Abstract

Experiments demonstrating entanglement swapping have been alleged to challenge realism about entanglement. Seevinck (2006) claims that entanglement "cannot be considered ontologically robust" while Healey (2012) claims that entanglement swapping "undermines the idea that ascribing an entangled state to quantum systems is a way of representing some new, non-classical, physical relation between them." My aim in this paper is to show that realism is not *threatened* by the possibility of entanglement swapping, but rather, it should be *informed* by the phenomenon. I argue—expanding the argument of Timpson and Brown (2010)—that ordinary entanglement swapping cases present no new challenges for the realist. With respect to the delayed-choice variant discussed by Healey, I claim that there are two options available to the realist: (a) deny these are cases of genuine swapping (following Egg (2013)) or (b) allow for existence of entanglement between timelike separated regions. This latter option, while radical, is not incoherent and has been suggested in quite different contexts. While I stop short of claiming that the realist *must* take this option, doing so allows one to avoid certain costs associated with Egg's "orthodox" account. I conclude by noting several important implication of entanglement swapping for how one thinks of entanglement generally.

Swapping Something Real

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1 Introduction

The phenomenon of quantum entanglement has been taken to have broad metaphysical implications.[1] Such implications presuppose a broadly realist view of entanglement, one that recognizes a genuine physical relation between the subsystems that compose an entangled system. This entanglement relation, in turn, is used to explain the sorts of non-local correlations found in the measurement results of EPR-B[2] and related experiments. These correlations are "non-local" in that they hold between distant measurement events that occur at the same time—i.e., at spacelike separation.

Recent experiments involving "entanglement swapping," threaten to complicate our typical understanding of entanglement. Some have even suggested that these experiments threaten to undermine the realist position altogether. Below I will argue that this isn't the case. However, entanglement swapping is not without important implications for the realist. Indeed, I claim that delayed-choice entanglement swapping gives us reason to consider extending

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[1] Ladyman and Ross claim that "entanglement as described by QM teaches us that Humean supervenience is false, and that all the properties of fundamental physics seem to be extrinsic to individual objects" (2007, 151). A similar claim is made by Esfeld (2004), who claims that entanglement recommends a "metaphysics of relations." Quantum entanglement also pays a critical role in Schaffer's (2010) defense of monism, the view that there is ultimately only one object: the entire universe.

[2] I use "EPR-B" to refer to variations of the experimental arrangement due to Einstein et al. (1935) and extended by Bohm (1951). The variations most relevant in what follows will be those involving photon pairs with entangled polarizations.

entanglement into the temporal dimension. By allowing for timelike entanglement, the realist is able provide a unified account of a variety of experimental results. Even if one rejects this radical suggestion, ordinary cases of entanglement swapping alone require revising widely-held views about the nature of entanglement.

2 Preliminaries

Quantum theory doesn't wear its metaphysics on its sleeve. Different interpretations of quantum theory radically diverge on what (if anything) it tells us about the world. Accordingly, it is impossible to undertake our investigation without making some interpretative assumptions. That said, many of the issues here cross-cut interpretations and I hope to remain as neutral as possible between the various realist interpretations. I begin with the orthodox view of how entanglement arises in the formalism of (ordinary, non-relativistic) quantum mechanics.

2.1 Nonseperable quantum states

Quantum mechanics allows for nonseparable quantum states. To keep matters as simple as possible, consider two particles, 1 and 2, each of which can be assigned a pure quantum state. The standard approach represents the quantum state of each particle with a vector (ray) $|\psi\rangle$ in a Hilbert space $\mathcal{H}$. The quantum states of two systems 1,2, then, correspond to vectors $|\psi\rangle, |\phi\rangle$ in Hilbert spaces $\mathcal{H}_1, \mathcal{H}_2$, respectively. The joint state of the system they compose is represented by the vector $|\Psi\rangle$ in the tensor product Hilbert space $\mathcal{H}_{12} = \mathcal{H}_1 \otimes \mathcal{H}_2$. If the state vector $|\Psi\rangle$ in $\mathcal{H}_{12}$ can be expressed as a product of vectors $|\psi\rangle, |\phi\rangle$ in Hilbert spaces $\mathcal{H}_1, \mathcal{H}_2$, then $|\Psi\rangle$ is *separable.* But, in general, a vector in $\mathcal{H}_{12}$ cannot be expressed in the form $|\Psi\rangle = |\psi\rangle \otimes |\phi\rangle$, with $|\psi\rangle \in \mathcal{H}_1$ and $|\phi\rangle \in \mathcal{H}_2$. Such states are called *nonseparable quantum states.*

On the standard view, entanglement occurs when distinct physical systems are attributed nonseparable quantum states. Thus, if two photons 1,2 are prepared in the nonseperable joint polarization state $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$, they (or their quantum states) are mutually entangled. While this standard view of entanglement has been criticized (Ghirardi et al. 2002; Ladyman et al. 2013), all of the cases considered below will count as entangled on any suitable definition. Accordingly, I will bracket worries about the precise formulation of entanglement in the quantum formalism and simply assume the standard account for ease of exposition.

