EPR Paradox as Evidence for the Emergent Nature of Spacetime

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Abstract

After a providing a review of the EPR paradox which draws a distinction between what is here called the locality and the influence paradoxes, this paper presents a qualitative overview of a framework recently introduced by this author in which spacetime is assumed to emerge from areatime. Two key assumptions from this framework allow one to make the notion of quantum effects originating from 'outside' spacetime intelligible. In particular, this framework assumes that until a quantum object is measured, it does not actually exist in spacetime and that there are connections between quantum particles in areatime which are independent of metric relations in spacetime. These assumptions are then shown to permit one to conceptually understand both the locality and the influence paradoxes, and lead to the overall conclusion that spacetime is emergent in the sense that a very large number of discrete events which correspond to 'measurements' in quantum mechanics aggregate to give rise on a large scale to the apparently smooth reality we experience in our daily lives.

Keywords: Non-locality, EPR locality Paradox, EPR influence paradox, Bell's Theorem, Dimensional Theory, Emergence of Spacetime

1 Introduction

It is well known that one of the most mystifying features of quantum theory, which is also one of its most pervasive [4], is what is commonly called *non-locality* [1, pp. 131-144][3, pp. 437-455]. In general terms, non-locality in non-relativistic quantum mechanics refers to the phenomenon in which the measurement of some property of one part of a quantum system seems to somehow influence the outcome of a similar measurement at some distance of another part in cases in which the two parts of the system are described by a non-separable wavefunction, or, in more colorful language, when they are 'entangled'. The type of experiment which demonstrates that entanglement really is a feature of nature was first described in a paper by Einstein, Rosen and Podolsky, and hence the mystery it describes is often called the 'EPR paradox'.

There are actually two separately mysterious aspects which pertain to the EPR paradox. The first one is that which already appears in non-relativistic quantum mechanics and involves the non-local influence which enforces the correlations. The other aspect is an extra twist which appears when this phenomenon is considered in a more fully special relativistic context. Here the mystery is that for any spacelike separated measurements of entangled particles two distinct frames can be found in which the order of the influence is reversed. In order to keep these two issues separate, we will refer to the first as the *EPR locality paradox* and to the second as the *EPR influence paradox.*

This paper is organized as follows: Section 2 will provide a brief overview of the EPR paradox which emphasizes the distinction between the EPR locality and influence paradoxes. Section 3 will introduce as a 'story' i.e. in purely qualitative terms, a framework recently proposed by this author which is meant to elucidate the fundamental physical processes behind the formalism of quantum mechanics. The two key

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points of this framework specifically applicable to the EPR paradox are (1) the idea that quantum objects do not actually exist in spacetime until they are 'measured' (in a manner to be described more clearly below) and (2) the metric relations which they obey prior to measurement are independent from the spacetime metric, so that at least in the sense of this independence, (both versions of) the EPR paradox can be said to involve transmission of an influence 'outside' spacetime. Section 4 uses these two key ideas to reduce the EPR influence paradox to a spacetime version of the EPR locality paradox. Finally, section 5 presents a 'story' of how one might intuitively 'make sense' of the spacetime version of the EPR locality paradox, given these two assumptions. The overall conclusion drawn is that if the explanations provided are correct, then the EPR paradox is evidence that spacetime is emergent.

2 Background: Quantum Non-locality vs. Special Relativity

As Maudlin has pointed out, the non-local influence associated with entangled particles is different from other kinds of influences which occur in physical theories and are commonly labeled as action-at-a-distance in at least three notable ways [5, pp. 22-24]:

- *It is unattenuated:* The 'strength' of the influence seems to be unaffected by distance.
- *It is discriminating:* The influence only seems to act exclusively on those specific parts of the system which are described by the same non-separable wave-function.
- *It is faster than light or instantaneous:* In fact, a recent experiment to measure the speed of this influence found a lower bound of at least $10^4 c$ [6].

Of these, the last property introduces a tension with special relativity (SR). That is because according to SR the speed of light c is invariant in all inertial frames and this invariance is commonly interpreted to establish c as a limit on the speed of transmission of a range of possible phenomena.

