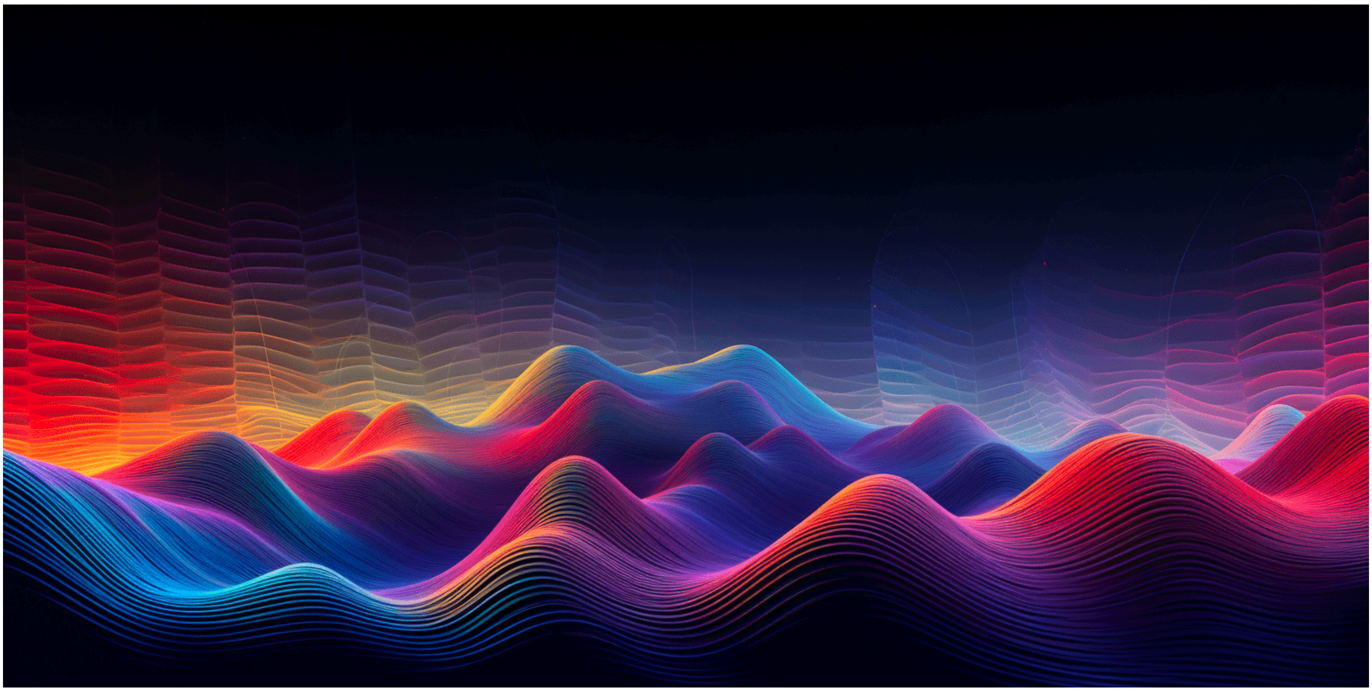
Locating nondeterministic events and their causes in spacetime for a wave function that represents both objective and subjective uncertainty

David Gentile



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Abstract:

Two of the most important challenges to an objective interpretation of the wave have solid proposed partial solutions. We summarize two recently published ideas and focus on where and when nondeterministic events occur in spacetime. Specifically, we look at (Hobson, 2022), which describes an objective wave function with no additional collapse hypothesis. We try to elucidate this proposed solution to the measurement problem and focus on where it positions nondeterministic events in spacetime. We then turn to (Price H, 2015), which builds on (Costa de Beauregard, 1953). The "zigzag" causality presented there seems to be generally misunderstood as retrocausality. However, no signals are sent into the past light cone. We discuss how this idea can overcome the problems that objective wave function interpretations have with special relativity, and again, we focus on the loci of nondeterministic events. Taken together, they provide an answer to the most serious objections to an objective interpretation of the wave function and answer the question of when and where objective uncertainty associated with the wave function becomes subjective uncertainty.

Keywords:

Objective wave functions, Measurement problem, Nonlocality, Nondeterministic events, Spacetime.

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Abstract

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Contents

1. Introduction.

Two of the most important challenges to an objective interpretation of the wave function have solid proposed partial solutions. We summarize two recently published ideas and focus on where and when nondeterministic events occur in spacetime. Specifically, we look at (Hobson, 2022), which describes an objective wave function with no additional collapse hypothesis. We try to elucidate this proposed solution to the measurement problem and focus on where it positions nondeterministic events in spacetime. We then turn to (Price H, 2015), which builds on (Costa de Beauregard, 1953). The "zigzag" causality presented there seems to be generally misunderstood as retrocausality. However, no signals are sent into the past light cone. We discuss how this idea can overcome the problems that objective wave function interpretations have with special relativity, and again, we focus on the loci of nondeterministic events. Taken together, they provide an answer to the most serious objections to an objective interpretation of the wave function and answer the question of when and where objective uncertainty associated with the wave function becomes subjective uncertainty.