2.2 Entanglement realism

In order to say more about entangled systems, we must go beyond the formalism of quantum theory. What is the significance of ascribing entangled states to a set of physical systems?

In what follows, I will be concerned with views that accord the quantum state a *descriptive* role. Thus, when we attribute entangled states to composite systems, that tells us something about the relation between the physical subsystems in question. I will aim to remain as neutral as possible about the nature of this relation. The following are two possible views about the nature of this relation:

Action at a Distance: On this view, distant entangled subsystems are capable of having an immediate and unmediated causal influence on each other.

Ontological Holism: On this view, a compound entangled system is viewed as a nonseparable whole, which is irreducible to the subsystems it comprises.

Other variations of these views are possible as well. Some maintain that entangled systems are connected by a new *non-supervenient relation* while others speak of non-local influence that fails to be genuinely causal. It is not my aim here to adopt any particular approach to the metaphysics of entanglement. Rather, what will be at issue is the following thesis:

Entanglement Realism: Entangled systems bear a genuine physical relation to one another—one that is constitutive of their mutual entanglement.

Entanglement realism cross-cuts interpretations of quantum theory. Broadly "anti-realist" interpretations such as instrumentalism and other epistemic views will deny the thesis, but so will some characteristically "realist" views as well. First, consider an instrumentalist that views the quantum state epistemically. On this view, the assignment of a non-separable quantum state is a way of summarizing our information about the system. While ascribing such a quantum state allows us to predict non-local correlations, this view stops short of recognizing a physical entanglement relation between the particles themselves (if there are such things). Second, consider a Bohmian who takes the motion of particles to be fundamental and understands the wavefunction as a law-like feature of how particles move. On such a view, an entangled quantum state does not support the existence of a new physical relation between particles, but only describes/guides the motion of the particles so as to generate non-local correlations. There is not space to discuss all possible interpretations of quantum theory and their relation to entanglement realism, nor is this the appropriate place to debate the merits of the view. Instead, I'll conclude this section with two remarks intended to clarify the position.

First, whether an interpretation endorses entanglement realism depends solely on whether there is a physical relation R that can be attributed to a compound physical system in virtue of it being ascribed a nonseparable quantum state; being a "realist" interpretation isn't sufficient (though it may be necessary). Second, as with other forms of realism, the primary motivation for entanglement realism is explanatory. However the entanglement relation is understood, it should enable robust explanations of non-local correlations in measurement results. Relatedly, views the deny entanglement realism do so at the potential cost of being unable to adequately explain non-local correlations. Thus, there is at least some reason (*ceteris paribus*) to prefer interpretations of quantum theory that countenance entanglement realism.

3 Entanglement swapping

The experiments that motivate entanglement across time make use of the technique of *entanglement swapping*. Entanglement swapping is a relatively recent phenomena, and as a result has received relatively little consideration by philosophers. A simple experimental arrangement is depicted below (figure 1). Consider two sources that each produce a pair of photons in the state $|\psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$. One source produces the entangled pair (1,2) and the other produces (3,4). Initially, the quantum state of the four-particle system is simply the product of two pair states $|\Psi\rangle = |\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34}$. This state is separable into the states $|\psi^-\rangle_{12}$ and $|\psi^-\rangle_{34}$, each of which is an entangled two-photon state. Accordingly, entanglement realist would initially recognize two distinct entanglement relations—R_{12} and R_{34}—but no such relations between the pairs or between photons from different pairs.