The first well-known instance in which the tension between non-locality and Special Relativity came to be appreciated occurred when Einstein, Rosen and Podolsky (EPR) presented an argument in 1935 meant to demonstrate that quantum mechanics was an incomplete theory of nature: According to the argument, either "(1) *the quantum mechanical description of reality given by the wave function is not complete* or (2) *when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality*"(italics in original)[7]. This argument, applied to two entangled parts of a quantum system some distance apart, implicitly assumed that such influences could not propagate at infinite or at least superluminal speeds, and thus if according to the theory a measurement on one part instantaneously or superluminally changed the state of the other, thereby indicating that the latter did not describe a reality simultaneous with the first, then this could only confirm their conclusion, and hence there would have to be some additional specifications, commonly called 'hidden variables' which would be required to give a complete account of nature beyond that provided by standard quantum mechanics.

The subsequent debate it engendered seemed merely philosophical until in 1964 Bell presented a way by which two possibilities, that quantum mechanics is complete but non-local or that it is incomplete but must be supplemented by local hidden variables, could be distinguished from each other in the most general way [8]. The distinction was based on a difference in predictions between the two theories of statistical correlations between repeated measurements of the type proposed by EPR (actually a modified version proposed by Bohm and Aharanov [9]). More specifically, he showed that the difference in predictions could be phrased in terms of an inequality obeyed by *any* local hidden variable theory but violated by canonical quantum mechanics.

In 1982, Aspect *et al.* performed the relevant experiments and found that Bell's inequalities were indeed violated[10]. Similar experiments were (and had been) performed by others and the results were found to also agree with the violation[11][12]. It is important to note that these experiments not only confirmed quantum mechanics but also foreclosed the possibility that any serious candidate for a successor theory would be local. Thus, at least in this respect, then, nature seems to be indeed non-local. This, however, raises the question of how such influences can apparently travel at superluminal speeds in light of the constraints imposed by SR. As mentioned in the introduction, this apparent contradiction will be referred to as the EPR *locality* paradox.

What is in this paper called the EPR *influence* paradox presents an added mystery arising from the relativity of time ordering for those spacelike separated events which correspond to the emission and arrival of the influence that enforces the correlations between two entangled systems: Suppose we have an EPR type set-up in which observers A and B are spacelike separated and perform the experiment in which two entangled particles are sent out in order for a certain property to be measured. If two events are spacelike separated, then there exists a frame in which the two measurements are simultaneous. For simplicity, and without loss of generality, let us suppose that for the above experiment this was the rest frame of the emitter. Figure 1 is a spacetime diagram that illustrates this situation as observed in that frame.

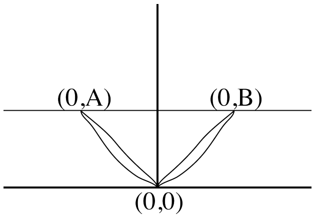

Figure 1: A Frame in which the two measurement events $(0,A)$ and $(0,B)$ are simultaneous. For each particle, the two separate world lines *represent a single world line* to illustrate the superposition of two possible measurement outcomes of some property such as spin. It is understood that there are infinitely many other such worldlines, each corresponding to a path that is part of the path integral.

Here, (0,0) marks the spacetime event which is the emission of the entangled particles, $(0,A)$ marks the event which is A's measurement of some property of particle a which has two possible outcomes (e.g. spin if these are spin 1/2 particles) and $(0,B)$ marks that which is B's measurement of the same property of particle b. As mentioned, in this frame $(0,A)$ and $(0,B)$ are simultaneous. From the path integral formulation we know that associated with each particle there are an infinite number of paths. Since the standard path integral formulation makes no distinction between paths that contribute to the path integral and classical paths, it is natural to assume that to each path there corresponds a separate worldline. As it would be impractical to represent all such worldlines in the diagram, we content ourselves with depicting just one worldline for each particle with the understanding that there are infinitely many others. This worldline, however, is represented as two separate worldlines in order to visually depict the particle as existing in a superposition of two mutually exclusive states as it pertains to the property that will be measured. We are employing this 'visual device' in order to accentuate the counterintuitiveness of the EPR influence paradox. Let us now consider the same set of events in the frame of an observer for whom $(0,A)$ occurs before $(0,B)$, as illustrated by fig. 2.

