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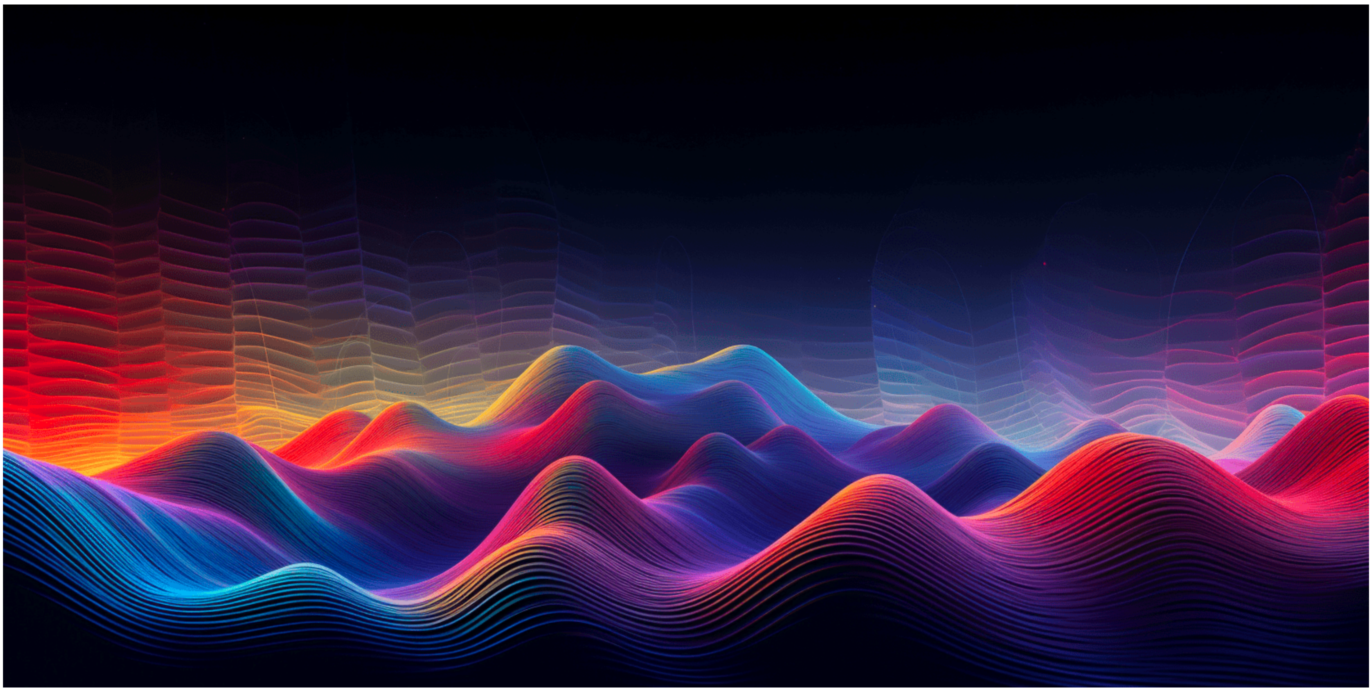
A single hidden variable interpretation of the quantum wave function

David Gentile



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Author: David Gentile

Location: Riverside, IL, USA

ORCID: 0000-0001-5777-761X

E-mail: gentile.david31@yahoo.com

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Abstract

An interpretation of quantum mechanics is presented in which there is one hidden variable. While this number of hidden variables is insufficient to explain Bell nonlocality it can help solve the measurement problem. It also provides an explanation of the delayed choice quantum eraser experiment that does not involve retroactive erasure of "which way" information and is more intuitive than current explanations. In addition, it offers a solution to the new Wigner's friend paradox. The key idea is that from the perspective of an outside observer, not entangled with an observed system, we treat all interactions within the system as unitary. However, from the perspective of an "observer" inside the system, entangled with the system, we treat all new entanglements as "micro-observations" and as a projection onto some basis of measurement. One particle can "observe" another. Thus, particles will have a defined value on one measurement basis from the inside perspective. This means that the wave function, from the outside view, will at times describe an objective uncertainty, at other times a subjective uncertainty and at yet other times a combination of both. The wave function describes the total uncertainty, the minimal uncertainty that is present for any observer outside of the system, while for an observer inside the system, only the objective part of the uncertainty remains. The hidden variable is invisible to the outside observer.