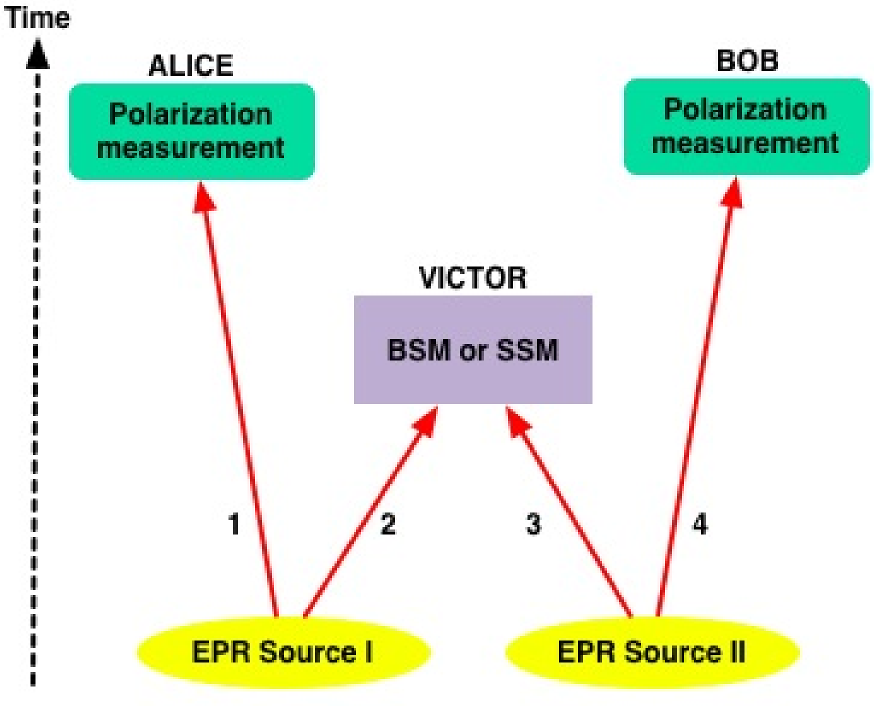

Figure 1: Entanglement Swapping Configuration

The outermost particles are sent off to polarization detectors at Alice and Bob. The inner particles are sent to a common location, Victor, which contains a switchable Bell-state analyzer. When switched on, a Bell-state measurement (BSM) is performed, which has the effect of projecting the indent particles into one of the four entangled Bell-states.[3] Otherwise, a separate state measurement (SSM) is performed. If the analyzer is off and the particles are measured separately, then, as expected, correlations are found between (1,2)and (3,4) as in an ordinary EPR-B experiment.

If the analyzer is on, however, particles 2 and 3 are projected into one of the entangled Bell-states and, as a result, the remaining particles 1 and 4 are projected into an entangled Bell-state as well. This can be seen by writing the initial four-particle state in the basis given by the Bell-states of (1,4):

$$|\Psi\rangle = \frac{1}{2}[|\psi^+\rangle_{14}|\psi^+\rangle_{23} - |\psi^-\rangle_{14}|\psi^-\rangle_{23} - |\phi^+\rangle_{14}|\phi^+\rangle_{23} - |\phi^-\rangle_{14}|\phi^-\rangle_{23}]. \quad (1)$$

Given this expression of $|\Psi\rangle$, we can see that if a BSM is performed at Victor with the result $|\psi^+\rangle_{23}$, then the remaining particles are projected into the state $|\psi^+\rangle_{14}$, and similarly for the other Bell states. Crucially, regardless of the outcome of the BSM at Victor, photons 1 and 4 become entangled as a result. This is the case despite the fact that they have never interacted.

At least some have taken this case to problematize entanglement realism:

> that one cannot think of entanglement as a property [which] has some ontological robustness can already be seen using the following weaker requirement: anything which is ontologically robust can, without interaction, not be mixed away, nor swapped to another object, nor flowed irretrievably away into some environment. Precisely these features are possible in the case of entanglement and thus even the weaker requirement for ontological robustness does not hold. (Seevinck 2006, 1582)

The intuition underlying this challenge is that something real would require a genuine "interaction" to be altered, but entanglement swapping allows us to move the entanglement around without such an interaction. But is it

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[3] For polarization measured along the H/V axis these are:

$$|\psi^\pm\rangle = \frac{1}{\sqrt{2}}[|H\rangle|V\rangle \pm |V\rangle|H\rangle], \quad |\phi^\pm\rangle = \frac{1}{\sqrt{2}}[|H\rangle|H\rangle \pm |V\rangle|V\rangle].$$

really the case that there is no interaction responsible for the swapping? After all, particles 2 and 3 are directly affected by the BSM performed at Victor. However, nothing is done directly to the remaining particles 1 and 4, and it is these that become entangled, so perhaps there is something amiss. Indeed, it is puzzling how exactly 1 and 4 become entangled remotely and instantaneously, but this is simply the original problem of entanglement in another form.