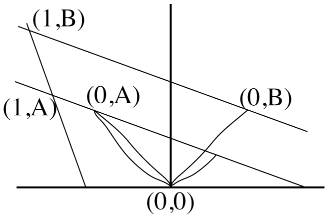

Figure 2: Added to the previous situation is an observer in whose frame $(0,A)$ occurs before $(0,B)$. In this observer's frame $(1,A)$ and $(1,B)$ are simultaneous with $(0,A)$ and $(0,B)$, respectively, and $(0,A)$ is taken to 'collapse' the state of particle b instantaneously with respect to the property to be measured at $(0,B)$

Let us denote this observer and his frame by the number 1. Here the intersection of the two spacelike hyperplanes (i.e. surfaces of simultaneity) containing $(0,A)$ and $(0,B)$ with the worldline of observer 1 are marked as $(1,A)$ and $(1,B)$, respectively. The 'speed' of the influence is taken to be infinite, so that in frame 1, the occurrence of $(0,A)$ instantaneously 'collapses' the superposition state of particle b. This is the kind of situation one would encounter when measuring the spin of two entangled spin 1/2 particles along the same axis: A measurement of, say, $+\hbar/2$ on one particle is always accompanied by a measurement of $-\hbar/2$ of the other[1]. Let us also remind ourselves that we know from the violation of Bell's inequalities that it could not have been the case that the particles were emitted such that their measurement outcomes were already pre-determined. So in this frame, the observer clearly seems to be able to claim that a measurement on particle a influenced the outcome of the measurement of part b.

Next, we consider the same set of events as depicted in fig. 1 in a frame, denoted by the number 2, in which $(0, B)$ precedes $(0, A)$, as illustrated in fig. 3.

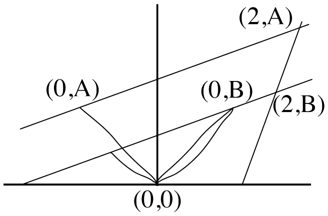

Figure 3: Here, $(0, B)$ occurs before $(0, A)$ in frame 2. The EPR influence paradox is that according to this observer, particle b was in a superposition state until $(0, B)$ occurred, but according to the observer of fig. 2 it wasn't. Thus, the observers disagree about which way the influence traveled. Notice that this can also be framed as a disagreement about the observers' accounts of the events on the world line of particle b and applies to *every* worldline associated with a path that contributes to b's path integral. Of course, this disagreement also applies, in reverse order, to particle a.

It is now that the paradox becomes evident: In fig. 2, the observer in frame 1 seemed to be able to claim that the influence traveled from $(0, A)$ to particle b so that by the time its property was measured at $(0, B)$, it no longer was in a superposition state. But that plainly contradicts the account of the observer in frame 2, as can be seen in fig. 3. According to this observer, the order of the influence is reversed: B's measurement of b at $(0, B)$ which is simultaneous with $(2, B)$ on his worldline sent out an influence which 'collapsed' the superposition state of particle a, so that by the time its property was measured at $(0, A)$ which is simultaneous with $(2, A)$ on the observer's worldline, it was no longer in a superposition state.

As described here, it is evident that the disagreement can be framed in terms of conflicting accounts about where the collapse events occur on the worldlines of the particles, as can be found in figs. 2 and figs. 3 by inspection. Because the pair of hyperplanes, when extended on both sides to infinity, intersect all possible paths from the initial emission event to the measurement events, this disagreement applies to *every* path that contributes to the path integral.

So, what gives? If the measurement outcomes could be used to send signals, or information, perhaps it would open the door for true paradox, but as this has been proven to not be possible [19], all each observer can really say is that only after both measurement results are collected in a single frame, will the effect of these influences become apparent in the form of unexpected correlations.