2. Types of uncertainty

Let's define two different types of uncertainty. One we will call intrinsic or objective uncertainty, and the other is epistemic or subjective uncertainty. The first represents real uncertainty in the universe, and the other is about what information we have available. In statistics, historically, these conceptions of probability divided mathematicians into two camps, classicists and Bayesians, although today, both are mostly accepted as two valid but different approaches to probability. One simple example of a coin flip is enough to illustrate the difference. Suppose someone flips a coin and holds the result behind their back. To a classical statistician, the coin is represented as a random number generator. The odds are 50/50 heads/tails before the flip. However, when the coin is flipped but still hidden, the probability is now 1 or 0. We just don't know which. To the Bayesian, the odds are still 50/50 until we learn the result because Bayesian statistics is concerned with the information available to us.

While completely epistemic interpretations of quantum mechanics exist (Ali Barzegar, 2022), here, we assume that quantum systems can and do exhibit real objective, intrinsic uncertainty. This can be illustrated by many experiments, but the most well-known may be the classic 2-slit experiment. The photons in this experiment clearly seem to pass through both slits in order to interfere with themselves. Both states exist in superposition with each other. This kind of uncertainty is more than us just not knowing which path the photon took. We might say the universe does not even "know".

Our macroscopic world does not exhibit this sort of behavior, nor does classical physics. The coin flip in classical physics would not be described as intrinsically random, but rather, we just lack enough information about the momentum and rotation of the coin, air currents, details of the surface it will land on, etc. Somehow in moving from the quantum world up to the macroscopic world, intrinsic uncertainty is lost.

Here, we assert that the wave function can represent objective uncertainty, subjective uncertainty, or a combination of both, depending on the circumstances and that the transformation from one type of uncertainty to another is invisible in our standard Dirac notation. From the perspective of an "outside" observer, not entangled with an observed system, we treat all interactions within the system as unitary. The wave function then gives a perfect description of the system from this perspective, but what portion of it represents objective versus subjective uncertainty is unclear in the standard notation.

From the perspective of an observer "inside" the system, entangled with the system, we treat all new entanglements as "micro-observations". One particle can "observe" another. This transforms some objective uncertainty into subjective uncertainty, at least temporarily[1], with every new entanglement. Assuming a new measurement is not completely compatible with the previous measurement, a "coin is

[1] Micro-observations can be easily erased. Performing a new observation on an orthogonal basis to an existing measurement will destroy the information gathered by the previous measurement and create new objective uncertainty regarding the previously measured values.

flipped" when this happens. A nondeterministic event takes place[2]. That is, from inside the system, projection onto some (unknown) basis has occurred, and a variable measured on that basis now has a definite value, while from an outside perspective, subjective uncertainty remains. Objective uncertainty also persists, however. Other variables which would have to be measured on an incompatible orthogonal basis remain objectively undetermined.

The wave function describes the total uncertainty, objective and subjective combined. One might ask "Exactly who's subjective uncertainty?" So, to be more precise, the wave function describes the minimal uncertainty that is present for ANY observer outside of the system. An individual observer could have greater uncertainty, for some idiosyncratic reason, unrelated to physical laws, but not less uncertainty. We label it "subjective" because the uncertainty is due to a lack of information. The information exists but is unavailable. Similarly, the objective uncertainty represents the minimal uncertainty that any observer must have, even if entangled with the system. We label it "objective" because the information needed to resolve this sort of uncertainty does not exist.

3. The measurement problem

In (Hobson, 2022), a pair of entangled photons or a biphoton is considered. Suppose two experimenters, Alice and Bob, each receive one of the pair. Each of the photon paths has been split into two paths they can follow with 50% probability. Because the states are correlated, if Alice receives a photon via path 1, then Bob will as well and the same for path 2. We can write the wave function as:

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (1)$$

Suppose Bob puts a phase inhibitor on one path and tries to get his photon to interfere with itself. He will not be successful. As (Hobson, 2022) points out, experiments have shown that this does not happen. (Hobson, 2022) following (M. A. Horne, 1990) and (M. A. Horne, 1989) also explains the theoretical reason interference does not appear; the nonlocal photon's contribution needs to be considered. When this is done, the phases always line up so that the photons decohere each other[3]. Thus, all experimental evidence of superposition has been eliminated. Other quantum phenomena such as entanglement persist, of course. The experimental setup discussed is diagramed below (fig. 1):

[2] Special relativity poses a challenge for locating these nondeterministic events in spacetime and we address this in section 4.

[3] This is not the first suggestion that decoherence can solve the measurement problem (Bacciagaluppi, 2020), but it is a useful current example and a good jumping off point for our discussion here.