According to the realist who posits non-local influence, the ordinary EPR case is already one in which the measurement of a spacelike separated system affects the properties of a system entangled with it. If, however, we have some way of understanding such influence in terms of a physical entanglement relation, then presumably that relation can do the necessary work needed to account for entanglement swapping. In the case of a SSM at Victor, measurements of 1 and 4 will display correlations with the results obtained at Victor. In the case of a BSM, there are not simple correlations between the measurement at Victor and those at Alice and Bob, but rather, a more complex pattern of relations best accounted for by attributing an entangled Bell-state to the joint (1,4) system.

Timpson and Brown (2010) agree that entanglement swapping fails to provide a convincing case against entanglement realism. They suggest an analogy with gravity in Newtonian physics to illustrate:

> We do not think that the relative distance between two planets in Newtonian physics is not a genuine feature of reality because of the action-at-a-distance of the gravitational interaction. (Timpson and Brown 2010, 317)

I take the suggestion to be the following. Just as the Newtonian might seek to explain a pattern in the motion of two planets by appeal to a pattern in the motion of two other planets connected to them by an instantaneous gravitational influence, entanglement relations could provide a similar connection between the pairs of particles between which entanglement is swapped. Note, however, that adopting such a view requires a somewhat broader understanding of action at a distance than is ordinary supposed. Standard formulations focus on the *intrinsic properties* of systems. For instance, in his Stanford

Encyclopedia article on the topic, Berkovitz defines action at a distance as:

> a phenomenon in which a change in intrinsic properties of one system induces a change in the intrinsic properties of a distant system without there being a process that carries this influence contiguously in space and time. (Berkovitz 2016).[4]

To account for entanglement swapping in the manner above, the proponent of action at a distance must allow that the relational properties of particles (i.e., their entanglement relations) can influence the relational properties of the particles with which they are entangled.

How significant of a revision is this? One could claim, along holist lines, that entanglement is an intrinsic property of the *compound* system, in which case the ordinary version of action at a distance perhaps could be preserved. At least on the "orthodox" understanding of quantum mechanics, however, there is no clear basis for attributing an intrinsic property to a bipartite system on the basis of entanglement between its constituents. The extension from intrinsic properties to relations is certainly in keeping with the spirit of action at a distance, as the analogy with Newtonian gravity suggests, but it is a significant change none the less. Entanglement must now be understood as capable of spreading new entanglement relations, which is no doubt an interesting result.

Similar revisions are required for the holist to account for entanglement swapping. When the photons are created there are two pairs of mutually entangled particles. Hence, the holist would recognize (fundamentally) two two-photon wholes, (1,2) and (3,4), that are spreading out spatially with time. Victor's measurement is performed on both wholes and immediately alters both. If a SSM is performed, each two-photon system dissolves leaving photons 1 and 4 to be detected later. If a BSM is performed, again each two-photon system is changed, but in a way that the new wholes (2,3) and (1,4) are formed. Thus, the holist must allow that certain measurements are capable of generating new wholes out the parts of the original ones. Again this is does seem to mark an important revision in the view, but not one that creates any

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[4] This is the broader of two definitions given by Berkovitz, both of which contain a reference to intrinsic properties.

obvious problems.

Before moving to the next section, it is worth noting that entanglement swapping is not a mere philosophical curiosity, but is part of an active research program in physics with numerous practical applications, including: constructing a quantum telephone exchange, speeding up the distribution of entanglement, correcting errors in Bell states, preparing entangled states of a higher number of particles, and secret sharing of classical information (Bouwmeester et al. 2000). This makes its dismissal or reinterpretation difficult to motivate from a realist perspective. A key tenant in realist thinking recommends endorsing those parts of scientific theory that facilitate predictive and technological successes such as these.

4 Delayed-choice entanglement swapping

The revision to our understanding of entanglement required by entanglement swapping cases like that depicted in figure 1 is consistent with the central ideas of action at a distance or ontological holism. Entanglement swapping with delayed-choice, by contrast, threatens to undermine such notions completely.