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[1] we ignore here that in non-relativistic quantum mechanics the path integral technically describes only spinless particles in favor of a providing a simple visual exposition of the problem. This visual exposition can, however, be used to accurately represent the argument of the original EPR paper, where it was not spin but relative position which was correlated. To do this, each of the two paths per particle originating from $(0, 0)$ is now interpreted as standing for an infinite number of worldlines between $(0, 0)$ and two distinct positions. The correlation manifests itself in the fact that after the relevant *position* measurements are carried out, it will be found that based on a knowledge of the relative distance between the two, measuring the position of one particle would instantaneously allow one to predict the position of the other.

3 A Story About Quantum Non-locality emerging from 'Outside Spacetime'

Given the continuing perplexity posed by this problem, at least one well-respected researcher, Gisin, has publicly stated that quantum effects may originate 'outside spacetime' [14]'. On the face of it, this unorthodox claim seems highly provocative. Gisin explains that by this claim it is meant that "physics has no story in space and time to explain or describe how these correlations happen. Hence, somehow, non-local correlations emerge from outside space-time". The obvious question then becomes, what sort of story *could* be told according to which quantum non-locality emerges from outside spacetime?

It turns out that this author has worked on a theory which appears to coherently incorporate the notion of quantum non-locality emerging from 'outside spacetime' and which he labels the *Dimensional Theory.*

Presented as a 'story' i.e. in purely conceptual terms, it is very simple to tell, although the assumptions on which it is based may seem unfamiliar: This theory assumes that there exists a limit, called $|U_{3max}|$, in which space vanishes and spacetime reduces to a one-dimension reduced version called *areatime.* The passage of time associated with events in this limit is postulated to be related to the passage of time in spacetime via a certain symmetry, called *angular dual bilateral symmetry*, which can be decomposed into two phases of opposite sign. The symmetry requires that the proper time of a system in areatime and that of an observer in spacetime be 'orthogonal' to one another in the sense that nothing that actually exists in areatime 'ages' (i.e. is observed to have time passing for it) relative to anything that actually exists in spacetime and vice versa. The absence of aging in spacetime gives both a basis for claiming that entities which actually exist in areatime actually exist 'outside spacetime' and implies that an object that actually exists in areatime cannot be associated with an intrinsic actual history in spacetime (i.e. in its 'frame' there is no actual history in spacetime to be observed). By assumption, the absence of an intrinsic actual history leads to a linear superposition of all possible actualizable histories, where 'actualizable' simply means 'capable of becoming actual'. Each actualizable history can be associated with an actualizable path. Each actualizable path is one component of the spacetime manifestation of a system that actually exists in areatime and must be associated with a phase because the phase (due to the underlying symmetry) provides the means by which the passage of time in areatime and in spacetime can be compared to one another in the face of the orthogonality of the proper times. The sum of all possible actualizable paths, each multiplied by each phase, gives a full description of how a system that actually exists in areatime manifests itself to a spacetime observer over time.

As may have been already noticed, this 'story' begins with events originating 'outside' spacetime but ends up with a description that is strikingly similar to that given by Feynman's path integral formulation of quantum mechanics [15], except that it makes an ontological distinction between actualizable and actual paths whereas the standard path integral formulation makes no such distinction.

Where this distinction comes into the foreground is when there are interactions in areatime resulting in a combined system that exceeds the limit $|U_{3max}|$. In those instances, the areatime interaction of the system with some other system that actually exists in areatime brings about the 'actualization' i.e. the coming into actual existence, of one possible state in spacetime out of the superposition of actualizable states into which the superposition of actualizable paths can be mathematically transformed. The linear superposition of actualizable states 'collapses' to an actual one, and the symmetry, and therefore also the phase associated with the state, disappears (even if only temporarily in a quantum system) because the now actual state, as long as it exists, does not require a comparison between orthogonal proper times. This corresponds to what is in quantum mechanics called a 'wave function collapse'. Furthermore, it can be interpreted as a process by which a local region of spacetime 'emerges' from areatime.