Contents

1. Introduction.

We begin in section 2 by defining two types of uncertainty, objective and subjective. We then assert that the wave function represents the total uncertainty to an outside observer not entangled with the system, a combination of objective and subjective uncertainty. From this outside perspective, all interactions are treated as unitary interactions. From a perspective inside the system, all entanglements are treated as projections onto some basis. The particles "observe" each other and give each other definite values on some (unknown) measurement basis. From this inside perspective, only objective uncertainty remains. Thus, from the outside perspective, there is one hidden variable – a definite value on some measurement basis that is unknown. One hidden variable is insufficient to explain Bell nonlocality; however, it is helpful with other problems. We attempt to show, for example, that it offers a

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solution to the measurement problem. In section 3, after the most basic example, we first discuss a configuration in which, from the outside perspective, only subjective uncertainty remains. We then turn to a situation in which measurement by one observer, Alice, will resolve subjective uncertainty, but another, by Bob, will resolve objective uncertainty. In this configuration, we attempt to show that the results of the delayed choice quantum eraser experiment can be addressed, and that this explanation is more intuitive than existing explanations. Then, in section 4, we turn to cases in which there is objective uncertainty for both experimenters. These examples will involve accounting for nonlocal correlations in order to explain their results. Then, in section 5, we attempt to tackle the measurement problem. In section 6, we consider various taxonomies provided by the new Wigner's friend thought experiment and show how this interpretation would resolve that paradox. Finally, in section 7, we provide a brief philosophical discussion.

2. Types of uncertainty

Let us 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 (Jaynes, 2003), 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 (Barzegar & Oriti, 2022), here, we assume that quantum mechanical 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 (Ananthaswamy, 2018). 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 that 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 simply lack sufficient information to make predictions. 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 from outside the system. 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 or at least gives us probabilities that accurately predict all experimental results, but what portion of it represents objective versus subjective uncertainty is unclear.

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From the perspective of an observer "inside" the system[1], entangled with the system, we treat all new entanglements as "micro-observations"[2]. One particle can "observe" another. This transforms some objective uncertainty into subjective uncertainty, at least temporarily[3], with every new entanglement. Assuming a new measurement is not completely compatible with the previous measurement, a "coin is flipped" when this happens. A nondeterministic event takes place. That is, from the perspective 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 regarding that variable's value remains. Objective uncertainty also persists, however. Values for 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[4]. We label the subjective part of the wave function "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. Thus, from an inside perspective, every entanglement pushes the amount of uncertainty present down toward the minimum allowable limit[5] (Heisenberg, 1925) (Ozawa, 2003) (Bastos, et al, 2015).

3. The basic idea and the delayed choice quantum erasure experiment.

Perhaps it is best to start with the simplest possible case as an example. Suppose we have one single random photon that we are not entangled with. From this outside perspective, we might write the wave function as:

$$|\psi\rangle = |\psi_{Initial}\rangle \quad (1)$$

Representing a superposition of all possible states. However, here, we assert that there is a hidden variable, only visible from an inside view, entangled with the system. The photon

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[1] This outside/inside language is borrowed from (Ormrod, Vilasini, & Barrett, 2023) where it is used to describe macroscopic observers with inside and outside perspectives in the new Wigner's friend thought experiment.
[2] We use the term "micro-observations" to describe entanglements, because like classical observations, the claim here is that they transform the wave function by projection onto some basis, from an inside, entangled perspective. However, they differ from classical observations in that they are not performed by a human, but rather by other particles, and unlike macroscopic observation they can be erased.
[3] 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.
[4] (Colbeck & Renner, 2011) show that any extension of QM can not yield improved predictions. In the interpretation presented here, knowledge of the hidden variable could yield better predictions, if it could be known from outside the system, but it cannot be known.
[5] Technically, there could be more than one hidden variable, so long as they were all compatible, since this is allowed by the uncertainty principle.