> The delayed-choice entanglement-swapping experiment reinforces the lesson that quantum states are neither descriptions nor representations of physical reality. In particular, it undermines the idea that ascribing an entangled state to quantum systems is a way of representing some new, non-classical, physical relation between them. (Healey 2012, 31)

The idea of delayed-choice entanglement swapping was first proposed by Peres (2000). We begin with two entangled systems as in the ordinary case, but rather than have Victor preform his measurement prior to Alice and Bob, we delay particles 2 and 3 so that Victor can perform his measurement *after* his colleagues. Because the explanation of the collapse of equation 1 into entangled Bell-states of (2,3) and (1,4) didn't specify any times, quantum mechanics suggests that the same results would obtain. In particular, when

Victor successfully performs a BSM, entanglement will be swapped to 1 and 4.

And, in fact, these results seem to have been confirmed by an experiment conducted by Ma et al. (2012) depicted below (Figure 2). We begin as before: two pairs of entangled photons (1,2) and (3,4) are produced by two EPR sources in the state $|\psi^{-}\rangle_{12} \otimes |\psi^{-}\rangle_{34}$. At this point the photons 1 and 2 are mutually entangled, as are 3 and 4, but the 4-particle state is separable, and hence there is no entanglement across the two pairs. Alice and Bob each perform a polarization measurement of their photon (1 and 4, respectively) along one of three freely-chosen axes ($|H\rangle/|V\rangle, |R\rangle/|L\rangle, |+\rangle/|-\rangle$) and the data from these measurements are saved for later analysis. Particles 2 and 3, meanwhile, enter an optical delay, and only reach Victor at time M_V, nearly 500ns after M_A and M_B, the times at which Alice and Bob perform their measurements.

As before, Victor "chooses" between performing a Bell-state measurement (BSM) or separate state measurement (SSM) on (2,3). In the actual experiment, the switchable Bell-state analyzer was linked to a quantum random number generator which determined the measurement (BSM or SSM) to be performed. The photons 2 and 3 are projected into either an entangled state ($|\phi^{+}\rangle_{23}$ or $|\phi^{-}\rangle_{23}$) if BSM is performed or a separable state in the case of SSM. When Victor's results are compared with those of Alice and Bob, they are found to be consistent with ascribing an entangled state to photons 1 and 4 ($|\phi^{+}\rangle_{14}$ or $|\phi^{-}\rangle_{14}$) when BSM is performed and a separable state otherwise. Thus, it seems that entanglement has been swapped to particles (1,4) *after* they have already been detected (at M_V)!

This is puzzling to the entanglement realist. It seems that Victor's later measurement has an effect on the earlier state of particles 1 and 4. This is would seem to saddle the realist with a commitment to backward causation, which many would find beyond the pale. Indeed, the authors themselves seem to take the experiment to show the inadequacy of the realist approach.

> If one views the quantum state as a real physical object, one could get the seemingly paradoxical situation that future actions appear as having an influence on past and already irrevocably recorded

