Entanglement and Disentanglement in Relativistic Quantum Mechanics

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Abstract

A satisfactory formulation of relativistic quantum mechanics requires that one be able to represent the entangled states of spacelike separated systems and describe how such states evolve. This paper presents two stories that one must be able to tell coherently in order to understand relativistic entangled systems. These stories help to illustrate why one's understanding of entanglement in relativistic quantum mechanics must ultimately depend on the details of one's strategy for addressing the quantum measurement problem.[1]

1 Relativistic Quantum Mechanics and Entanglement

Work on the conceptual foundations of relativistic quantum mechanics is most often done without any direct engagement with the quantum measurement problem. Since finding a satisfactory resolution to the measurement problem has proven to be extraordinarily difficult, setting it aside has the manifest virtue of allowing one to consider other, perhaps more tractable, conceptual problems.[2]

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[2] Much of the recent work in relativistic quantum mechanics by philosophers of physics has been focussed on formulations of algebraic quantum field theory (AQFT). Hans Halvor-

The problem with this approach is that how one represents states and one's choice of dynamics must ultimately depend on how one seeks to address the quantum measurement problem. And relativistic considerations, if taken seriously, strongly constrain strategies for addressing the quantum measurement problem. More specifically, the argument here is that a clear understanding of relativistic quantum mechanics and of the entangled states of spacelike separated systems requires a concrete relativistic solution to the quantum measurement problem.

That quantum mechanics makes essential explanatory and predictive use of the states of entangled systems represented in configuration space was central to Einstein's worries over the measurement problem. As early as 1927, he expressed his view that both the standard collapse dynamics *and* what he took as the essential use of configuration space to represent the states of spacelike separated entangled systems in quantum mechanics implied "a contradiction with the postulate of relativity" (Instituts Solvay 1928, 256).[3] While Bell's Theorem shows that Einstein ultimately wanted too much from quantum mechanics, it remains unclear how one might formulate a relativistic quantum mechanics that accounts for the determinate observed properties of

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son and Michael Müger's (2007) review of AQFT is an example of careful conceptual work in this area. In Section 5 they briefly consider the measurement problem and conclude that the standard strategies for responding to the measurement problem in nonrelativistic quantum mechanics encounter serious obstacles when one seeks to formulate a relativistic quantum field theory. They then set the measurement problem aside to report on further developments of AQFT. Another example is Laura Ruetsche's (2011) recent book. While Ruetsche also briefly discusses the quantum measurement problem, she does not aim to characterize the relationship between how one understands measurement and entanglement and how one understands relativistic field theories. Indeed, a central motivation behind Reutsche's project was to "address something other than the measurement problem and/or the Bell Inequalities" (2011, *xi*). See also the other papers in the present issue. This is not to say that no one has worried over measurement in the context of relativistic field theory. See the references in footnote 5 for examples of both physicists and philosophers of physics who have considered how one might explain determinate measurement records in the context of relativistic field theory.

[3] See Bacciagaluppi and Valentini (2010) for a discussion of the position Einstein took at the 1927 Solvay Congress.

entangled spacelike separated systems. The problem has proven particularly difficult if one wants an account that explains determinate measurement outcomes in terms of the possessed states of physical systems and one requires the dynamics of one's theory to track those states. Indeed, the difficulties were sufficient to lead John Bell to express his own willingness to give up relativistic constraints by adopting a version of Bohmian mechanics in order to get a descriptive account of the behavior of entangled particles and fields that he could take as satisfactory.[4] And others have subsequently expressed a similar willingness.[5]

The purpose of this paper is to explain as clearly as possible the problem with entangled spacelike separated systems and why one's understanding of relativistic entangled systems must ultimately depend on one's solution to the quantum measurement problem. To this end, we will consider two stories that one must be able to tell coherently in order to provide a clear understanding of entangled spacelike separated systems. If one cannot tell both stories in a way that allows for consistent state attribution in the context of one's relativistic formulation of quantum mechanics, then one lacks a clear dynamical understanding relativistic entanglement and hence does not understand even the most basic EPR-Bell experiments in a relativistic context. The first story concerns how one treats the entanglement of spacelike separated systems and the second concerns how one treats their disentanglement.[6]

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[4] See for example Bell (1982) and (1984). Bell later took GRW also to be a serious contender for providing a satisfactory resolution to the measurement problem.

[5] Notable examples among philosophers of physics include Tim Maudlin (1994) and (1996), David Albert (1992), (1999), and (2007), and David Albert and Rivka Galchen (2009). See also Jeff Barrett (2002) for a discussion of the tension between relativistic field theory and explaining determinate measurement records and (2005a) for a positive, but ultimately, unattractive proposal. See I. Bloch (1967), Siegfried Schlieder (1968), Yakir Aharonov and David Albert (1981), and John Bell (1984) and (1987) for notable examples of physicists worrying over the basic conceptual difficulties one faces in reconciling relativistic field theory with quantum measurement.