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already has a determined value on some basis. This value was determined by its most recent interaction.

$$|\psi\rangle = |U_+\rangle \quad (2)$$

This indicates a positive value on some unknown basis of measurement. But then, of course, on some orthogonal basis of measurement, say V, we could also write the wave function as a superposition.

$$|\psi\rangle = \frac{|V_+\rangle + |V_-\rangle}{\sqrt{2}} \quad (3)$$

In equations (2) and (3), we see the minimum possible uncertainty that must exist for any observer, even if they are entangled with the system. There is no uncertainty on some basis and objective uncertainty on some orthogonal basis. If we then consider equation (1), we can see that while it correctly predicts the results we will see if we measure multiple photons – namely, a random result on any basis on which we measure – it represents a mix of subjective and objective uncertainty. If we happen, by accident, to measure on the U basis, then our measurement will only resolve our subjective uncertainty as to the preexisting value. However, if we happen to measure on basis V, orthogonal to U, then our result is objectively undetermined until we measure, and a nondeterministic event occurs.

Let us now turn to a more complex example. 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 from an outside perspective, which represents the minimum uncertainty we must have from that perspective as:

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

Suppose Bob puts a phase shifter 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), citing (Horne, Shimony, & Zeilinger, 1990) and (Horne, Shimony, & Zeilinger, 1989), also says that the theoretical reason why interference does not appear is that the nonlocal photon's contribution needs to be considered. When this is done, the phases always line up so that, as (Hobson, 2022) puts it, "the photons decohere each other", that is, they prevent each other from creating an interference pattern. Thus, all experimental evidence of superposition has been eliminated in this configuration. (Hobson, 2022) contends that this represents a measured state[6]. The experimental setup discussed is diagrammed below (fig. 1):

[6] This is not the first suggestion that decoherence can solve the measurement problem (Bacciagaluppi, 2020), and while we do not completely agree with the presentation in (Hobson, 2022), it a good jumping off point for our discussion here, since it was while trying to understand the claim in (Hobson, 2022) that we had the idea for this paper.

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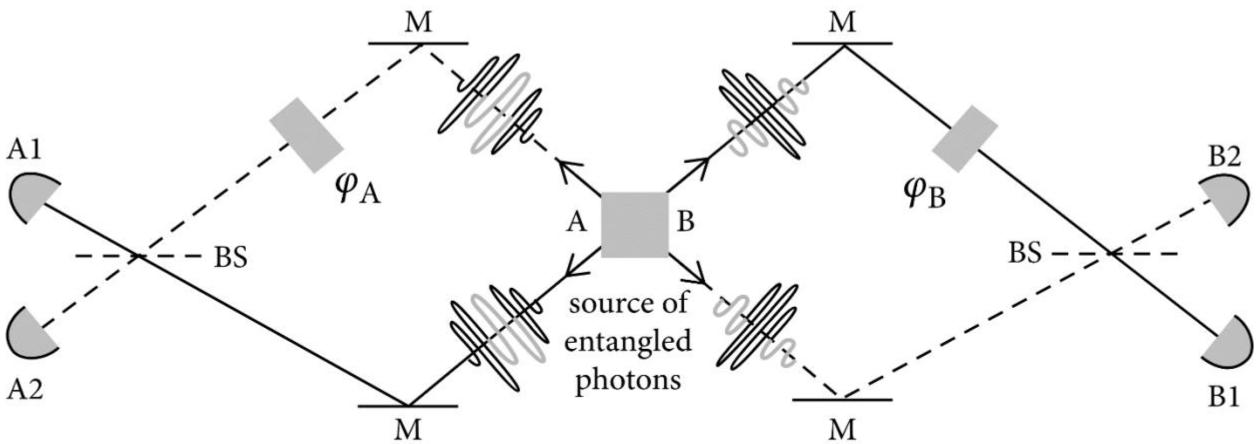

Figure 1 – A diagram of the experimental apparatus discussed here and in (Hobson, 2022).