The reader who encounters this 'story' here for the first time is encouraged to consult the references where aspects of this framework are described in greater detail [16][17][18]. It may be surprising that as unorthodox as this theory seems, it supports most strongly the orthodox interpretation of quantum mechanics in that it supplies it with a genuine physical underpinning. According to the orthodox interpretation, a quantum system does not have any definite properties until those properties are measured (except, in most practical situations, when the exact same measurement had just been performed)[2, p. 420]. This seems consistent with the perspective presented here, according to which it would make no sense to attribute definite spacetime properties to something that actually exists in areatime, until, as a result of the interactions collectively given the label of 'measurement', it has actualized into something that actually exists *in* spacetime.

4 A Partial Explanation of the EPR Influence Paradox

The framework just described suggests a rather simple conceptual solution to the EPR *locality* paradox. It tells us that we should understand non-locality as the manifestation of events which can be said to exist 'outside' spacetime because they exist in areatime (unless they actualize to spacetime entities), and thus are not bound to metric relations in spacetime but rather to those in areatime. This is most directly a consequence of the orthogonality of the proper times (a feature of the postulated symmetry), which are proportional to the metrics. The orthogonality of the metrics renders distance relations in areatime independent from distance relations in spacetime. In brief, according this framework it is possible for two components of a system that actually (i.e. intrinsically) exists in areatime to be local in areatime *and* lead to non-local phenomena in spacetime.

However, it still remains to be explained how these ideas address the EPR *influence* paradox. Let us return to fig. 2 and re-examine our assumptions. We know that according to the standard path integral formulation, the state of a particle is determined by an integral over an infinite number of paths (multiplied by a phase factor) and we assumed that there corresponds to each path a worldline. In figs. 2 and 3. we picked one worldline as a 'stand-in' for all the world lines in the path integral. We then found that the paradox can be expressed in terms of contradictory accounts of the events on all of the world lines of each particle. Let us again emphasize that our particular choice of the worldline to represent the integral was arbitrary and does not affect this problem.

Framing the problem in terms of path integrals provides us with the clue to explain this paradox: one assumption about this scenario which seems trivially obvious is that while the measurement outcomes were undetermined until a measurement was performed, the particles themselves on which the measurements were performed actually existed in spacetime 'all along'. But this is precisely the assumption which would need to be modified if the previously described framework is correct, since the outcome of a measurement here corresponds there to the actualization in spacetime of the particle which prior to the performance of the measurement did not actually exist in spacetime. To reconcile this idea with the standard path integral account we must attach the following interpretation to the distinction between actual and actualizable paths: *An actual path has a worldline associated with it, but an actualizable path does not.* This renders coherent the idea that the path integral represents an entity that manifests itself only actualizably in spacetime. It is natural to ask whether this new assumption introduces a 'loophole' which can shed further insight on the EPR influence paradox. Here is how it can be shown that it does. We first note the following:

1. Any assertion about relations in spacetime requires a comparison between actual spacetime events.

2. By our new assumption, no actual spacetime event whatsoever can be associated with a particle until it (i.e. one of its spacetime properties) is measured.

Fig. 4 depicts the same set of events as fig. 2 does, but now with our new assumption.

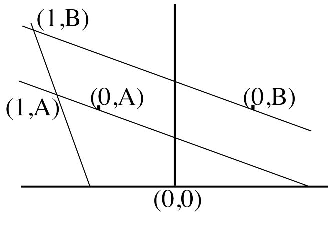

Figure 4: According to our new assumption, the particles do not actually exist in spacetime until they are measured. Thus, A's measurement of a does not exert any influence on b until $(0, B)$ occurs because there is nothing (in spacetime) to influence before then. The 'influence' is not only non-local in space but also non-local in time. The 'blips' are meant to represent that shortly after measurement, the particles once again are only describable by a path integral, which means that once again, they no longer actually exist in spacetime