[6] Both stories are directly related to how one explains the statistical correlations between determinate measurement outcomes that are exhibited in EPR experiments. Note that they concern whether or not and when the states of spacelike separated systems are

It is important to be clear regarding the structure of the argument up front. As initially told, each of the following stories is muddled. But precisely what missteps are made depends on what formulation of quantum mechanics one adopts and on how one understands what it should mean for quantum mechanics to be compatible with relativistic constraints. The argument here is that it is only possible to retell these stories clearly in the context of a particular formulation of quantum mechanics; and, consequently, how one tells each story will depend on how one tells the other. Why one needs a resolution of the quantum measurement problem to unmuddle such stories is manifest precisely when one attempts to tell them without first clearly addressing the measurement problem. Unfortunately, so far, the clearest resolutions of the measurement problem that allow one to assign objective states to physical systems and track them are manifestly incompatible with relativistic constraints as typically understood.

2 Story 1: Spacelike Entanglement

Consider three spin-1/2 particles. Friend A is on Earth with particles 1 and 3, and Friend B is somewhere near α-Centauri with particle 2. Suppose further that particles 1 and 2 are entangled in the EPR state

$$\frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle_1|{\downarrow_x}\rangle_2 - |{\downarrow_x}\rangle_1|{\uparrow_x}\rangle_2) \tag{2.1}$$

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entangled and the conditions under which one might understand such systems to exhibit determinate local values for the entangled observables subject to relativistic constraints. As far as I can tell, this issue is independent of whether the states of such systems might be taken to exhibit such features as *operational independence* as characterized by proponents of AQFT. See Miklós Rédei and Stephen J. Summers (2010), Miklós Rédei and Giovanni Valente (2010), and Section 3 of Halvorson's and Müger (2007) for discussions of this notion. Rather than start with a feature of one's theory, then seek to explain why it is a virtue; the thought here is to start with the virtues that one might expect from a satisfactory account of relativistic entangled systems, then consider whether one's theory has them.

and that particle 3 is in a ready state $|r\rangle_3$ as characterized in the interactions below. Friends A and B have clocks that are synchronized in the laboratory frame.

At noon on 1 January 2020, as prearranged between the two friends, Friend A correlates the x-spin of particles 1 and 3 by way of a local unitary interaction that takes state $|\,r\rangle_3|{\uparrow_x}\rangle_1|{\downarrow_x}\rangle_2$ to $|{\uparrow_x}\rangle_3|{\uparrow_x}\rangle_1|{\downarrow_x}\rangle_2$ and takes state $|\,r\rangle_3|{\downarrow_x}\rangle_1|{\uparrow_x}\rangle_2$ to $|{\downarrow_x}\rangle_3|{\downarrow_x}\rangle_1|{\uparrow_x}\rangle_2$. Assuming that the composite state evolves linearly, Friend B reasons, this interaction should leave the three-particle system in the state

$$\frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle_3|{\uparrow_x}\rangle_1|{\downarrow_x}\rangle_2 - |{\downarrow_x}\rangle_3|{\downarrow_x}\rangle_1|{\uparrow_x}\rangle_2). \tag{2.2}$$

After all, she reasons, since the x-spins of particles 1 and 2 were anti-correlated and since the local interaction between particles 1 and 3 correlated their x-spins, the linear dynamics requires that the x-spin particle 2 end up entangled with the x-spins both particles 1 and 3.[7]

But, given relativistic constraints, Friend B reconsiders. Reflecting on the state of particle 2 at noon plus one minute on 1 January 2020, according to her clock, she wonders whether it is entangled with just particle 1 or whether it is entangled with both particles 1 and 3. Since Friend A's correlation of the x-spins of particles 1 and 3 and Friend B's consideration of the state of her particle are spacelike separated events, there is an inertial frame where the interaction between particles 1 and 3 occurs *before* B's consideration of state, the laboratory frame is one of these, and an inertial frame where the interaction between particles 1 and 3 occurs *after* B's consideration of state. Friend B believes that there must be a physical matter of fact concerning whether particle 2 is entangled with one particle or with two particles and

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[7] Given the eigenvalue-eigenstate link, none of the particles here have determinate x-spins or even determinate pure states to call their own. Hence, to say that the x-spins of particles 1 and 3 are correlated, for example, just means that the composite state is an eigenstate of particles 1 and 3 having the same x-spin. To say that their x-spins are entangled is to say that they are correlated but not determinate. See also footnote 9.