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

$$\psi_{A1,B1} = \psi_{A2,B2} = \frac{1 + exp(i\,\phi_B)}{2\sqrt{2}} \quad (5)$$

$$\psi_{A1,B2} = \psi_{A2,B1} = \frac{1 + exp(i\,\phi_B + \pi)}{2\sqrt{2}} \quad (6)$$

where ϕ_B is the phase change imposed by Bob, and we have assumed that Alice is not altering her photon and that the various phase changes imposed by the experimental setup have been subsumed into a zero phase shift in eq. (5) and a shift of π in eq. (6)[7].

The joint probabilities are then given by:

$$P(A1,B1) = P(A2,B2) = |\psi_{A2,B2}|^2 = \frac{1 + cos(\phi_B)}{4} \quad (7)$$

and

$$P(A1,B2) = P(A2,B1) = |\psi_{A2,B1}|^2 = \frac{1 + cos(\phi_B + \pi)}{4} \quad (8)$$

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.

In this specific configuration, where Alice happens to measure her photon on the basis the photons measured each other, and Bob has set his phase shift to zero, let us suppose that the paths to detectors A1 and B1 represent reality. Then, to an outside observer unentangled with the system, who has subjective uncertainty, equation (4) still appears to be the correct description of the system and still describes their minimum possible uncertainty. Over many observations of many photons with unknown preestablished values on unknown bases, it will give correct statistical predictions. However, for a "micro-observer" entangled with the system, in this specific case, equation (9) is correct.

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[7] 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.

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$|\psi_{AB}\rangle = |A1\rangle|B1\rangle$ (9)

The "coin" has already been flipped in this case. A nondeterministic event occurred as the photons separated. Thus, one crucial component of what we need a measurement to accomplish has already happened - projection onto a basis of measurement. One single entanglement counts as a "micro-observation". We can legitimately speak of Alice's photon as the observed system and Bob's photon as our measuring device, which we have not yet queried. From the outside, however, we cannot know what the measurement basis was nor what value was obtained from that micromeasurement. This is not yet a macroscopic measurement, we can still do things such as erase the micromeasurement and reintroduce objective uncertainty. but for the moment Bob's photon has measured Alice's and vice versa.

One might object that having this information preexisting when the photons are still together constitutes hidden variables. However, Bell's inequality (Bell, 1964), (Maccone, 2013) only tells us that it is not possible for values on multiple incompatible orthogonal measurement bases to be preexisting (Napolitano & Sakurai, 2021). It is not possible in this example that a value on some unknown measurement basis, U, is preexisting and then also have preexisting values on an incompatible orthogonal basis 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[8].

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

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (10)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\pi/2)}{4} + \frac{1 + cos(\pi/2 + \pi)}{4} = 0.25 + 0.25 = 0.5 \quad (11)$$

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 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 equations. 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.

$$P_T(B1) = P_S(A1) * P_O(B1|A1) + P_S(A2) * P_O(B1|A2) \quad (12)$$

$$P_T(B1) = 0.5 * \frac{1 + \cos(\phi_B)}{2} + 0.5 * \frac{1 + cos(\phi_B + \pi)}{2} \quad (13)$$