There are no longer any worldlines (which we interpret, as we implicitly did previously, as actual rather than actualizable ones), because the paths of the path integral are no longer taken to be associated with them. Further, the measurement events $(0, A)$ and $(0, B)$ are assumed to only originate extremely short worldlines ('blips') for a and b to reflect the fact that very soon after these events, the particles once again evolve into a superposition state and hence fail to be representable by worldlines once over. So, although we intuitively imagine that a and b are actual particles before (and even long after) the events $(0, A)$ and $(0, B)$ occur, respectively, our new assumption requires us to abandon this intuition. More pertinently, our new assumption introduces an asymmetry between any spacetime observers and such particles, as can be illustrated by considering observer 1: whereas this observer can perfectly well make assertions about relations involving spacetime events earlier than $(1, B)$ on his own worldline, he cannot associate these with b, since $(1, B)$ is simultaneous with $(0, B)$ (because $(0, B)$ is the earliest event in the worldline of b). One spacetime event on his worldline that is earlier than $(1, B)$ is $(1, A)$. So, he can say nothing about the spacetime relation between $(1, A)$ and b at least until $(1, B)$ occurs (assuming, for simplicity, that he had access to the information about the outcome at $(0, B)$ instantaneously). But in frame 1, $(1, A)$ is simultaneous with $(0, A)$. So neither can he say anything about how $(0, A)$ relates to b until at least $(1, B)$ occurs. In particular, and this is important, *he cannot make any assertions about the outcome of A's measurement at* $(0, A)$ *influencing the outcome at* $(0, B)$ at least until $(1, B)$ occurs. That is because there is, in his frame, *nothing there* in spacetime to "influence" until $(0, B)$ occurs. But does this not contradict our earlier illustration of the difficulty? Yes, but that is only because in that description, we applied a notion of simultaneity carried over from non-relativistic QM to the assumption that the particles actually existed in spacetime prior to measurement. This led us to assume that it is sensible to transfer to relativity the notion that a measurement on one entangled particle instantaneously influences the other one. Our new assumption leads us to conclude that instead of a description in terms of an influence that instantaneously propagates from one particle to another, the proper description of the situation must be as follows: Assuming an infinite speed for the influence, the outcome of B's measurement in frame 1, *would have been* determined by A's measurement outcome (had b actually existed in spacetime), but it was in fact undetermined until B carried out his measurement, the result of which was 'influenced' by A's measurement outcome. Similarly, in frame 2 the outcome of A's measurement *would have been* determined by B's measurement outcome (had a actually existed in spacetime), but it was in fact undetermined until A carried out his measurement, the result of which was 'influenced' by B's measurement outcome. It follows from this description that any assertion about the time order of the influence of one measurement outcome on the other can only be made after the information about the last outcome in that frame has arrived at the location of the observer.

Where on the observer's worldline the arrival of this information marks an event depends on its speed of transmission. If it were to go infinitely fast, then in this situation it would arrive at $(1, B)$, as we have assumed so far. But an infinite speed of transmission of information conflicts with relativity. A more realistic speed would be c, in which case the observer would obtain information about each of the measurement events later than we assumed, but since that does not change the time ordering of the events in his frame, his conclusion is still only based on events on his own world line. By symmetry, everything described of observer 1 also applies to the observer 2 except that now the order of the events is reversed. Thus, as fig. 5 indicates, in his frame $(0, B)$ occurs first, but once again, there is *nothing there* in spacetime to influence until $(0, A)$ occurs.

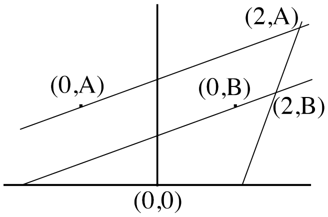

Figure 5: According to the observer in frame 2, B's measurement of b does not exert any influence on a until $(0, A)$ occurs because there is nothing (in spacetime) to influence before then. Thus, he is no more entitled to claim that B's measurement influenced a than the observer in frame 1 is to claim that A's measurement influenced b.

But then, that means that even though the order of events is reversed in his frame, there is no contradiction about which event intrinsically influenced which because such a conclusion can be drawn by the observer only after the information about the last measurement event is received, and can therefore only be based on the order of events on his own worldline.

To summarize, if it is accepted that a quantum mechanical 'measurement' corresponds to the actualization of a particle in spacetime, then no spacetime observer has a privileged claim about the time order of the influence of any correlated measurement events such as $(0, A)$ and $(0, B)$. This explanation is highly reminiscent of the old paradoxes involving the relativity of simultaneity. The EPR influence paradox goes one step further in confounding our intuitions about time by making the time-ordering of quantum events relative to the observer because, according to this idea, it involves things which, until they are measured, don't actually exist in spacetime.