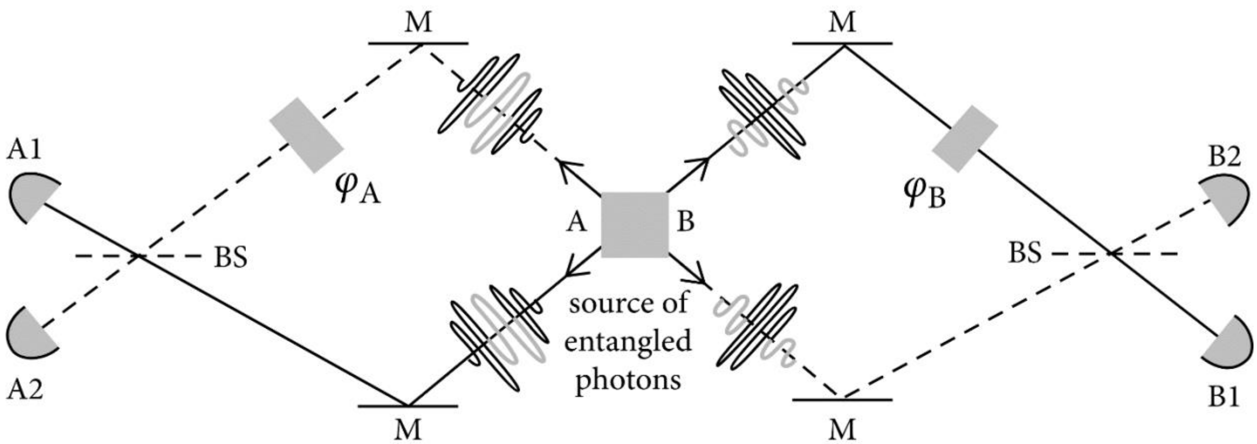

Figure 1 – A diagram of the experimental apparatus discussed.

We can write the two-point nonlocal quantum field amplitudes at the detectors as:

$$\psi_{A1,B1} = \psi_{A2,B2} = \frac{1 + exp(i\,\phi_B)}{2\sqrt{2}} \; (2)$$

$$\psi_{A1,B2} = \psi_{A2,B1} = \frac{1 + exp(i\,\phi_B + \pi)}{2\sqrt{2}} \; (3)$$

where ϕ_B is the phase change imposed by Bob and we have assumed Alice is not altering her photon and the various phase changes imposed by the experimental set up have been subsumed into a zero phase shift in eq. (2) and a shift of π in eq. (3)[4].

The joint probabilities are then given by:

$$P(A1, B1) = P(A2, B2) = |\psi_{A2,B2}|^2 = \frac{1 + cos(\phi_B)}{4} \; (4)$$

and

$$P(A1, B2) = P(A2, B1) = |\psi_{A2,B1}|^2 = \frac{1 + cos(\phi_B + \pi)}{4} \; (5)$$

Then, we have P(B1) = P(A1,B1) + P(A2,B1) = 0.5 regardless of the phase. And in general, P(A1) = P(A2) = P(B1) = P(B2) = 0.5 regardless of any phase change added by Bob.

The lack of superposition allows us to interpret equation (1) in different ways. If we suppose that intrinsic uncertainty still exists, we will obtain the right answers using our mathematical expressions. However, we can also suppose that intrinsic uncertainty has been eliminated and that all that now remains is epistemic uncertainty about which path the photon has taken. Either interpretation gives us the same results – 50% probability, consistently, at every detector.

Here, we assume the latter. The "coin" has already been flipped. Thus, one crucial component of what we need a measurement to accomplish has already occurred. One single entanglement counts as an "observation". We can legitimately speak of Alice's photon as the observed system and Bob's photon

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[4] In effect what we have done is to assume that Alice and Bob are initially measuring on a pure state basis, before any phase shift is introduced by Bob. This will not be the case in general, but it makes the example pedagogically simpler and changes nothing important in the analysis.

as our measuring device, which we have not yet queried. A nondeterministic event has occurred which as (Gillis, 2019) points out, must take place at some point in an objective wave function interpretation. We are not suddenly dealing with a classical system of course. We can still do things like erase the measurement or reintroduce objective uncertainty, but for the moment Bob's photon has measured Alice's and vice versa and the pair can now be viewed as having one or another determined value on the measured basis but not both values, we simply do not know which.

