocal entanglement, one of these problematic states, is a demonstrated fact and it is not a potentiality. Quantum entangled systems are probabilistically correlated across distances.

The entanglement phenomenon is as an extraordinary degree of correlation between states of quantum systems. This correlation cannot be given an explanation in terms of common cause. QE (quantum entanglment) can occur between two or more quantum systems. Most interesting is the case when the correlations occur between systems that are space-like separated. This means that changes made to one system are immediately correlated with changes in a distant system (even

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though there is no time for a signal to travel between them). We speak in this case of non-local correlations. From mathematical point of view, two particles, 1 and 2, whose states (pure) can be represented by the state vectors ψ_1 and ψ_2. We can represent the composite two-particle system by wave-function ψ_{12}. Now, if the particles are unentangled, the composite state is the tensor product of the states of the components,

$$\psi_{12} = \psi_1 \otimes \psi_2 \tag{1.1}$$

This state is said to be factorable or separable. The state is entangled if an only if it cannot be factored:

$$\psi_{12} \neq \psi_1 \otimes \psi_2 \tag{1.2}$$

For mixed states, which must be represented by density operators rather than state vectors, the definition of entanglement is generalized: an entangled mixed state is one that cannot be written as a convex combination of products:

$$\rho_{12} = \sum_i p_i(\rho_{1i} \otimes \rho_{2i}) \tag{1.3}$$

where the sum of the p_i is equal to unity. This definition is for a bipartite system, that is, a composite system of only two parts, 1 and 2. For multipartite mixed quantum systems the situation is more complicated; there is no single acceptable entanglement measure applicable to the full set of possible states of systems having a greater number of parts. The search for a fully general definition and measure of entanglement remains an active area of research. As we know, despite the fact that the phenomenon of entanglement was recognized very early on in the development of QM, it remains one of the least understood aspects of quantum theory. A few philosophers of science and theoretical physicists explain these apparently counterintuitive phenomena as evidence of an acausal relational rather than causal dynamic world. Others approaches propose an atemporal models, superluminal models. Physics has struggled with non-locality for centuries. In its current guise, QE poses fundamental questions. Several contemporary philosophers, physicists, and mathematicians suggest that quantum non-locality requires us to revise many of our basic notions.

In Western science, the philosophical problem of action-at-a-distance or non-locality is at least four hundred years old. In the 17th century, Newton had introduced non-local action at a distance by suggesting that gravity is exerted between masses according to an inverse square law instantaneously at any distance.

Almost two hundred years later, studying rotational motion, Mach restated the problem, hypothesizing that each particle in the universe is instantaneously affected by every other particle.

In 1916, Einstein sought to remove action-at-a-distance in General Relativity (GR). In that formulation, local effects expressed as gravity (space-time curvature) were propagated at the speed of light. But the statistical nature of QM required the reemergence of non-locality. In the 20th century, non-locality appeared as a necessary corollary of the probabilistic nature of QM. As we know, in 1927, Max Born reemphasized the probabilistic nature of QM. He argued that the Schrödinger equation did not represent an electron (or other particle) as spread out over an area of space, but was instead a probabilistic estimate of its location. Following Born's interpretation, the entanglement (after Bell Theorem) is not only probabilistic correlation, but a real phenomenon. Although QM is the widely accepted probabilistic view of the world, some theorists continue to wonder if we could describe reality more concretely (i.e EPR argument, see Bohm's Interpretation)[1] In fact, EPR paper was the first that drew attention to the phenomenon of entanglement. As we have seen, in the introduction of thesis, the phenomenon of entanglement in MQ was taken by EPR as reductio ad absurdum. They show that there is a fundamental flaw with the theory: "since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system". Since QM implies such an "absurd" situation, QM must be incomplete at best. QE, however, precisely is such a non-classical relationship between quantum particles whereby changes made to one particle of an entangled pair can lead to changes in the other particle even though they no longer interact. Shortly after the appearance of the EPR paper, Schrödinger coined the term "entanglement" (Verschränkung) to describe this phenomenon. The first published occurrence of the term is in an article of his, written in English, which appeared in October of 1935. In this article, Schrödinger places the phenomenon of entanglement at the center of quantum theory:

When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endow-

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[1] In the Bohmian Mechanics (BM) interpretation of QM, particles maintain a specific position and velocity but they cannot be detected. Any measurement destroys the pilot wave (and information) associated with the particle. Like orthodox QM, Bohmian mechanics is in many respects, nonlocal. The "hidden variables" supplies information shared by entangled particles. A change in any state (for example "up spin") of one particle of an entangled pair is immediately made in the corresponding state of the other (for example, "down spin").

ing each of them with a representative of its own. I would not call that one but rather the characteristic trait of QM, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled (Schrödinger 1935).

Despite this early recognition of the importance of the phenomenon, very little effort or progress was made over the next thirty years in developing a theory of entanglement or in answering Schrödinger's concerns regarding how this phenomenon could be consistent with relativity. It would be almost thirty years before another significant step toward a theory of entanglement would be made with John Bell's seminal (1964) paper on quantum non-locality. In that paper Bell considered a pair of particles in the singlet state that had interacted in the past, had become entangled, and then had separated. He derived an inequality involving the probabilities of various outcomes of measurements performed on these entangled particles that any local definite (i.e., hidden-variable) theory must satisfy. He then showed that QM violates this inequality; that is, the experimentally well-confirmed quantum correlations among entangled particles cannot be locally explained. BellŠs theorem does not rule out the possibility of hidden-variable theories in general, only those hidden-variable theories that are local. Indeed, Bell took the lesson of his theorem to be that any theory that reproduces the experimentally well-confirmed predictions of QM must be non-local. He writes:

It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty . . . This [non-locality] is characteristic, according to the result to be proved here, of any theory which reproduces exactly the quantum mechanical predictions (Bell 1964).

Bell (Bell, 1964) showed that no physical theory of local hidden variables could produce the results of QM. Bell showed that either QM must be reconciled with nonlocality (not necessarily contravening SR) or the objective reality of particle properties (e.g., quantum states) had to be denied. Modifying the EPR thought experiment, Bell proposed a two measurement experiment of a pair of distant, entangled particles. The first would test predictions of "quantum theory", the second would test "local reality" predictions, espoused by the EPR paper Bell's predictions were so explicit that they were later tested and verified. Although his theory has been interpreted that way, Bell did not totally dismiss "hidden variables.'" His inequalities (only) demonstrate that "local" hidden variables contradict predictions of QM. Bell affirming that causality at the quantum level must be nonlocal.

What is remarkable about Bell's theorem is that it is a general result arising from an analysis of the relevant probabilities of various joint measurement outcomes, and does not depend on the details of any hidden-variable theory or even on the details of QM itself. Since then a number of different Bell-type inequalities have been derived, such as the Clauser, Horne, Shimony, and Holt (CHSH, 1969) inequality, which has proven particularly useful for experimental tests of non-locality. Following Bell, a number of experiments demonstrated not only that non-locality is a genuine physical phenomenon characteristic of our world (e.g., Aspect et al. 1982), but also that non-locality can be experimentally produced,controlled, and harnessed for various applications.
Another theoretical development came with Jarrett's (Jarrett, 1984) analysis showing that Bell's locality condition can be viewed as the conjunction of two logically independent conditions: a "controllable" locality, which if violated would conflict with special relativity, and an "uncontrollable" locality whose violation might "peacefully coexist" with relativity (Shimony,1984 and an opposing point of view see Maudlin (2002)). Hence, the violation of Bell's inequality could logically be due to a violation of one, the other, or both of these locality conditions. Jarrett's analysis has been taken by some to provide the solution to Schrödinger's worries about a conflict between quantum theory and relativity, as long as one assumes that the violation is in fact solely a violation of the uncontrollable locality.