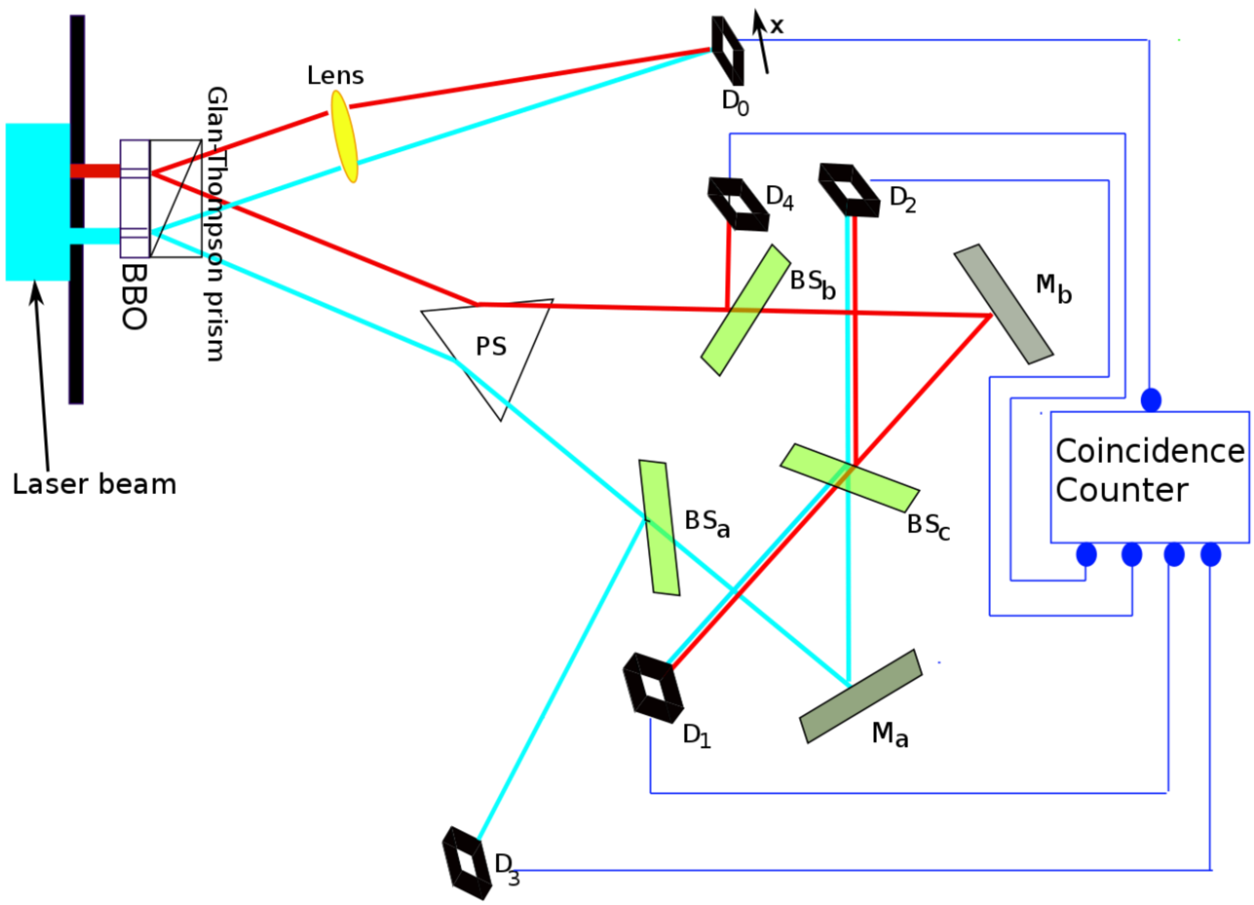
$$P_T(B1) = 0.5 * 0.5 + 0.5 * 0.5 = 0.5 \quad (14)$$

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 gained from the first measurement is destroyed (Napolitano & Sakurai, 2021). Alice's photon measured Bob's photon, and Bob's photon was

[8] 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 (Einstien, Podolsky, & Rosen, 1935), and Bohr believed the wave function was a complete description of the system.

in a definite state where only subjective uncertainty existed until Bob erased this information and reintroduced objective uncertainty.

Some readers may notice that in this configuration, we are very close to the configuration of the delayed choice quantum erasure experiment (Kim, Yu, Kulik, Shih, & Marlan, 2000). We only need to have Alice direct her two beams each into one hole of a two-slit experiment and place Bob significantly farther from the photon source than Alice, and Bob then plays the role of the eraser. Standard interpretations with no hidden variables struggle to explain the results of this experiment without resorting to hypothesizing retroactive erasure of “which way” information[9], and multiple hidden variables are ruled out by Bell’s inequality. Our “one hidden variable interpretation”, however, has no difficulty explaining the results of the experiment, in an intuitively straight-forward way.



[9] We don’t want to imply that the results of this experiment are inexplicable without retrocausal effects in standard interpretations. (Fankhauser, 2017) (Qureshi, 2020). However, we do try to show that the account here is more intuitive.