To complete a classical observation, however, we have a couple more steps. First, one of the photons, let's say Bob's, must become entangled with Bob's measuring device and then with Bob. Something important happens in each of these steps. We then have:

$$|\psi_B\rangle \otimes |Device\rangle \otimes |Bob\rangle \quad (6)$$

Once entanglement with the macroscopic device takes place, the measurement can become thermodynamically irreversible. Whereas we could have erased the "memory" of a single photon, the result has now left an indelible mark on the universe[5]. Finally, Bob looks at the measurement. Let's say he finds the photon took path 1. Now, we can finally write:

$$|\psi_A\rangle = |A1\rangle \quad (7)$$

with no uncertainty. No wave function collapse postulate is needed here. Since Bob is now part of the entanglement, he now knows which path has been taken. However, from the moment of the first entanglement forward, the wave function for path 1 represented reality, whereas the wave function for path 2 merely represented Bob's ignorance as to the result[6] and a potential, alternate, uninstantiated reality.

One thing to note here is that the Dirac notation we use is perfectly suited for the Copenhagen interpretation of QM, which dominated physics for decades. The unmanifested part of the wave function only disappears when a human observation takes place and only then does epistemological uncertainty disappear. The notation makes no distinction between objective and subjective uncertainty. This is understandable since it does not need to make such a distinction in order to make correct probabilistic predictions.

Let us then be more explicit about where each type of uncertainty exists in our equations. At the time of the initial entanglement, we posit that the photons are set to a pure state on some unknown basis, say u, for "unknown". For simplicity let's assume that Alice and Bob both just happen to be set up to measure on this basis. The case then is that we either have $|A1\rangle|B1\rangle$ or $|A2\rangle|B2\rangle$ each with 50% subjective probability. The coin has already been flipped in this case, and no new uncertainty is introduced. Bob's photon has measured Alice's on one basis and vice versa.

One might object that having this information "preset" when the photons are still together constitutes "hidden variables". But Bell's inequality only tells us that it is not possible for multiple measurement bases to be preset (Storz, 2023). It is not possible in this example that values on the u measurement basis are preset and then also have preset values on an incompatible orthogonal basis

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[5] More on this point, below in this section.

[6] Again, this assumes that Bob and Alice happen to be measuring on the same basis with which the photons measured each other although this need not be the case in general.

such as v or w. Hidden variables sufficient to explain Bell nonlocality have been ruled out experimentally; however, that does not mean there cannot be an ANY hidden variable[7].

Let us now have Bob change the phase by π/2.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (8)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (9)$$

We now have introduced new objective uncertainty because Bob's basis of measurement has changed. Bob's measurement is now completely uncorrelated with Alice's, and the result is intrinsically uncertain before measurement. We still have a 50% subjective chance of A1 or A2. And now, in each case, there is a 50% objective chance of B1 or B2. That objective uncertainty will be resolved when Bob's photon first becomes entangled with his measuring device. This distinction between types of uncertainty is invisible, however, in our notation. We might instead wish to write something like the following where P_T, P_O, and P_S represent the total probability, the objective probability, and the subjective probability, respectively.

$P_T(B1) = P_S(A1) * P_O(B1)|P_S(A1) + P_S(A2) * P_O(B1)|P_S(A2)$ (10)

$P_T(B1) = 0.5 * 0.5 + 0.5 * 0.5 = 0.5$ (11)

Carefully inspecting the above argument might cause an objection. We have posited that Bob's photon was on one path or the other, but not both until he changed the phase and made a measurement on an incompatible orthogonal basis. Now it is on both paths again, with an objective uncertainty as to which. Clearly, the wave function did not disappear or "collapse", and we are not claiming it has. It still represented a potential alternative reality, but not an instantiated one. A well-known result in quantum mechanics is that if we perform a measurement and then measure again on an incompatible orthogonal basis, the information from the first measurement is destroyed. Alice's photon measured Bob's photon, and Bob's photon was in a definite state where only subjective uncertainty existed until Bob erased this information and reintroduced objective uncertainty.

We have not left the world of quantum weirdness behind; at best, we are starting to straddle the line between the quantum and macroscopic worlds. Measurements can be erased, and objective uncertainty reintroduced. Thus, the removal of objective uncertainty is only a partial solution to the measurement problem. To complete the "trip" to the macroscopic world, we need many entanglements, where each micro-observation changes a bit of objective uncertainty into subjective uncertainty, and then thermodynamic irreversibility ensures that the result cannot be erased.

In a chaotic macroscopic object, most new entanglements will neither perfectly preserve previous measurements nor perfectly erase them. To simulate a new random entanglement let's have Bob set the angle to $\pi/4$.

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[7] This idea takes the middle ground in the historical Einstein, Bohr debate where Einstein thought there must be sufficient hidden variables to avoid any nonlocality and Bohr believed the wave function was a complete description of the system.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\pi/4)}{4} + \frac{1 + cos(\pi/4 + \pi)}{4} = 0.43 + 0.07 = 0.5 \quad (12)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\pi/4)}{4} + \frac{1 + cos(\pi/4 + \pi)}{4} = 0.43 + 0.07 = 0.5 \quad (13)$$

$P_T(B1) = P_S(A1) * P_?(B1)|P_S(A1) + P_S(A2) * P_?(B1)|P_S(A2)$ (14)

$P_T(B1) = 0.5 * 0.85 + 0.5 * 0.15 = 0.5$ (15)

Here, we have used $P_?$ for a probability that is neither purely objective nor subjective. Knowing the measurement from Alice's photon here would give us 85% certainty about the path of Bob's photon. We might somewhat arbitrarily say 70% of the uncertainty is now subjective and 30% of the uncertainty is objective, depending on how exactly we wish to quantify it. We don't know Alice's result so overall, including our subjective uncertainty, the results are still 50/50, but the objective uncertainty is not as great as when Bob completely erases the previous measurement.