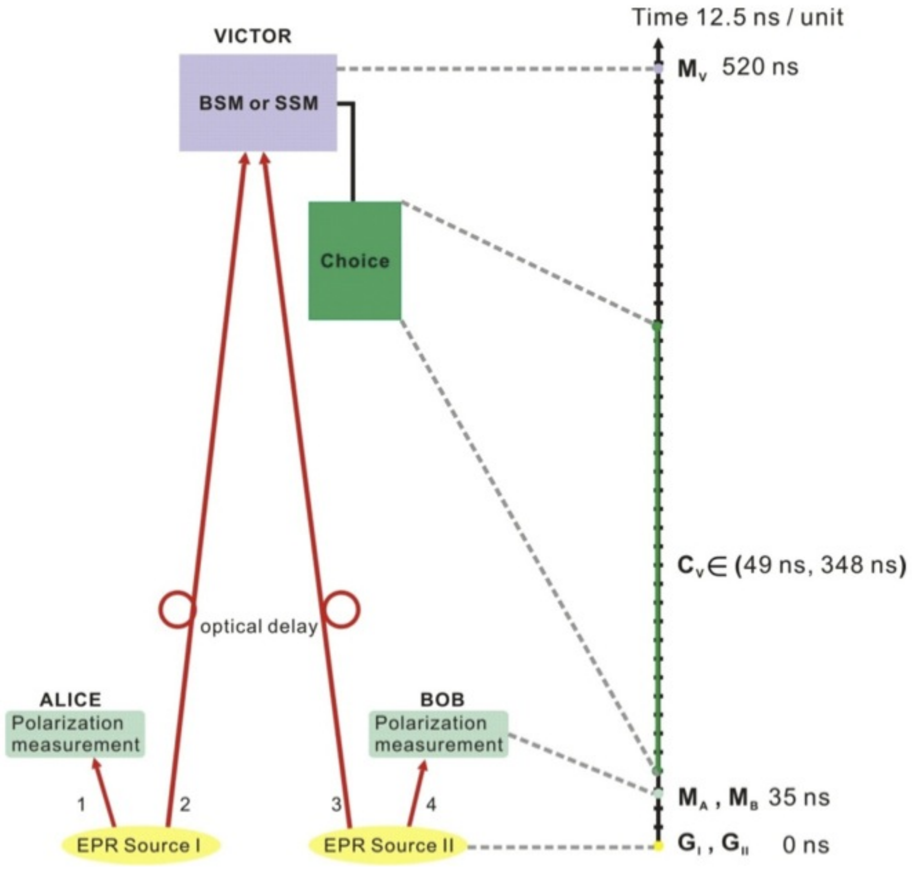

Figure 2: Delayed-choice entanglement swapping arrangement of Ma et al. (2012)

> events. However, there is never a paradox if the quantum state is viewed as to be no more than a “catalogue of our knowledge.” (Ma et al. 2012, 483)

The committed realist must either deny that entanglement can be swapped from (2,3) to (1,4) in this case, or else provide some account of how it can occur. If one seeks to give the same explanation as in the case of entanglement swapping without delayed-choice, then they must allow that entanglement can obtain between (1,2) and (3,4) at the time of Victor’s measurement. Of course, 1 and 4 do not exist at the time of Victor’s measurement, so the entanglement relation must obtain between events at different times. We will return to this idea below, but first, it's worth considering a way the realist may avoid this consequence.

4.1 Avoidance maneuvers

Matthias Egg (2013) offers a reply on behalf of the entanglement realist. He urges that to describe the foregoing as a genuine case of entanglement swapping is to beg the question against the realist. According to Egg's realist, the particles (1,4) are either entangled or not at the time of their detection (M_A, M_B), and later measurements cannot change this fact. In the case of entanglement swapping without delayed-choice, entanglement has been "swapped" to (1,4) as their quantum state has changed to become non-separable as a result of the measurement taken at Victor. Yet, according to Egg, the quantum state of (1,4) was separable when measured (M_A, M_B) in Ma's experiment and hence there was never a physical entanglement relation between (1,4) regardless of which later measurement Victor performs on (2,3).

So what should we make of the experimental evidence in favor of entanglement swapping to (1,4) after their detection?

> The Bell measurement on the [2,3] pair allows us to sort the [1,4] pairs into four subensembles corresponding to the four Bell states. Without delayed choice, this has physical significance, because each [1,4] pair *really is* in such a state after the [2,3] measurement. But if the [1,4] measurements precede the [2,3] measurement, the [1,4] pair *never is in any of these states.* This is entirely compatible with the fact that evaluating the [1,4] measurements *within* a certain subensemble shows Bell-type correlations. (Egg 2013, 1133)

Egg's reply focuses on an aspect of Ma's experiment that was omitted from the initial presentation. Unlike a simple EPR-B experiment, the correlations in the data recorded by Alice and Bob are only apparent once that data has been *sorted* into subsets ("subsenembles") according to the measurement performed and results obtained by Victor. Once we sort the results obtained by Alice and Bob in this way, we find that the subsets of data associated with Victor performing a BSM exhibit correlations indicative of entanglement.

Egg's point is that these correlations only appear once we sort the results in this manner, and such sorting needn't have any physical significance. It's unsurprising that correlations of *some* kind can be found when we conditionalize on the results obtained by Victor; after all, the photons measured by Victor were entangled with photons 1 and 4 until the latter were detected. Only when Victor's measurement actually causes a change in particles 1 and 4 are we justified in taking this process of sorting to have physical significance. Here we, as realists, should not allow that Victor's measurement has an effect on particles 1 and 4—doing so would require us to countenance backward causation—and hence the correlations obtained after sorting should not be taken to provide evidence for a genuine entanglement relation between particles 1 and 4.

4.1.1 Conflict with special relativity

Egg's reply requires that the entanglement realist make an important distinction between cases in which Victor's measurement occurs before Alice and Bob's measurements and those in which the time-order is reversed. Only the former, says Egg, are cases in which (1,4) are genuinely entangled. Yet, special relativity teaches that time-order is not an objective, frame-independent notion. If, for example, Victor's measurement (M_V) were spacelike separated from Alice and Bob's (M_A, M_B), then there would be no (frame-independent) fact of the matter about the time-order of the events. This scenario is not a mere hypothetical possibility either. In the much-publicized recent experiment of Hensen et al. (2015), entangled photon pairs are created via entanglement swapping from a location C that is spacelike separated from the measurement locations A and B (see Hensen et al. 2015, fig. 1e and 2a). Given such cases exist, adopting Egg's response would commit the realist to the claim that there is no (frame-independent) fact of the matter about whether the entanglement relation obtains. This would saddle the realist with a problematic sort of metaphysical indeterminacy.