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Figure 2 – Diagram of the delayed choice quantum eraser experiment. In this diagram, "Alice" would be the detector at D_0, and "Bob", perhaps temporarily renamed "Don", would be the detectors at D_1 and D_2. We will, however, continue to refer to our hypothetical Alice and Bob experiment.

The experiment will of course involve many pairs of entangled photons, and each photon will measure the other half of its pair on some random basis. For our simple example here, we will assume they either measure each other's path information or phase information rather than all possible bases on which they could measure each other[10]. There will then be populations of biphotons with preexisting values on some measurement basis. Those that happen to be predetermined to be on path A1 we can call "population A1", and they will be objectively undetermined between the B detectors – these will only go through Alice's slit number one. Additionally, those biphotons that happen to have measured each other's phase information rather than path information and are now predetermined to arrive at detector B1 will be objectively undetermined on the A paths. Those photons will go through both of Alice's slits and interfere with each other. This means that if we only look at the results on Alice's detection screen that correspond to photons that were measured at detector B1, we will see an interference pattern. Suppose for simplicity, rather than every possible population, we have only four populations - those biphotons that are 100% determined to be destined for detectors A1, A2, B1, or B2[11]. From the inside perspective, we can write:

$$|\psi_A\rangle \; = \; |A1\rangle \,, |\psi_B\rangle \; = \frac{|B_1\rangle + |B_2\rangle}{\sqrt{2}} \quad (15)$$

$$|\psi_A\rangle \; = \; |A2\rangle \,, |\psi_B\rangle \; = \frac{|B_1\rangle - |B_2\rangle}{\sqrt{2}} \quad (16)$$

$$|\psi_B\rangle \; = \; |B2\rangle \,, |\psi_A\rangle \; = \frac{|A_1\rangle - |A_2\rangle}{\sqrt{2}} \quad (17)$$

$$|\psi_B\rangle \; = \; |B1\rangle \,, |\psi_A\rangle \; = \frac{|A_1\rangle + |A_2\rangle}{\sqrt{2}} \quad (18)$$

From an outside perspective, the system is still described as a superposition of all the possible states, and the wave function describes the minimum uncertainty that must be present from that outside perspective and still makes correct statistical predictions from that perspective. However, from the inside perspective, these different predetermined populations exist.

Detector B1 will pick up all the population B1 biphotons, of course, and then also half of each of the A1 and A2 populations. The A1 and A2 populations in the mix will smear the pattern out slightly on Alice's detection screen, but an interference pattern will remain. This is a heuristic argument, but it shows that one hidden variable is all we need to explain the results of this experiment intuitively, without resorting to retro-erasure. One "coin flip" already happened as the photons were created, so it does not matter how delayed Bob's measurement choice is. The population B1 biphotons were always going to be objectively undetermined on the A paths and interfere with themselves at Alice's detector. Population B2 biphotons interfere with themselves as well; however, the pattern is 180 degrees out of phase with the pattern produced by the B1 population. If viewed together, the patterns wash each other

[10] Section 4 takes up the issue of what happens when the preexisting measurement basis does not match at least one of the experimenters' bases.
[11] This toy model is also arrived at in (Argaman, 2010).

out. All Bob does, after Alice's results have been recorded, is choose to look at some of the existing populations and not others. He does not retroactively erase "which way" information.