For a macroscopic measuring device, however, the basis of measurement will not be random. Bob has separated the photon's paths by a macroscopic distance. When multiple entanglements take place at his detector, they will all be measuring on a very similar positional basis. Thus, while each measurement might erase a small portion of the information gained by the previous measurement, most of the information from each measurement will be preserved, and there will be a myriad of separate, perhaps slightly imperfect, records of the event, each with very little, if any, objective uncertainty. Thus, objective uncertainty is essentially eliminated by the time we reach the macroscopic observer.

Additionally, and importantly, macroscopic observations cannot be erased. It will not be possible to introduce a single new observation on a basis that is completely orthogonal to the bases of all the existing micro-observations. We have "too many witnesses" now, each with a slightly different perspective. In addition, thermodynamic chaos will ensure that we cannot address each particle individually. With a macroscopic number of "witnesses" even if each of them only has a partial "memory" of the event, when taken together, they represent a permanent record that the event took place.

Let us suppose, for example, that after many entanglements, an attempt at a hypothetical macroscopic measurement on an orthogonal basis is made, such as is done in the new Wigner's friend thought experiment. For example, see (Nick Ormrod, 2023). It cannot be on a basis orthogonal to the bases used for all the existing micro-measurements, however. So, although perhaps it can mostly erase them, it cannot do so completely. Let's suppose an original value of "1" is recorded in a quantum experiment rather than an alternative "0". Initially, a myriad of micro-measurements on nearly parallel bases all record it as "1". After an attempt at erasure, suppose the typical particle or "micro-measurement device" only retains a small degree of correlation with the initially measured particle. As in (12) and (13), we have a combination of uncertainty types. In this case, objective uncertainty predominates, but subjective uncertainty is not completely eliminated. Even if knowing the result of a given micro-measurement would now only give us only 51% certainty that the initial result was "1", we can repeatedly use Bayes' formula[8] for probability updates across a macroscopic number of micro-

[8] $P(H_i|E) = P(H_i)\ P(E|H_i)/P(E)$

where:

observations. The result will be (almost) 100% certainty that the initial result was "1". To an observer entangled with the system, with potential access to all these micro-measurements, there is still zero uncertainty as to the initial result. Erasure failed. To an observer outside the system, of course, subjective uncertainty persists until they "open the box and take a look at the cat". Until then, the wave function still describes their epistemological state but no longer describes a potential uninstantiated alternate reality. That path is now permanently closed.

4. Zigzag causality

Now, let us suppose that both Alice and Bob alter their basis of measurement by π/2. This presents a new problem for locating the nondeterministic event in spacetime. Both of them have caused a measurement to take place, and both results, taken individually, are random, but they perfectly correlate when considered together. We know from recent experiments (Storz, 2023) that nonlocal correlation is demonstrated fact[9]. But even this is not enough to resolve the problem. There is no definite ordering of events with space-like separation in SR. (Gillis, 2019) writes, "In general, it is very difficult to construct a coherent account of effects that are both nonlocal and nondeterministic without assuming some underlying sequence."

If we, for example, say that Alice caused a nondeterministic event and locate it with her and then say Bob's photon was instantly correlated at a distance, observers in some reference frames would disagree since Bob's measurement happened first in their frame. How can there be two separate causes for what we could describe as one event? The biphoton will have its intrinsic uncertainty resolved into subjective uncertainty, but who caused this? And, what exactly does "instantaneous" correlation mean in a relativistic context where observers cannot agree on what events are simultaneous? What is needed is a Lorenz invariant definition of "instantaneous". Fortunately, one is available.

The past light cone of an event is Lorentz invariant. For this discussion, we will want to define "Lorentz invariant instantaneous" transmission of information as transmission of information from an event along the surface of the past light cone of that event. Importantly, this is not retrocausality. No information reaches the interior of the past light cone. In addition, it conforms with at least one common sense notion of instantaneous. Let us use a sci-fi example here. Alice is on a space station in the Alpha Centauri system, four light years from Earth. Bob is on Earth and, via ordinary light speed communication, receives the words of an important conference on the station. Bob then gets in his warp teleporter and arrives "instantaneously" in time for the conference by traveling along the surface of his past light cone. This is of course impossible and allows for superluminal signaling and time travel paradoxes, etc. However, it illustrates the sense in which this is "Lorentz invariant instantaneous" transport.

