Quantum Entanglement vs Non-Locality

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Abstract

In this brief paper, we argue about the relationship between quantum entanglement and non-locality.

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1 Entanglement vs non-locality?

Despite these important advances, it was still only a handful of physicists who were deeply interested in entanglement. Philosophers of physics recognized the importance of entanglement and Bell's work, but many continued to think of entanglement as an "all or nothing" phenomenon and described entanglement as simply a spooky action-at-a-distance or mysterious holism. In the last two decades new discoveries, many of which are associated with the investigation of quantum information, have shown that much philosophical and foundational work remains to be done to deepen our understanding of entanglement and non-locality.

Toward the end of the 1980s and the beginning of the 1990s a number of important transformations in our understanding of entanglement took place. First, it was recognized (e.g., Shimony,1995) that entanglement can be quantified; that is it comes in degrees ranging from "maximally entangled" to not entangled at all. Moreover, entanglement can be manipulated in all sorts of interesting ways. For example, Bennett et al. (Bennett, 1996) have shown that one can take a large number of electrons that are all partly (that is, "a little bit") entangled with each other, and concentrate that entanglement into a smaller number of maximally entangled electrons, leaving the other electrons unentangled (a process known as entanglement distillation). Conversely, one can take a pair of maximally entangled electrons and spread that entanglement out over a larger number of electrons (so that they are now only partly entangled) in such a way that the total entanglement is conserved (a process known as entanglement dilution). The notion of a "degree of entanglement" seems to have been first recognized through the related notion of a degree of violation of the Bell inequalities, indeed, this was used as the first measure of entanglement in the case of pure states: the greater the degree of violation of the inequalities, the greater the amount of entanglement. There are, however, limitations to using a violation of Bell's inequality as a general measure of entanglement. First, there are Bell-type inequalities whose largest violation is given by a non-maximally entangled state, so entanglement and non-locality do not always vary monotonically. Werner (Werner, 1989) showed that there are some mixed states (now referred to as Werner states) that, though entangled, do not violate Bell's inequality, so we can have entanglement without non-locality. Popescu (1995) has shown that even with these local Werner states one can perform a non-ideal measurement (or series of ideal measurements) that "distills" a non-local entanglement from the initially local state. The Horodecki family (Horodecki, 2009) subsequently showed that not all entanglement can be distilled in this way there are some entangled states that are "bound." These bound entangled states are ones that satisfy the Bell inequalities (i.e., they are local) and cannot have maximally entangled states violating Bell's inequalities extracted from them by means of local operations. Not only can one have entanglement without non-locality, but also, as Bennett et al. (1999) have shown, one can have a kind of "non-locality without entanglement." There are systems that exhibit a type of non-local behavior even though entanglement is used neither in the preparation of the states nor in the joint measurement that discriminates the states (see Cerf et al, 1997). This work highlights another facet of the concept of non-locality, which, rather than involving correlations for space-like separated systems, involves instead a kind of indistinguishability based on local operations and classical communication. The relationship between this new notion of non-locality and the traditional one involving space-like separated systems remains to be worked out.

These recent developments point to the need for a new, more adequate way of measuring and quantifying entanglement. They show that the concepts of entanglement and non-locality are much more subtle and multifaceted than earlier analyses based solely on Bell's theorem realized. Much philosophical and foundational work remains to be done on understanding precisely how the important notions of entanglement and non-locality are related.
These questions of how to quantify entanglement and non-locality and the need to clarify the relationship between them are important not only conceptually, but also practically, insofar as entanglement and non-locality seem to be different resources for the performance of quantum information processing tasks. As Brunner (Viola, Brunner 2007) and colleagues have argued, it is important to ask "whether in a given quantum information protocol (cryptography, teleportation, and algorithm, it is better to look for the largest amount of entanglement or the largest amount of non-locality" (Brunner et al. 2007).

2 Entanglement and Information

Arguably it is this new emphasis on the exploitation of entanglement and non-locality for the performance of practical tasks that marks the most fundamental transformation in our understanding of these concepts. The newly formed field of quantum information theory is devoted to using the principles and laws of QM to aid in the acquisition, transmission, and processing of information. In particular, it seeks to harness the peculiarly quantum phenomena of entanglement, superposition, and non-locality to perform all sorts of novel tasks, such as enabling computations that operate exponentially faster or more efficiently than their classical counterparts (via quantum computers) and providing unconditionally secure cryptographic systems for the transfer of secret messages over public channels (via quantum key distribution). By contrast, classical information theory is concerned with the storage and transfer of information in classical systems. It uses the "bit" as the fundamental unit of information, where the system capable of representing a bit can take on one of two values (typically 0 or 1). Classical information theory is based largely on the concept of information formalized by Shannon in the late 1940s. Quantum information theory, which was later developed in analogy with classical information theory, is concerned with the storage and processing of information in quantum systems, such as the photon, electron, quantum dot, or atom. Instead of using the bit, however, it defines the fundamental unit of quantum information as the "qubit." What makes the qubit different from a classical bit is that the smallest system capable of storing a qubit, the two-level QS, not only can take on the two distinct values $|O\rangle$ and $|1\rangle$,but can also be in a state of superposition of these two states:

$$\psi = \alpha_0|0\rangle + \alpha_1|1\rangle. \tag{3.4}$$

Quantum information theory has opened up a whole new range of philosophical and foundational questions. The first cluster of questions concerns the nature of quantum information.A second cluster of important philosophical questions concerns how it is that quantum information protocols are able to achieve more than their classical counterparts. A third important cluster of philosophical questions concerns what new insights recent work in quantum information theory might provide into the foundations of QM. Some authors have argued that an information-theoretic approach may provide a new axiomatic basis for QM and provide deeper insight into what makes QM different from classical mechanics. Zeilinger (Zeilinger,1999) has proposed a new information-theoretic "foundational principle" which he believes can explain both the intrinsic randomness of quantum theory and the phenomenon of entanglement.In another approach, Fuchs (Fuchs,2002) has adopted a Bayesian approach and argued that QM just is quantum information theory a more sophisticated gloss on the old idea that a quantum state is just a catalogue of expectations. Bub (Bub,2008) in particular has taken this ("CBH") theorem to show that quantum theory is best interpreted as a theory about the possibilities of information transfer rather than a theory about the non-classical mechanics of waves or particles. Much philosophical work remains to be done assessing these various claims that quantum information provides a new, more adequate way of conceiving quantum theory.

The second contribution in this thesis focuses on the concept of entanglement and how the notion of entanglement might be generalized for situations in which the overall system cannot be easily partitioned into separated subsystems A and B. The standard definition of entanglement for pure states depends on being able to define two or more subsystems for which the state cannot be factored into product states. For strongly interacting quantum systems, such as indistinguishable particles (bosons or fermions) that are close enough together for quantum statistics to be important, the entangled systems cannot easily be partitioned into subsystems in this way. In response to this problem, Viola and Barnum (Viola, 2007)(see chap.5) have developed a notion of "generalized entanglement", which depends on the expectation values of a preferred set of observables, rather than on a partitioning of the entangled system into subsystems. The intuition behind their approach is that entangled pure states look mixed to local observers, and the corresponding reduced state provides expectation values for a set of distinguished observables. They define a pure state as "generalized unentangled" relative to the distinguished observables if the reduced state is pure and "generalized entangled" otherwise (Barnum et al. 2004). Similarly a mixed state is "generalized unentangled" if it can be written as a convex combination of unentangled pure states. Their hope is that this new approach will lead to a deeper understanding of entanglement by allowing it to be defined in more general contexts. Recent developments in quantum information theory have renewed interest in finding a new axiomatic formulation of QM. In his paper for this volume, D'Ariano takes up this challenge of finding a new axiomatization. D'Ariano argues that a more promising approach to an operational axiomatization involves situating QM within the broader context of probabilistic theories whose non-local correlations are stronger than QM and yet are still non-signaling.

Another way in which considerations of probability have been at the center of foundational debates in quantum information theory is in the analogy that has been drawn between Bayesian conditionalization and quantum state updating upon measurement (e.g., Bub and Fuchs (2002)). In the Bayesian approach, named for the eighteenth-century mathematician and theologian Thomas Bayes, probabilities are interpreted as subjective degrees of belief, rather than frequencies.

Speaking of information, it has been argued that quantum information (QI) theory may hold the key to solving the conceptual puzzles of QM. Timpson (Timpson,

2006) takes stock of such proposals, arguing that many are just the old interpretative positions of immaterialism and instrumentalism in new guise. Immaterialism is the philosophical view that the world at bottom consists not of physical objects but of immaterial ones, in this context, the immaterial stuff of the world is information. As Timpson shows, this immaterialist view can be seen underlying Wheeler’s (1990) "It from bit" proposal and Zeilinger’s "foundational principle" (1999). Similarly, instrumentalism is another philosophical approach that it has long been popular to invoke in the context of QM, and has found new life in the context of quantum information theory. Instrumentalism is the view that the task of scientific theories is simply to provide a tool for making predictions not to be a description of the fundamental objects and laws actually operating in the world. In this context instrumentalism argues that the quantum state is merely a representation of our information, one that allows us to make predictions about experiments, but which should not be thought of as a description of any objective features of the world. Timpson (Timpson, 2006)argues that merely re-dressing these well-worn philosophical positions in the new language of information theory does not in fact gain any interpretive ground. After providing a detailed critical analysis of Zeilinger’s foundational approach, Timpson concludes that there is indeed great promise for gaining new insights into the structure and axiomatics of QM by focusing on information-theoretic phenomena, as long as one steers clear of the non-starters of immaterialism and instrumentalism.

As we have seen in this brief overview, quantum information science is in the process of transforming our understanding of both QM and information theory.

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