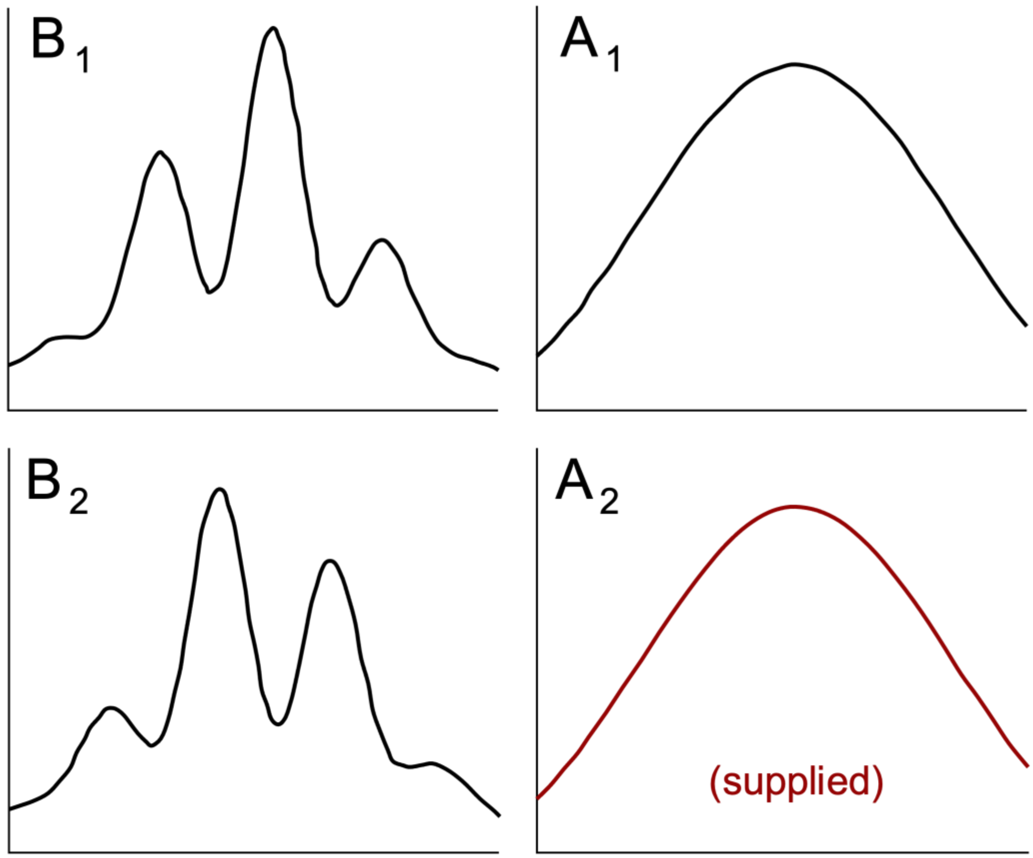

Figure 3 – Results of (Kim, Yu, Kulik, Shih, & Marlan, 2000) relabeled for our Alice and Bob thought experiment.

4. Nonlocality addressed

Now, let us suppose that both Alice and Bob alter their basis of measurement by π/2.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\phi_B - \phi_A)}{4} + \frac{1 + cos(\phi_B - \phi_A + \pi)}{4} = 0.5 \quad (19)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\phi_B - \phi_A)}{4} + \frac{1 + cos(\phi_B - \phi_A + \pi)}{4} = 0.5 \quad (20)$$

Both have now measured on a basis orthogonal to the basis on which the photons measured each other, and both results, taken individually, are objectively undetermined, but they perfectly correlate, even nonlocally, when considered together. Assuming we do not allow superdeterminism, this nonlocal correlation has been conclusively experimentally demonstrated (Hensen, Bernien, & Dréau, et al, 2015), (Storz, Schär, & Kulikov, et al., 2023). The description of the system in this case would be no different than in standard interpretations. From both the inside and outside perspectives, equation (4) describes the state of the system. There is, based on the discussion thus far, only objective uncertainty in this case, as knowledge of the hidden variable adds no useful information.

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$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle+|A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

The perfect correlation makes it appear as if Alice and Bob were somehow forced to measure on the preexisting basis, or alternately, the basis altered itself to match their measurement basis. The latter is what we will now assert happens. In order to match all experimental results, we propose the following: The biphoton has a "head" and a "tail". One of the two photons, randomly, is the head or "control photon". If Alice receives the control photon, she rotates the basis of the biphoton to match her basis of measurement. Bob's half gets "dragged along for the ride" even nonlocally. If the photon is not a control photon, Alice leaves its basis unchanged. Those will have their basis altered to match Bob's measurement basis, and then Alice's photon gets dragged along with it to some new basis. The analysis then proceeds just as above but on the new bases as if at least one of them had been the preexisting basis all along.