In a footnote earlier in the paper, Egg offers the following rejoinder:

> Some of the most widely discussed realistic versions of quantum theory (e.g., Bohmian mechanics and the matter-density version of

> GRW) involve a commitment to a preferred foliation of spacetime. If these proposals are reasonable, then so is the assumption that there is a definite (although undetectable) temporal ordering between any two events. (2013, 1130, n.7)

It is of course true that a preferred foliation of space-time would solve the problem, and, indeed, this has been invoked in the service of some interpretations of quantum mechanics, but no such foliation (or a determinate time-ordering of spacelike separated events) is provided by our best theory of spacetime.[5] In order to take this option, the entanglement realist would be forced to claim that special relativity must be amended or at least, supplemented. This is a significant cost.

4.1.2 Parity of reasoning

Even if we ignore the conflict with relativity, there is a further worry with Egg's proposal.

The realist who would deny the reality of entanglement between (1,4) in the delayed-choice setup must claim that the standard argument for entanglement realism fails in this case purely because doing so leads to the undesirable result of backward causation. The argument for attributing entanglement in the ordinary swapping case relies only on the four-photon state (1) and the result obtained by Victor, without any mention of time. That same argument applied to the delayed-choice case delivers the same result, namely, that 1 and 4 are entangled. This result is confirmed by analyzing the data obtained by Victor, Alice, and Bob. Thus, there seems to be a tension in entanglement realism (so construed): on the one hand, it recommends recognizing a physical entanglement relation when it is instrumentally successful to do so, but, on the other hand, we should not posit such a relation in this case despite meeting the *very same* conditions that typically merit such an attribution. The failure to

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[5] Of course, *general* relativity is our best theory of spacetime, and the situation there is more complicated. There are several candidates for a preferred foliation in general relativity, such as the "cosmological time" of relativistic cosmology. However, it is far from clear that any of these candidates should be taken to provide *the* metaphysically privileged way of carving up spacetime.

recognize entanglement in this case is an ad hoc measure to avoid the perceived alternatives of antirealism or backwards causation.[6]

5 Entanglement across time

If we reject Egg's attempt to reinterpret the outcome of these experiments, we are forced to consider whether the entanglement realism is consistent with genuine delayed-choice entanglement swapping. In particular, can the account of ordinary entanglement swapping be extended to cover the delayed-choice case? Because swapping is facilitated by entanglement relations, the answer to this question will depend on one's preferred metaphysics of entanglement. Suppose we adopt the action at a distance view. This would seem to saddle the realist with backward causal influence form Victor's measurement of (2,3) to particles 1 and 4 prior to their measurements by Alice and Bob.

But not so fast! First, we might question whether the influence is really *backward* in time. It is tempting to assume that Victor's measurement must bring about the earlier entanglement of 1 and 4, but the dependence between these events has a certain symmetry. Just as in the ordinary EPR-B case, it's hard to know which direction we should take the causal influence to go. Perhaps we should regard the earlier entanglement of (1,4) to cause the later BSM of (2,3). This might create worries about Victor's free will (or the randomness of the quantum random number generator), but these may not be decisive (see Evans et al. 2012, §7.1). Second, we might wonder whether entanglement-mediate influence should be understood as causal. It differs from paradigm instances of causation in many respects, including: (a) it fails to diminish with distance; (b) it cannot be shielded; (c) it doesn't involve a transfer of energy and; (d) it cannot be used to send signals. The last two conditions are of special importance as most paradoxes associated with backward causation seem to require them. In addition to these differences, action at distance must allow

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[6] The sort of "instrumental success" I have in mind here is primarily the successful prediction of correlations in measurement results. We may also recall that in cases of entanglement swapping without delayed-choice, the attribution of an entangled state has important applications in quantum information theory. It is not unreasonable to suppose that related applications might be found for the attribution of an entangled state in the delayed-choice case as well.

for instantaneous influence to account for standard EPR-B experiments and, as a result, requires the rejection of the ordinary temporal asymmetry of cause and effect.