2 Quantum Nonlocality After Bell: Not only does God play dice, but he plays with nonlocal dice.

From experimental point of view until 1990 no one paid much attention to quantum nonlocality. But in the 1990's two things changed. First, a conceptual breakthrough happened thanks to Ekert and to his adviser Deutsch (Deutsch, 1985). They showed that quantum nonlocality could be exploited to establish a cryptographic key between two distant partners and that the confidentiality of the key could be tested by means of BellŠs inequality. This was the first time that someone suggested that quantum nonlocality is not only real, but that it could even be of some use. Today, according Gisin (Gisin,2005), we can say that "not only does God play dice, but he plays with nonlocal dice!". According Gisin, QM predicts the existence of a totally new kind of correlation that will never have any kind of mechanical explanation. And experiments confirm this: Nature is able to produce the same randomness at several locations, possibly space-like separated. The standard explanation is "entanglement", but this is just a word, with a precise technical definition. Still words are useful to name objects and concepts. However, it remains to understand the concept. Entanglement is a new explanation for correlations. Quantum correlations simply happen. Entanglement appears at the same conceptual level as local causes and effects. It is a primitive concept, not reducible to local causes and effects. Entanglement describes "correlations without "correlata" in a holistic view. In other worlds, quantum correlation is not a correlation between 2 events, but a single event that manifests itself at 2 locations. Historically this was part of the suspicion that entanglement was not really real, nothing more than some exotic particles that live for merely a tiny fraction of a second. But today we see a growing number of remarkable experiments mastering entanglement. In few words, entanglement exists and is going to affect future technology. It is a radically new concept, requiring new words and a new conceptual category.

From foundational point of view, years after Bell demonstrated the need for quantum nonlocality, theoreticians continued to ask about a relationship between the structures described by QM and local reality. Zukowski (Zukowski et al 2008)and Brukner (Brukner et.al 2004)(Institute for Experimental Physics, Vienna) notes, "No local realistic theory agrees with all predictions of QM as quantitatively expressed by violation of Bell's inequalities. Local realism [...] is based on everyday experience and classical physics [...] and supposes that measurement results are predetermined by the properties the particles carry prior to and independent of observations. Locality supposes that these results are independent of any action at "spacelike separations". After Bell, quantum nonlocality was the practical basis for quantum computing and quantum cryptography. In 1967, Simon Kochen and Ernst Specker (Kochen et al 1968) developed a strong position against Bohmian and similar hidden variable arguments for interpreting QM as deterministic. Kochen and Specker showed that the apparently QM equivalent statistical results of Bohmian hidden variables "do not take into account the algebraic structure of quantum observables. Kochen-Specker advanced the position that QM mathematics represented probabilities instead of physical reality. The Kochen-Specker proof demonstrates the impossibility of Einstein's assumption, made in the famous EPR paper, that quantum mechanical observables represent "elements of physical reality". More generally

does the theorem exclude hidden variable theories requiring elements of physical reality to be noncontextual (i.e. independent of the measurement arrangement).
In 1982, Aspect (at the Institut d'Optique in Paris) and co-workers verified Bell's theory of inequalities. A pair of photons created as a single decay event was emitted by the source. They traveled in opposite directions for a distance until they hit variable polarizers, the results of their interaction with the polarizers was recorded at each end. When the outcome was analyzed, the results verified QM nonlocality and showed a correlation that could not be supported by hidden variables A few years later (1986), Ghiraldi, Rimini, and Weber (Ghirardi et al 2005) proposed a solution to the collapse and nonlocality problem by changing QM. Their approach allows the quantum state of a QS to develop according to Schrodinger's equation. At random instants, development stops and the quantum state spontaneously collapses into a single local state. But like Bohm's formulation, GRW assumes instantaneity. Random collapses occurs faster superluminally, violating Special Relativity (SR).
In 1997, Zeilinger (at the University of Innsbruck in Austria) and collaborators conducted a "quantum teleportation." The essential information contained within one of two entangled photons was transmitted instantaneously over a distance, materializing in the form of a third photon identical to the first. At the same instant, the first photon disappeared. Again, the influence causing the nonlocal change occurred at a superluminal speed. Quantum nonlocality is now empirically verified.

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