5 A 'Story' about the EPR Locality Paradox

The explanation just given reduces the EPR influence paradox to a spacetime version of the EPR locality paradox because the influence is now not only non-local in space, it is also non-local in time. Technically, the framework described in section 3 already provides an explanation for how these sorts of events can be non-local in spacetime: Since they are manifestations of entities that actually exist in areatime and metric relations there are independent of metric relations in spacetime, one *should* (to put it provocatively) even expect non-local phenomena in these circumstances, if this framework is believed.

Alas, it is unlikely that this explanation will be intuitively satisfactory, so, in an attempt to show how to 'make sense' out of this idea, we will tell another 'story' about how the EPR locality paradox can be thought of as a consequence of the independence of the distance relations between events in areatime and spacetime. Let us consider the same situation as before but, to illustrate our point, consider the straight worldline from $(0, 0)$ to each of the measurement events, as in fig. 6.

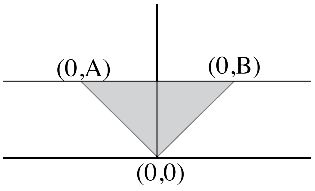

Figure 6: A region of spacetime enclosed by the world lines of the two particles and a worldline that connects them.

If, under the assumption that there were actual worldlines circumscribing the legs of the triangular spacetime region with vertices $(0, 0)$, $(0, A)$ and $(0, B)$ connecting these events with one another, these particles exhibited non-local behavior, then the EPR paradoxes could be expressed in terms of this region: The difficulty with the EPR influence paradox in this context is that the *shape* of the triangle depends on the frame of the observer, and it is the frame-dependence of the triangle's shape coupled with the lack of pre-determination of the measurement outcomes which leads to contradictory accounts of which event influenced which. The difficulty with the EPR locality paradox is that, since we assumed that there are world lines leading from $(0, 0)$ to each of the measurement events, and that they are distinct, $(0, A)$ and $(0, B)$ themselves must be separated by a spacetime region across which the non-local connection simply "jumps" as if there was nothing there.

Our new assumption given in 2., however, radically changes everything: Neither exists there a worldline between $(0, 0)$ and $(0, A)$ that can be related to a (since a only actually exists at $(0, A)$ on this 'triangle') nor exists there a worldline between $(0, 0)$ and $(0, B)$ that can be related to b (since b only actually exists at $(0, B)$ on this 'triangle'). There simply are no spacetime events along any worldlines that 'separate' and thereby distinguish either $(0, A)$ as it relates to a or $(0, B)$ as it relates to b from $(0, 0)$. But if neither $(0, A)$ as it relates to a nor $(0, B)$ as it relates to b can be distinguished from $(0, 0)$ in terms of any spacetime relations, then neither can they be distinguished from one another in terms of any spacetime relations. Insofar as they have any connection with $(0,0)$, the absence of a worldline in effect collapses both $(0,A)$ and $(0,B)$ unto $(0,0)$ for the purposes of describing any connections between the three events. That there are any connections between them in the first place is given by the locality of these events in areatime. It does not seem intuitive to think of $(0,A)$ and $(0,B)$ in this way, but that is because we imagine that a and b have worldlines that connect these spacetime events to $(0,0)$.

Put differently, the absence of world lines sets up a description of the connection between the vortices at two levels:

- *At the level of the inherent relationship between the particles and the emitter at the vertices:* At this level, our new assumption, in effect, 'collapses' this triangle to a pointlike region, so that in order to consider the interactions between these three events, we must ignore the 'enclosed' triangular spacetime region. Doing so, however, removes the contradictions we encountered before when we framed them in terms of this region: Since the shape of a pointlike region is frame-*in*dependent, the EPR influence paradox seems no longer paradoxical. Similarly, since in that pointlike region there are now no longer any events separating the vertices, the connection between $(0,A)$ and $(0,B)$ is no longer 'non-local'.
- *At the level of the spacetime relationship among all the neighboring events within that region:* At this level, there is of course a triangular spacetime region between the three events. But these are of no use in determining the inherent relation between a at $(0,A)$ and b at $(0,B)$ because spacetime events between a and b up until they have 'actualized' have no bearing on the inherent relation between them, as these are given by metric relations in areatime, not in spacetime. The spacetime events in between do, however, help an observer determine what the spacetime relations between these events *would haven been* had $(0,A)$ and $(0,B)$ been ordinary spacetime events (i.e. with world lines connecting them to $(0,0)$). The juxtaposition of the intersection of the future light cone of all these spacetime events within the triangular region with an observer's world line give the observer an indication of the time order of $(0,A)$ and $(0,B)$ in his frame, but this means that the best an observer can do is to relate the results of the outcomes of the measurements according to the order in which he receives them, which is to say, to order them as they occur on his own worldline.

Our choice of straight worldlines forming a triangular enclosed spacetime region was arbitrary. Therefore, the same argument can be extended to any worldline between the emission event and one of the measurement events, and in particular worldlines that maximize the region of spacetime enclosed. Given that the path integral is formed out of all possible paths, this means that all spacetime events enclosed by the worldlines associated with these paths are excluded from the determination of the inherent interactions between the events.

6 Conclusion

This paper attempted to provide an explanation of the EPR paradox based on a framework recently introduced by this author called the dimensional theory. The explanation for the EPR paradox, however, does not necessarily follow just from the dimensional theory, e.g. that quantum objects are manifestations of events that actually exist in areatime. It appears that any theory will be able to provide it if it contains these assumptions: (1) quantum particles do not exist in spacetime until they are measured, and (2) there are connections between quantum particles outside spacetime.

It seems inevitable to come to the overall conclusion that if the explanation for the EPR paradox provided in this paper, even if based just on these two assumptions, is correct then spacetime is emergent in the following sense: a very large number of discrete events that correspond to what in quantum mechanics are called 'measurements' aggregate to give rise on a large scale to the apparently smooth reality we experience in our daily lives.

References

[1] J Townsend *A Modern approach to Quantum Mechanics* McGraw-Hill, New York (1992)

[2] D Griffiths *Introduction to Quantum Mechanics* Pearson Education, Upper Saddle River 2nd. Ed. (2005)

[3] L Ballentine *Quantum Mechanics* Prentice Hall, New Jersey (1990)

[4] S Summers, R Werner *Phys. Lett.A* **110**, 257-259 (1985)

[5] T Maudlin *Quantum Non-locality and Relativity* Blackwell Publishing, Malden 2nd Ed., (2002)

[6] D Salart *et. al* Nature **454** 861-863 (2008)

[7] A Einstein *et al.* Phys. Rev. **47**, 777-780 (1935)

[8] J Bell Physics, **1**, 195-200 (1964)

[9] D Bohm, Y Aharanov Phys. Rev. **108**., 1070-1076 (1957)

[10] A Aspect *et. al.* Phys. Rev. Lett. **49**, 1804 (1982)

[11] Phys. Rev. Letters **28**, 938 (1972)

[12] Phys. Rev. Letters **81**, 5039 (1998)

[13] G Belot *Philosophy of Quantum Mechanics* Lecture Notes of Course given at University of Michigan, Ann Arbor (03/08/2011)

[14] N Gisin *Are There Quantum Effects Coming from Outside Space-time? Non-locality, free will and "no many-worlds"* arxiv:quant-ph/1011.30440 (2010)

[15] R Feynman, A Hibbs *Quantum Mechanics and Path Integrals* Dover publications, New York (2010)

[16] A Nikkhah Shirazi *Ontology and the Wave Function Collapse* http://deepblue.lib.umich.edu/handle/2027.42/83153 (2011)

[17] A Nikkhah Shirazi *A Derivation of the Quantum Phase* http://deepblue.lib.umich.edu/handle/2027.42/83154 also available at http://www.fqxi.org/community/forum/topic/954 (2011)

[18] A Nikkhah Shirazi *Quantum Superposition, Mass, and General Relativity* http://deepblue.lib.umich.edu/handle/2027.42/83863

[19] W Wootters, W Zurek Nature, **299**, 802 (1982)