Let's set up a spacetime diagram with space along the x-axis and time along the y-axis. In the diagram below (fig. 2), Alice and Bob now have a space-like separation. Let's locate Alice's observation at

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$$P(E) = \sum_{i=1}^{n} P(H_i)\, P(E|H_i)$$

H_i here represents the hypothesis "1" and E is the slight evidence from each individual micro-measurement.

[9] Assuming we do not allow superdeterminism.

(-1,0) or what we will call (A,0) and Bob's at (1,0) or (B,0). Since they have a space-like separation, a frame of reference in which they are simultaneous will exist, and this is the frame we are choosing for convenience. The observations need not be exactly simultaneous in their rest frame. The origin of the diagram will be the midpoint between them in the chosen frame of reference, (M,0). Spatial units are equal to the time units multiplied by c. If Alice and Bob are receiving a pair of photons that have traveled unimpeded through empty space, then point (M, -1) will be the origin point of those photons[10]. However, if they are dealing with subluminal particles or if the light has been disturbed in some way, this will not be the case.

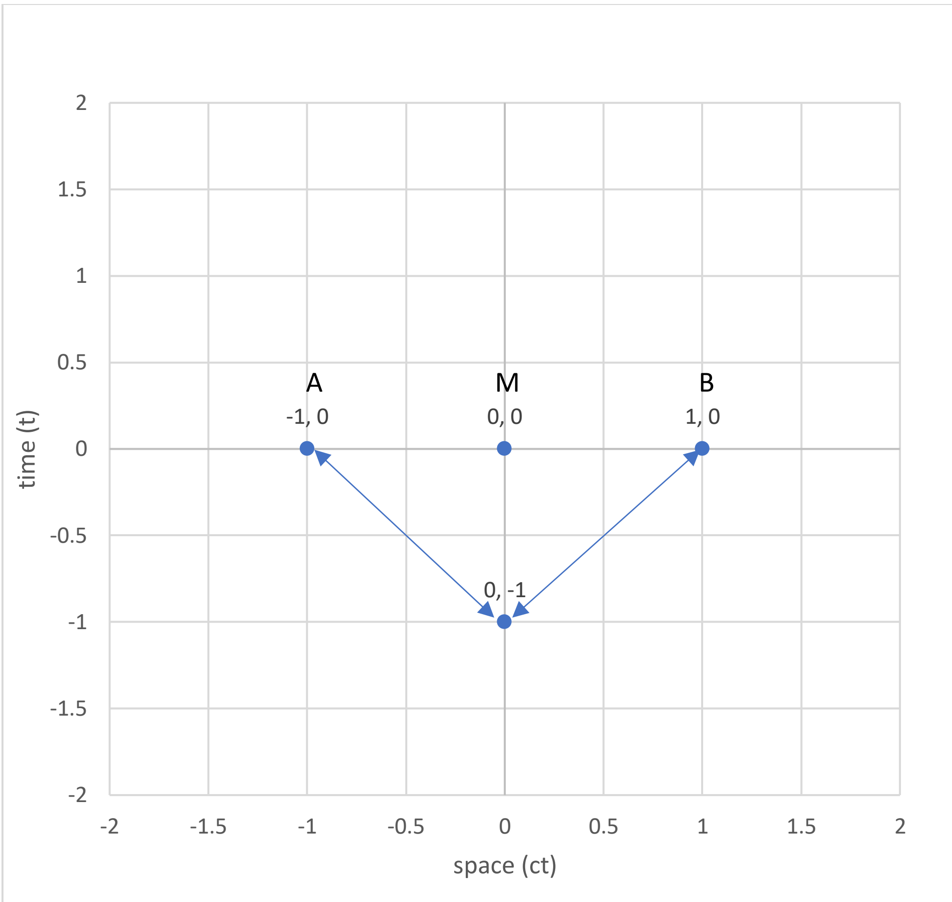

Figure 2 – A spacetime diagram showing the locations of Alice's and Bob's measurements and a location between them.

How do the observations which Bob and Alice each make become correlated? One's first thought would be that somewhere in the past light cones of A and B there was a causal event that resulted in this correlation. However, "hidden variable" models such as this have been eliminated experimentally (Storz, 2023). We might also suppose there is superluminal communication between them and locate the cause of the correlation in the "other-where", or we might even try to locate the cause of the correlation somewhere in the future light cones of the events and suppose retrocausality exists. However, signals

[10] Or in reality, (M,-1) will be just slightly forward in time from the creation event of the photons, since the measurements Alice and Bob perform will take some short time.

such as these violate Einstein's theory of special relativity. This, then, should not be our first choice, and we should look here only if there are no better alternatives.