that this fact ought to be represented in the state of the composite system. After all, there are physical observables of the *composite system* that would distinguish between a state like 1.1 with particles 1 and 3 uncorrelated and a state like 1.2 where particle 2 is entangled with both 1 and 3. But, she reasons, there are inertial frames where particle 2 is entangled with just particle 1 and inertial frames where it is entangled with both particles 1 and 3. Hence, insofar as physical matters of fact cannot depend on the choice of inertial frame there must, it seems, be no physical matter of fact concerning whether particle 2, as she considers the question, is entangled with just one particle or two. On such reflections, she finds herself entirely unsure how to assign states consistently to the three particles.[8]

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[8] Three quick points. First, the challenge will not to provide a retelling of story 1 by itself; rather, it will be to retell of story 1 in a way that is compatible with how one retells story 2. There are a number of ways one might go about telling a relativistic version of story 1 alone. Such retellings would offer advice to Friend B concerning how she should revise the classical understandings of state attribution and entanglement that she uses to reason about the states of the particles. But such a retelling is entirely unhelpful unless it also allows one to tell story 2 and explain its relation to story 1. We will return to this point after considering story 2. Second, note that the problem with retelling story 1 is not that it involves particles rather than fields as one can tell a fully equivalent story by considering the local values of a field $\mathcal{F}$ in three narrow spatial regions R_1, R_2, and R_3 that roughly correspond to the worldlines of the three particles. Regions R_1 and R_3 are contiguous to Friend A on Earth, and Friend A correlates the field values in these regions at noon on 1 January 2020, by his clock. Region R_2 is proximal to Friend B near α-Centauri and is correlated to the field value in region R_1 in the standard EPR way as the story begins. If one tells a field theoretic story, then one must also be able to translate that story back to talk of systems exhibiting particle-like properties in order to account for the experiments that we have actually performed. In particular, a satisfactory field theory must allow one to recapture the particle-like behavior exhibited by space-like entangled systems in standard EPR experiments. See Malament (1996) for an argument that relativistic quantum mechanics is incompatible with the existence of particles, or any other spatially bounded entities. See Barrett (2002) for a brief discussion of this argument in the context of explaining determinate measurement records in field theory. Finally, whatever story one ends up telling, one should expect that the three-particle system to exhibit standard EPR-Bell-like statistics. In particular, one should expect that particle 2 will behave as if it is entangled with the *composite system* of particles 1 and 3, not just particle 1 alone. If so, how one retells story 2 should explain such statistical behavior.

3 Story 2: Spacelike Disentanglement

Consider two spin-1/2 particles 1 and 2 and a recording particle 3. The recording particle might occupy any of three positions labeled "ready," "x-spin up," and "x-spin down" respectively. It starts in the "ready" position.

Again, Friend A is on Earth with particles 1 and 3 and Friend B is somewhere near α-Centauri with particle 2. Particles 1 and 2 are entangled in the EPR state, and friends A and B have clocks that are synchronized in the laboratory frame.

At noon on 1 January 2020, as prearranged by the two friends, Friend A measures the x-spin of particle 1 by correlating the position of the recording particle 3 with the x-spin of particle 1. The correlating interaction is such that the recording particle would move from the "ready" position to position "x-spin up" if particle 1 were x-spin up and to the position "x-spin down" if particle 1 were x-spin down.

Suppose that Friend B, remembering the arrangement with Friend A, considers the state of particle 2 at noon plus one minute on 1 January 2020. On reflection, Friend B notes that while she cannot know what measurement result Friend A got, given her long experience, she is sure that her friend has a determinate and reliable measurement record of the x-spin of particle 1 in the position of particle 3. Being committed to the standard interpretation of quantum-mechanical states, she also believes that a system only determinately has a property if it is in an eigenstate of having that property.[9] Hence,

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[9] Each direction of the standard eigenvalue-eigenstate link is an assumption that one may need to give up in order to resolve the measurement problem and hence to retell the stories clearly. David Wallace (2012) has argued that the eigenvalue-eigenstate link is not standard among physicists. While there may be some sense in which Wallace is right, many physicists should be committed to something very like the eigenvalue-eigenstate link given their other commitments. If one holds that the quantum-mechanical state provides an objective and complete description of a quantum system and that such a system has at most one value for a particular observable property, then the quantum state must be one that picks out that value and hence be at least close to the corresponding eigenstate of the property. And the other direction is perhaps even less contentious on similar assumptions. While a proponent of the many-worlds interpretation might be willing to give up the

Friend B reasons, particle 3 is either determinately at position "x-spin up" and particle 1 is determinately x-spin up or particle 3 is either determinately at position "x-spin down" and particle 1 is determinately x-spin down. But in each case, she concludes, particle 1 cannot be entangled with particle 2. Which by the symmetry of being entangled means that particle 2 cannot be entangled with particle 1.