So, the action at a distance view can be extended to the timelike case without being committed to "backwards causation" by denying that either of the terms apply. Alternatively, one may countenance limited backward causation, but seek to downplay its significance for the reasons above (especially, the inability to use it for signaling).

Adapting the holist approach to allow for timelike entanglement is less straightforward. Part of the difficulty is due to the lack of clarity in the view generally. Many philosophers have advocated understanding entanglement in terms of a non-supervenient relation (e.g., Teller 1986; Howard 1985, 1989; Esfeld 2004); the entangled state of the joint system merits the attribution of a relation between its subsystems that fails to supervene on their individual intrinsic properties. This is sometimes paired with a claim that the compound system is more *real* or *fundamental* than the subsystems it comprises. One version may regard the joint system as a single object spread, smeared, or scattered across space. Another might take the distinct locations inhabited by the object to be unified in a more fundamental space of higher dimensionality.

The former case, in which joint systems are thought of as wholes scattered in space, seems to allow for extension to timelike separation without major problems. Temporally-scattered objects are not hard to imagine—a play with an intermission exists in two discontinuous timelike separated regions of spacetime—but, it's not obvious how such an approach is capable (on its own) of accounting for Bell-type non-local correlations. Indeed, Henson (2013) shows that the non-locality resulting from Bell's theorem is not avoided by denying separability. In some ways, this result is unsurprising. Merely redescribing the two photons in an EPR-B scenario as parts of a non-separable 2-photon whole does little to explain the correlations revealed by their measurement. This is not to say such an approach is hopeless, but it's unclear how it avoids the necessity of non-local influence.[7]

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[7] It's possible that the advocate of this version of holism may wish to endorse action at a distance as well. Perhaps the reason *why* non-local influence is possible is that entangled systems form a

The other version of holism, in which joint systems are located at a single location in some higher-dimensional reality, promises to offer a more satisfying account of Bell-type correlations. The rough idea is to grant that the world is non-local in four-dimensional spacetime, but regard this as a reflection of a more fundamental space of higher-dimensionality which is entirely local (see Ismael 2012).

Yet, even if the higher dimensionality approach offers a promising alternative to action at a distance, it's not easy to see how the picture would be adapted to the case of timelike entanglement. The best known higher dimensionality view, wavefunction realism (Albert 1996; Lewis 2004; Ney 2013; Ney and Albert 2013), posits a fundamental ontology that includes the quantum wavefunction in a very high-dimensional configuration space. While such view may have the desired effect of eliminating spatial non-locality, time is left untouched.[8] The wavefunction *evolves* in configuration space with time. Thus, non-local influence among timelike separated regions would remain.

Could it be possible that timelike separated systems are reduced to a single object in a higher-dimensional space? Certainly. But, there are no known candidates for such a view. While there is talk of the emergence of space-time in some theories of quantum gravity, these ideas remain highly speculative. Furthermore, there is no reason to think that such theories will have the right features to provide a satisfactory account of entangled systems, much less those that are timelike separated.

6 Lessons for the metaphysics of entanglement

There are several lessons to be drawn. Most importantly, entanglement swapping doesn't undermine realism, but rather provides important insight into the

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non-separable whole.

[8] It's unclear that wavefunction realism is able to account for entanglement in the manner suggested by Ismael. If *everything* is reduced to the wavefunction in high-dimensional configuration space, it doesn't seem able to account for what makes entangled systems special (c.f., Ismael and Schaffer 2013, 15).

nature of the entanglement relation. In particular, it compels the realist to revise certain aspects of their understanding of entanglement:

- Contrary to many presentations of the topic, entanglement does not require common preparation or previous interaction between entangled subsystems.
- Entanglement can account for changes in not just intrinsic (monadic) properties, but also the relations of entangled subsystems. Indeed, entanglement relations can beget new entanglement relations.
- Delayed-choice entanglement swapping can be accounted for in at least two ways:
    1. Following Egg, the realist can deny that genuine swapping occurs in delayed-choice setups.
    2. The realist can endorse the possibility of timelike entanglement.

  By taking the first option, the realist highlights their commitment to a time-ordering of spacelike events. Taking the latter option requires modifying the action at a distance or ontological holist views along the lines explored in the previous section.

I conclude by noting two very different potential sources support for timelike entanglement: (a) massless quantum fields in the Minkowski vacuum state (Olson and Ralph 2011, 2012) and (b) temporal analogues of Bell's theorem (Brukner et al. 2004; Fritz 2010). The import of these issues for a realist understanding of timelike entanglement remains to be seen.

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