Other possibilities include the idea that any cause for the correlation must be outside of spacetime or that there simply is no cause, and the correlations simply just happen. This essentially amounts to giving up and simply accepting the correlations as inexplicable. Such explanations "explain too much" in that they could be invoked to "explain" just about anything without truly giving us much if anything in the way of a real explanation. And thus again, we should search for a better choice and only turn to these options as a last resort.

This is almost an exhaustive list of the possibilities, but there is still one small loophole. We could locate a causal event on the surface of the past light cones of events A and B. Specifically, the future-most point where their past light cones intersect will be the point (M, 1), and we propose to locate the causal event here. Einstein does not prohibit it here since news of the "decision" made here is transmitted to (A,0) and (B,0) at light speed. Nor is this location eliminated by experiments eliminating hidden variables that were set prior to the times the observations were made since the information does not exist at A or B until the exact moment of the measurement. And while locating the cause here may have its own issues, it seems preferable to simply throwing up our hands and declaring the correlation to be causeless or the result of an unknowable cause. This is not a new proposal. (Costa de Beauregard, 1953) first articulated it, and more recently (Price H, 2015) added additional motivation for the idea. Here, we explore its implications for the location of nondeterministic events.

Let us suppose Bob performs a measurement at point (B,0) and causes a nondeterministic event. How could this information be present at point (M, 1)? First, one thing to note is that in a reference frame of an observer (or a quantum wave front) traveling at light speed from M to B, the two points (B,0) and (M,-1) are exactly the same point in spacetime, and there is no spatial separation at all. The Lorentz contraction has eliminated the separation distance. Similarly, for an observer traveling at light speed from M to A, the points (A,0) and (M,-1) are identical. It would, therefore, not seem to be a violation of the prohibitions of the theory of relativity for information about the wave function at (A,0) and (B,0) to be present at (M,-1). Additionally, we should consider the specific type of information that we are saying is available. Phase information about the wave function must be shared. And because the wave function propagates at the speed of light, the phase of Bob's photon at point (M,-1) and at point (B,0) will be identical.

In addition to the current phase of the quantum wave function, information about what basis Bob and Alice are measuring on must also be present at (M,-1) for the nondeterministic event to be located here. But again, when Bob measures at point (B,0), he also measures at point (M,-1) since it is the same point in spacetime when viewed from the reference frame of the moving wavefront. The same is true for Alice and her measurement of her photon. Information dependent on Bob's phase change can then propagate to Alice from (M,-1) at light speed and vice versa.

In the reference frame of a subluminal observer, we would say that "Lorentz invariant instantaneous" transmission of information about the measurement is sent from points (A,0) and (B,0) and point (M,-1) is where those two pieces of information first collide. A nondeterministic event takes place there, and the results are transmitted to (A,0) and (B,0) at ordinary light speed. Again, no retrocausality is involved here.

Alice and Bob jointly, through their choices of when and where to measure, cause the selection of the point (M, 1) rather than some other point in spacetime[11]. Their phase and measurement information are then Lorentz-invariant-instantaneously shared with point (M,-1). This then causes a "decision" about which particle orientation goes to whom to be made, and Alice and Bob then receive the results of this single nondeterministic event at light speed, arriving immediately after their measurement is made.

Notice how neatly this model avoids any superluminal signaling. No matter when and where Bob measures, his information only arrives as Alice measures. It is impossible for Bob to change Alice's probabilities before her measurement, which would allow for signaling.

What have we gained by supposing this "zigzag" causality? Firstly, we've put "spooky action at a distance" on a somewhat more relativity-friendly footing. We can think of the universe as a super observer that has access to any information any local observer could have in any reference frame. This would include, of course, all information in the past light cone, but it would also include access to at least wave function phase information along the surface of the future light cone. Again, this is not knowledge of the absolute future but Lorentz invariant instantaneous knowledge at a distance. In the sci-fi example, it would be Alice getting a message from Bob just before he steps into his warp teleporter to say that he is on his way. Bob will not bring with him any information about Alice's future since that information, traveling at light speed, has not reached him yet.

Secondly, we have only a single nondeterministic causal event rather than two events. This might make development of a quantum field theory for objective wave functions a much easier task. To date, one has not been developed (Ghirardi, 2020).

5. A brief taxonomy of this interpretation.

In recent years, a new, more complex version of the Wigner's friend experiment has garnered interest. (Frauchiger, 2018) A key feature of these thought experiments is that they treat an observer as a quantum system in a larger experiment and arrive at a contradiction. The contradiction can be resolved but only at a cost. Different authors have published proofs that enumerate all logical possibilities (Bong, 2020) (Nick Ormrod, 2023). This provides a couple of different taxonomical systems with which to classify interpretations. Working through the possibilities on a couple of these lists, let us start by saying what this interpretation is not.

1. Events are absolute. Two different observers don't disagree on the result of a measurement.[12]

2. There is only one world; no multi-world hypothesis is needed.

3. Bell nonlocality is a fact.

4. There is no superdeterminism. Choices are possible.

[11] The intersection of the past light cones is not just a single point, but (M, -1) is the only point directly between the observations and is the most time-forward point on the intersection. Nothing seems to be gained by considering the other points of intersection.