But since Friend A's measurement of the x-spin of particle 1 in the determinate position of particle 3 and Friend B's consideration of the state of her particle are spacelike separated events, there is also an inertial frame where the determinate measurement record that requires that particles 1 and 2 be disentangled occurs *after* B's consideration of state. In such an inertial frame, Friend B reasons, particle 2 must still be entangled with particle 1. Hence, she concluders insofar as physical matters of fact cannot depend on the choice of inertial frame, there is no physical matter of fact concerning whether particle 2, as she considers the particle before her, is entangled with particle 1. So she does not know how to assign states consistently.

4 Entanglement and Measurement

In each of the two stories Friend B encounters a problem in assigning quantum-mechanical states to the particles. The problem is not that the stories presuppose nonlocal interactions. Each of the particle interactions here is perfectly local. The stories do presuppose the possibility of spacelike separated entangled systems, but if this is the problem, then it is entirely unclear where to start since anything like the standard quantum explanation of the behavior of EPR systems depends on such states. Moreover, results in relativistic field

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assumption that a system has at most one value for a particular observable property and a Bohmian would be willing to give up the completeness of the standard quantum state, many physicists would hesitate to sacrifice either view. In any case, the sense in which one should give up the eigenvalue-eigenstate link, if at all, must ultimately depend on one's clear resolution of the measurement problem.

theory itself, like the Reeh–Schlieder theorem, suggest that the entanglement of spacelike separated systems is ubiquitous.[10]

Retelling the two stories in the context of relativistic quantum mechanics requires one to say how parts of spacelike entangled systems interact with other systems and how systems disentangle to allow for local determinate measurement records or why they need not disentangle for there to be such records. But how one accomplishes this depends on one's proposed solution to the measurement problem. The narrative constraint is that one be able to tell Friend B how to understand the state of her particle at each point along its worldline. Retelling story 2 requires one to say something about how systems disentangle with distant systems on measurement or why they need not disentangle for there to be a determinate measurement record. And what one says about this will have implications for how one understands quantum-mechanical states generally and entanglement in particular, which, in turn, constrains how one tells story 1. So one cannot tell story 1 without knowing how to tell story 2, and one cannot tell story 2 without a proposed solution to the measurement problem.

One can get a sense of how the two stories are related before considering how they might be told on specific proposed resolutions of the measurement problem. Consider story 2. Suppose that Friend A's measurement does not affect the state of particle 2 in any way, and suppose that particle 3 must at least have a determinate quantum-mechanical state of its own in the recording degree of freedom in order for there to be a determinate measurement record.[11] But, even on this much weakened version of the eigenvalue-eigenstate link, if particle 3 is entangled with the x-spin of particle 2, then

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[10] See Schlieder (1965) and Clifton and Halvorson (2000) for discussions.

[11] Without such an assumption there could be no explanation of the value of the resulting local measurement record solely on the basis of the local properties of his recording system. Note that this condition is much weaker than the standard interpretation of states. On the standard eigenvalue-eigenstate interpretation of states, Friend A has a determinate record if and only if his recording system has a determinate state *and* this state is an eigenstate of the recording variable.

there can be no determinate measurement record of the x-spin of particle 1 in the position of particle 3. But if correlating the position of particle 3 with the x-spin of particle 1 disentangles particles 1 and 2 in story 2, then one also needs to be able to explain why correlating the x-spin of particle 3 with the x-spin of particle 1 does not disentangle particles 1 and 2 *in story 1.*

Each story begins with the same entangled state and, in each, one simply correlates a property of particle 3 with the x-spin of particle 1. If there is a distinction to be made, it is one's resolution to the measurement problem that will explain why story 1 is just a correlation story while story 2 is a measurement story or explain why no distinction between the two stories is required to explain the evolution of nonlocal correlations in the first and account for determinate local measurement records in the second.

5 Three Ways to Tell the Stories

How one retells each story must ultimately depend on how one understands entangled states and on the dynamics one adopts, and this depends on one's resolution to the measurement problem. To see why concretely, we will consider, in brief, three ways one might retell the two stories. At least two of these ways are explicitly nonrelativstic. But how the retellings differ illustrates how one's understanding of entanglement must depend on precisely how one addresses the measurement problem.

In broad terms, there are two basic approaches to addressing the measurement problem if one requires a theory that explains the outcomes of measurements in terms of the objectively possessed states of the observed systems and the evolution of such states.[12] One might opt for a no-collapse

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[12] A third approach denies that there is an observer-independent matter of fact concerning the quantum state of a particular physical system and, hence, is relatively unconcerned with providing a complete dynamics for how quantum states evolve. This tradition has been recently pursued by Richard Healey (2012; and this issue) and others, but, in one form or another, there have been proponents of this strategy from Bohr on. Adopting the strategy would involve giving up on rich dynamical explanations for measurement out-

theory like Bohmian mechanics or Everett's pure wave mechanics or for a collapse theory like GRW. How one tells the two stories on each of these theories differs dramatically as each provides a different interpretation of the quantum-mechanical state and different dynamical laws. We will start with Bohmian mechanics and GRW, then return to pure wave mechanics.