[12] This is only true for macroscopic observers. "Micro-observations" can be erased and are therefore not absolute.

5. There is no superluminal causation or signaling, nor retrocausality, nor superluminal dynamics.

One implication of the above is that you cannot treat a macroscopic observer as a quantum system as is done in the new Wigner's friend thought experiment. Macroscopic systems constantly transform objective quantum uncertainty into ordinary subjective uncertainty with every particle entanglement. In addition, macroscopic observers differ from subatomic ones in that they are nonerasable. It will not be possible to make a single measurement on a basis that is perfectly orthogonal to all the existing micro-observations. And thermodynamic irreversibility ensures that the particles cannot all be addressed individually. The myriad imperfect micro-records of the event now add up to a permanent macroscopic record of the event.

Another implication is that information about the past is lost (Nick Ormrod, 2023). We can't simply rewind the film, so to speak. When nondeterministic events occur, they pick one path, and eventually, after multiple entanglements, there is essentially no record that the other path ever existed. This is the flip side of having a future that is not predestined. An arow of time exists, and paths not taken are forgotten.

While it is not our purpose here to reanalyze the thought experiment, it does provide a good context for a brief discussion about how we should think about a wave function that can represent objective uncertainty, subjective uncertainty or a combination of both. The total probability, objective plus subjective, is the probability to an observer outside of the system, where all interactions inside the system are treated as unitary interactions. It represents the minimal uncertainty that any outside observer must have. The objective probability is what is uncertain to an observer that is part of the system, where we treat the new entanglements as observations and as projections onto some measurement basis. It represents the minimal uncertainty that any observer must have. Thus, there is no wave function collapse when a human observer becomes involved; all that happens is that we are allowed an inside perspective once we ourselves become entangled with the system. However, the inside perspective has existed all along.

Our solution to the paradox does not pick just one of the possible resolutions to the puzzle but treats the list more like a menu and picks a little bit of a couple options.

1) Special relativity is "bent but not broken" to accommodate Bell nonlocality.
2) Micro-observations are not absolute because they can be erased.
3) Macroscopic observers cannot be treated as quantum objects because their observations are thermodynamically irreversible and nonerasable.

In short, in the thought experiment (Nick Ormrod, 2023), Alice and Charlie have a spacelike separation from Daniella and Bob. All perform measurements. Daniella precedes Bob. According to SR, both the pairs A-D and A-B can be regarded as simultaneous events. And given Bell nonlocality, we must assume that Alice's measurement will instantaneously correlate with both B and D. However, given the theory presented here, we can say that the nondeterministic event associated with the A-D measurement pair occurs earlier on the surface of Alice's past light cone than the nondeterministic event associated with the A-B measurement pair. The latter then supersedes the former, and Bob's measurement on an orthogonal basis to Daniella's measurement effectively erases hers, assuming Daniella's measurement is a quantum micro-measurement and not an observation by a macroscopic observer, in which case Bob will not be able to perform a completely orthogonal measurement.

Summary

We treat all new entanglements as micro-observations from an "inside" perspective. These observations transform objective uncertainty into subjective uncertainty on the basis measured but leave other potential bases of measurement objectively undetermined. This transformation of uncertainty is invisible in standard Dirac notation. If we look again at equation (1):

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (1)$$

Depending on the basis on which Alice and Bob choose to measure it may represent completely subjective uncertainty, in the case where they both measure on the same basis on which the photons measured each other. Or it may represent completely objective uncertainty in the case where they measure on a basis orthogonal to the original. Or it may represent a combination of both if they measure on some other random basis.

The wave function represents the total probability, objective plus subjective, the minimal uncertainty that any outside observer must have. The objective probability is what is uncertain to an observer that is part of the system, the minimal uncertainty that any observer must have.

On a quantum level, measurements are erasable. However, in general, random new entanglements will each reduce the ratio of objective to subjective uncertainty, and as these accumulate and become thermodynamically irreversible, we are left with only subjective uncertainty and results that cannot be erased.

If more than one measurement is performed on a biparticle and the measurements are at space-like separated locations in spacetime, then the nondeterministic event which transforms objective uncertainty into subjective uncertainty will take place at a point directly between the measurement events in space and situated at the intersection of the surface of the past light cones of the measurement events.

This gives us an interpretation of quantum mechanics that avoids difficult ideas such as non-absolute macroscopic events, many-world hypotheses, superdeterminism, superluminal dynamics and retrocausality. It does not abandon scientific realism as a purely subjective approach would. It acknowledges and accommodates the decisive experimental evidence for Bell nonlocality and refines a proposed solution to the measurement problem. It puts Einstein's "spooky action at a distance" on a more relativity-friendly footing and provides an arrow to time.

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