While the two stories are essentially the same in outline, Bohmian mechanics and GRW fill in the details in very different ways. While each theory sharply distinguishes between the two stories, they disagree on precisely how and why the two stories are different.

Consider story 1 as told in the context of Bohmian mechanics.[13] In Bohm's theory the three particles always have determinate positions, and the evolution of the composite entangled system in configuration space explains how they move. More specifically, the quantum-mechanical state of the composite system is represented by a single wave function in $3N$-dimensional

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comes. Insofar as one does not seek to assign states and track how they evolve, there is no dynamical role for relativity to play. If it turns out that something like this is what is ultimately required to get a coherent formulation of quantum mechanics in the context of relativistic constraints, that would be a dear lesson, but it is perhaps still too early to embrace such an explanatory retreat. A related strategy is to deny that there is any physical matter of fact concerning whether two spacelike separated systems are entangled. One line of argument against such a move goes like this. Since there are direct empirical consequences concerning whether proximal particles are entangled, there is a physical matter of fact concerning whether they are entangled when they are proximal. To adopt this proposal would be to deny that this matter of fact continues to hold when the particles are moved to spacelike separate locations then holds again, in precisely the same way, when they are brought back together. See Aharonov and Albert (1981) for the details of something like this in the context of a collapse formulation of quantum mechanics. Insofar as one favors such a view, one would need to argue its virtues over the three retellings considered here.

[13] See Bohm (1952), Bell (1982), Albert (1992), and Barrett (1999) for basic descriptions of the theory. The last two, in particular, describe how one might treat simple spin correlations in the theory. See Bell (1984) and Vink (1993) for discussions regarding how Bohmian mechanics might be used to make local field qualities, rather than particle positions, determinate. It is important to note that Bohmian field theory still requires a nonrelativistic configuration space. A point in field configuration space represents the field values everywhere at a time just as a point in standard configuration space represents the positions of all of the particles at a time. John Bell was among the most influential of supporters of Bohmian mechanics, and provided perhaps its most elegant expression.

configuration space, where $N = 3$, the number of particles. The quantum-mechanical state always evolves according to the standard nonrelativistic linear dynamics. When the x-spin of particle 3 is entangled with the x-spin of particle 1, the x-spin of particle 2 is instantaneously entangled with the x-spin of particle 3 as represented by the wave function of the composite system in configuration space.[14] And particle 2 remains entangled with particles 1 and 3 following the interaction between particles 1 and 3 unless very careful unentangling interactions are carried out that erase the correlations. The positions of the particles then evolve in a deterministic way that depends on three-particle configuration and on the deterministic linear evolution of the composite wave function in configuration space. It is the fact that the composite quantum-mechanical state is entangled that explains the dispositions of particles 2 and 3 to exhibit anti-correlated x-spins after the correlation in x-spin between particles 1 and 3 and other EPR-Bell statistics.

In story 2, because the positions of each of the particles is always determinate, Bohmian mechanics allows for Friend A to have a perfectly determinate measurement record of the x-spin of particle 1 in the position of recording particle 3 even though the position of particle 3 is entangled with the x-spins of particles 1 and 2 and the x-spins of particles 1 and 2 remain fully entangled and will continue to be so indefinitely unless very careful unentangling interactions are carried out that erase the correlations between the three particles.[15] Note that it is only because Bohmian mechanics violates the standard eigenvalue-eigenstate link that there can be a determinate measurement record in the position of particle 3 on this telling of the story. The composite wave function does not describe particle 3 as being in an eigenstate of position. Indeed, particle 3 fails to even have a quantum-mechanical

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[14] Such entanglements just involve correlations in degrees of freedom of the wave function. In Bohmian mechanics, the particles themselves have no intrinsic spin properties; rather, such properties are contextual and determined y the effective wave function.

[15] All particle positions are fully determinate in Bohm's theory. The entanglements here just involve correlations in degrees of freedom of the wave function. Such correlations may, however, have observable consequences.

state of its own after its interaction with particle 1. But on Bohm's theory, it need not have even a determinate quantum-mechanical state of its own to have a determinate position and hence represent a determinate measurement result. Here particle 3 always has a determinate position regardless of the quantum-mechanical state of the composite system.[16]

Now consider story 1 as told by GRW.[17] Unlike Bohmian mechanics, GRW does not add anything to the standard quantum-mechanical state. But like Bohmian mechanics, GRW depends on the nonrelativistic evolution of the wave function in $3N$-dimensional configuration space to explain the behavior of a N-particle composite system.[18] Again, when the x-spin of particle 3 is correlated with the x-spin of particle 1, the x-spin of particle 2 is instantaneously entangled with the x-spin of both particles 1 and 3 as represented by the wave function of the composite system in configuration space. And, since the three systems are entangled only in x-spin, particle 2

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[16] In field-theoretic versions of Bohmian mechanics, the wave function evolves in a field-configuration space, and it typically describes each local field value as being entangled with each other at a time. The local field values themselves are always determinate, and they evolve by transition probabilities determined by the deterministic evolution of entangled wave function of the composite system. See Bell's (1984) and Vink's (1993) extensions of Bohmian mechanics to field observables.

[17] For descriptions of the theory see Ghirardi, Rimini, and Weber (1986) and Albert (1992).

[18] Roderich Tumulka (2006) presents a flash formulation of the theory as a relativistic formulation of GRW. Since the model assumes noninteracting particles, it is not appropriate for telling either of the two stories here. But further, calling this a relativistic formulation of GRW requires one to closely consider the question of what should count as a relativistic theory. If all one requires is that one have a rule for assigning local determinate properties of a field (or flashes) that satisfy the standard quantum statistics to each region of Minkowski spacetime, then getting a relativistic formulation of field theory is too easy. Indeed, if that is all it takes, one can give relativistic formulations of both Bohmian mechanics and GRW using frame-dependent constructions as described in Barrett (2005a). Ultimately, such a theory might be thought of as simply providing a set of possible spacetime maps, spacetimes each with determinate local event structures, and an epistemic probability distribution over the set characterizing the prior probability that each describes the actual event structure of our world. As one learns more about the actual structure of our world, one conditions on on what one learns. The reason that this is too easy is that one has simply given up on the hard task of providing a dynamics for interacting systems.

will remain entangled with particles 1 and 3 following the interaction between particles 1 and 3. But here whether they continue to be entangled following other correlating interactions depends on precisely what sorts of correlations are produce. In particular, GRW predicts that each particle has a positive probability per unit time of collapsing to a state characterized by a very narrow Gaussian in position. Particles initially entangled only in spin will not be disentangled by such collapses. But such collapses will tend to disentangle particles initially entangled in position.[19]

In story 2, particle 3's *position* is entangled with particle 1's x-spin, and this makes all the difference. Now if particle 3 collapses to an (approximate) eigenstate of position, and the GRW dynamics tell us it will if one waits long enough, that will give Friend A a determinate measurement record of the x-spin of particle 1 in the (approximate) position of particle 3.[20] But it will also instantaneously (approximately) disentangle the states of particles 1 and 2. The result will be a composite state where particle 1 is (approximately) one eigenstate of x-spin, particle 2 is (approximately) the other eigenstate of x-spin, particle 3 is (approximately) an eigenstate of the position that corresponds to the (approximate) x-spin of particle 1 and the quantum-mechanical states of the three particles are (approximately) disentangled.[21] Given how states are interpreted in GRW, this is enough to explain Friend A having a determinate record in the position of particle 3 and Friend B having a particle that for most intents and purposes can be though of as now having

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[19] Particle collapses are to narrow gaussian wave packets to limit the violation of conservation of energy. The fact that energy is not conserved illustrates the conflict between the GRW dynamics and relativistic constraints. So does the fact that one must specify the width of the gaussian and the collapse rate, quantities where there would not be agreement between inertial observers. While adopting a flash ontology may prove helpful in this regard, see footnote 18.

[20] If the position of only one particle is involved in the measurement interaction, then one would have to wait a very long time. The story is the same for more particles, just faster.

[21] See Albert (1992) for further discussion of how position collapses in GRW yield determinate results for measurement more generally.

its own quantum-mechanical state. And there is a determinate measurement record to the extent to which the collapse of particle 3 has disentangled the systems and left particle 3 close to an eigenstate of position.

Both Bohmian mechanics and GRW make essential use of configuration space in telling the two stories, and in each case it is attributing a state to the extended composite system at a time that does the work of explaining the correlated behavior of the distant entangled particles. It is this that most directly makes the two theories incompatible with relativistic constraints, at least as as typically understood.[22]

The practice of physicists and philosophers of physics who work with relativistic quantum mechanics, however, accords better with something like Everett's pure wave mechanics than with either Bohmian mechanics or GRW.[23] In pure wave mechanics there are no hidden variables and no collapses of the quantum-mechanical state. Rather, the standard quantum-mechanical state of the composite system is taken to be completely characterize its physical state and the deterministic linear dynamics is taken to provide a complete and accurate dynamical law.

There are two immediate virtues to this approach. First, there are no hidden variables that require a nonlocal dynamics as in Bohmian mechanics. And, second, one does not have instantaneous collapses as in GRW. One has

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[22] It does not bode well that the one thing the two clearest resolutions of the measurement problem agree on is precisely ultimately makes them incompatible with relativistic constraints. If one takes Bohmian mechanics seriously, one might find some solace in the fact that if the distribution postulate is satisfied, then one would never notice the violation of relativistic constraints. A flash version of GRW for noninteracting particles can be formulated in a way that is compatible with at least one understanding of relativistic constraints. But Bohmian mechanics can also be made compatible with a similarly weak understanding of relativistic constraints. See footnote 18. More generally, see Albert (1999) for a discussion of alternative ways of understanding relativistic constraints. See Barrett (2005a) and (2005b) for discussions of such hidden-variable approaches to relativistic quantum mechanics and a discussion of how Bell's (1984) hidden-variable field theory might be further developed.

[23] See Barrett (2011) and (2014) for recent discussions of Everett's pure wave mechanics, its virtues, and its interpretational problems.

only the task of writing the deterministic unitary dynamics in a form that is compatible with relativistic constraints.

One tells stories 1 and 2 in essentially the same way in the context of pure wave mechanics. And when one tells them, there is a simple matter of fact regarding whether a given particle (or field) in one spacetime region is entangled with another particle (or field) in another spacetime region. Any measurement-like interaction simply entangles the recording system with the system being measured, then leaves the local systems entangled.

There is no special problem telling the two stories consistently and attributing states in a way that would allow one to address Friend B's questions in the context of pure wave mechanics if one can avoid appealing to anything like $3N$-dimensional configuration space to represent the entangled composite system. The difficult problem, rather, is that it remains entirely unclear on such an approach how to account for determinate measurement records and the standard quantum statistics on story 2.[24] Since the global state predicted by pure wave mechanics is typically one that leaves the pointer on one's measuring device in an entangled superposition of recording mutually incompatible measurement results, one is faced with the task of explaining *determinate records* (how an entangled superposition of mutually incompatible records represents the determinate measurement record one observes at the end of a measurement) and the standard *quantum probabilities* (why such determinate records, once one explains what those are, should be expected to exhibit the standard quantum statistics when there are no stochastic collapse of the state or any epistemic uncertainty regarding the global state).

While one might argue that adopting the standard practice of relativistic quantum mechanics involves adopting pure wave mechanics, one should only adopt the assumptions of pure wave mechanics if one has a satisfactory resolution to the determinate record problem and the probability problem. Insofar

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[24] See Saunders, Barrett, Kent, and Wallace (eds) (2010), Wallace (2012), and Barrett (2011) and (2014) for recent proposals for interpreting pure wave mechanics and the problems one faces in doing so.

as there is no entirely satisfactory resolution to these interpretational problems, pure wave mechanics fails to provide one with a clear understanding of entanglement in relativistic quantum mechanics. Even if one is optimistic regarding one's chances of overcoming the interpretational problems, committing oneself to pure wave mechanics to justify the standard practice of relativistic quantum mechanics is not a move to be taken lightly. Pure wave mechanics, on even the most charitable reading, may require one to adopt a fundamentally new understanding of what one means in claiming that a physical theory is empirically adequate.[25] This does not rule out pure wave mechanics, but if one wishes to take that route responsibly, one must say so, then provide the careful explanations of determinate measurement records and quantum statistics required to make sense of it. A promissory note for such explanations is not a clear understanding.

6 Discussion

Since we do not have a formulation of quantum mechanics that is compatible with relativistic constraints and that satisfactorily addresses the measurement problem, we do not know whether there is such theory, let alone how one should understand spacelike entangled systems in such a theory if found. The argument is that just as a satisfactory resolution of the measurement problem is required to understand nonrelativsitic entanglement, a satisfactory relativistic resolution to the measurement problem is required to understand relativistic entanglement, so until we have one, we do not understand even the most basic EPR-Bell-type experiments in a relativistic context.

Our degree ignorance is noteworthy. A relativistic resolution to the measurement problem might disentangle particles 1 and 2 after a measurement-like interaction as GRW does or it might leave them entangled as Bohmian

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[25] See Barrett (2014) for a discussion of the sort of basic conceptual sacrifices involved in adopting pure wave mechanics.

mechanics and pure wave mechanics do or it might do something else that makes Friend B's questions somehow the wrong questions to ask. Without knowing which, one has no idea whatsoever how to understand entanglement in a relativistic context. What we do know is that if a genuinely relativistic resolution to the measurement problem is possible at all, at least as relativistic constraints are usually understood, it cannot work just like Bohmian mechanics or just like GRW. Their essential reliance on $3N$-dimensional configuration space renders them manifestly incompatible with relativistic constraints as usually understood. In this sense, these two theories provide alternative concrete realizations of Einstein's earlier worries over the essential use of configuration space representations to represent the entangled states of spacelike separated systems.

If one opts instead for pure wave mechanics, one must show how one can avoid something like configuration space in one's representation of the states of spacelike entangled systems, then explain how it is possible to have determinate measurement records distributed according to the standard quantum statistics when most every local state is typically entangled with most every other local state.

The point is that one needs some resolution of the measurement problem to even get started in retelling the two stories. It is clearly not enough simply to deny that Friend B's questions make sense, or to give advice to Friend B that addresses only story 1 for how to revise her understanding of entanglement. One only understands relativistic entanglement if one understands it in the context of both stories.

While setting the measurement problem aside and considering relativistic quantum mechanics implicitly using something like pure wave mechanics has allowed for progress of a sort, even here, the progress that has been made arguably makes the measurement problem, and hence a clear understanding of relativistic entanglement, all the more difficult to achieve. Insofar as the Reeh–Schlieder theorem, for example, gives one reason to expect that field values in disjoint regions of spacetime are typically entangled with each other, it makes accounting for determinate records at all in relativistic quantum mechanics difficult if one is committed to anything like the standard eigenvalue-eigenstate link for interpreting states.[26]

7 Conclusion

To start with an easy moral, moving to the relativistic context clearly does not make the quantum measurement problem any easier to solve. Indeed, it is all the more difficult because one now has to account for determinate measurement records subject to relativistic constraints. So, while it might have been methodologically convenient to be able to ignore the measurement problem in the context of relativistic quantum mechanics, it is all the more salient. The constraints on addressing it are stricter, and, as illustrated in the two stories, there is a tension between these constants and the standard understanding of entanglement.

One can retell each of the two stories without any of the muddle of the original tellings in the context of Bohmian mechanics or GRW. The dynamical reliance of these theories on $3N$-dimensional configuration space, however, means that one must sacrifice Friend B's commitment to satisfying relativistic constraints to do so. While Everett's pure wave mechanics does not face the same direct conflict with relativistic constraints as Bohmian mechanics or GRW, one would need to providing a state description for the space-like separated entangled composite system without appeal to anything like $3N$-dimensional configuration space and give a compelling story for how to understand quantum statistics in a deterministic theory where there is

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[26] The thought is that a local determinate measurement record requires local determinate field values, which on the standard interpretation of states, requires that those field values, contrary to what the Reeh–Schlieder theorem and related theorems suggest, are not entangled with anything else. See Clilfton and Halvorson (2000) for a discussion of the ubiquity of entanglement in relativistic field theory.

no epistemic uncertainty regarding the linear evolution of the state. Until we have this, it is unclear how to unmuddle the stories in the context of a many-worlds formulation of quantum mechanics grounded in pure wave mechanics.

The upshot is that while we do not understand relativistic entanglement and disentanglement, we do know what it would take to get a clear dynamical understanding. It would require the sort of clarity with which we can retell the two stories in Bohmian mechanics or GRW but without sacrificing the commitment to satisfying the dynamical constrains of relativity. In particular, one must be able to say how entangled states arise and how they evolve in the context of both local correlating interactions and interactions that lead to determinate measurement records. In short, one needs a resolution to the quantum measurement problem that is compatible with relativistic constants. And given the difficulty in telling the two stories subject to such constraints and such that the two stories are compatible with each other, one should expect that at least some of the intuitions regarding entangled systems that have been forged in the context of nonrelativistic quantum mechanics will not apply in the context of a truly relativistic quantum mechanics if such a theory is possible.

Since we do not know whether relativistic quantum mechanics will work something like Bohmian mechanics, something like GRW, something like Everett's pure wave mechanics, or something completely different, or whether such theory is even possible, we have no idea whatsoever how to understand entanglement in a relativistic context. An immediate consequence of this is that we cannot even explain something as basic to our understanding of quantum phenomena as why spacelike separated entangled systems should be expected to produce determinate physical records that exhibit the standard EPR-Bell statistics. And while I am tempted to say that pure wave mechanics provides the best prospect for making sense of relativistic quantum mechanics, given the serious interpretational problems it faces, this is much more a statement of how serious the problem is than a proposal for how to solve it.

A satisfactory formulation of relativistic quantum mechanics requires that one be able to provide state attributions and dynamical laws for spacelike separated entangled systems. It requires a resolution to the measurement problem that provides (1) a relativistic representation the entangled states of spacelike separated physical systems, (2) a relativistic account of how spacelike entangled systems entangle with other physical systems, and (3) either a relativistic account of how the states of the component systems disentangle to allow for determinate local measurement records or an explanation for why they need not disentangle for there to be a determinate local record.

A clear understanding of relativistic entanglement and a satisfactory relativistic solution to the quantum measurement problem come together or not at all.[27]

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