This has a number of benefits and consequences. For example, in the quantum eraser experiment, in the nonlocal case, there will ONLY be the 4 populations shown. Alice will reorient half of all biphotons to be populations A1 and A2, and Bob will reorient the other half to be populations B1 and B2. Additionally, a distinct benefit is that nonlocality becomes slightly less mysterious. One difficulty with instant correlation at a distance is that SR tells us that either Bob or Alice could be regarded as having acted first, so who influenced whom is a difficult question[12]. Our answer is that 50% of the time Alice influences Bob nonlocally and 50% of the time it is the other way around. Either way, we have only one nondeterministic event. If Alice reorients the basis of her photon, her result was predetermined,[13] and Bob's result for that photon is nondeterministic.

Note that assigning half the photons to Alice and half to Bob is not done merely to attempt to demystify nonlocality a little bit. The even division is needed in order to reproduce the results in experiments such as the quantum eraser. Assuming we exclude superdeterminism and assuming that micromeasurements occur and create a hidden variable as we have asserted, and assuming the hidden polarization affects the next measurement in a standard way, according to the Born rule, then the rotations to the new basis of measurement we've proposed must take place, and they must be distributed half to each observer, and there must be a predetermined head and tail. If this new hypothesis is correct, then this would have to be a property unique to entangled particles. Violations of the principle of conservation of angular momentum would happen if lone particles were rotated in this way. However, we would not need this hypothesis in those cases since there is no nonlocality to explain.

Let us suppose, as an example, Alice sets her phase to -π/3 and Bob sets his to π/3. Without nonlocal effects, the single hidden variable interpretation would give the wrong predictions in this case. Let us say that Alice receives the control photon. She reorients it to her basis of measurement. It is now as if, all along, she was measuring on the predetermined basis. Bob's photon rotates its basis with hers so that Bob is now at 2π/3 relative to the predetermined measurement basis. Alice will find A1 half the time and A2 half the time in these cases, since this outcome is subjectively uncertain on the

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[12] (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."

[13] To be more precise, it is predetermined following the rotation. We assume that the choice of which direction to rotate is partly nondeterministic and follows the standard Born rule.

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premeasurement basis. Bob's results can then be calculated to match hers 25% of the time and disagree 75% of the time.

$$P(\mathrm{B1}) = (P(A1) = 0.5) * (P(B1|A1) = \frac{1 + \cos(\phi_B)}{2}) + (P(A2) = 0.5) * (P(B1|A2) = \frac{1 + \cos(\phi_B + \pi)}{2}) \quad (21)$$

Finally, let us look again at the delayed choice quantum eraser experiment. In the delayed choice case, Alice acts first. In the cases where Alice receives the head of the biphoton, she will rotate those biphotons to match her path-information basis of measurement. These will be populations A1 and A2. The other unaltered photons will pass through both slits in various proportions and have their information determined by Alice's recording screen in nondeterministic events. As the biphotons are measured at the detector, their other half will be rotated so that they continue to have a basis exactly opposite to each other. Note that in the delayed case, we are still asserting that head and tail photons behave differently. The heads are rotated to specifically match the "which path" basis of measurement, and the tails are not. The tails are just measured relative to whatever basis they happen to have, and then they drag their counterparts along for the ride. Additionally, notice that only the heads cause nonlocal correlation. The tails' information is only communicated at luminal or subluminal speeds.

The information recorded on Alice's detection screen will be enough to largely separate the photons into populations B1 and B2, (see equations (17) and (18) and fig. 3)[14]. Bob receives population A1 and A2 photons that are objectively undetermined on his basis and then also receives Alice's initially unrotated photons that were undetermined before measurement on her end and are now largely predetermined on his end to be either population B1 or population B2. Of course, this does reraise the "which came first" question inherent in nonlocal situations. If either Alice or Bob can create populations B1 and B2 then in the nonlocal case, can we truly be certain who did so? While yes, in the nonlocal case, we could try to claim Alice was responsible for all rotations, this raises the question of why Alice is special. It seems far more elegant to assume that Alice and Bob were each responsible for half of the rotations in the nonlocal case and that all the rotations reorient the preexisting measurement basis to the new measurement basis.

We do not wish to take any firm position on exactly how these nonlocal correlations are accomplished. A good survey of suggestions can be found here: (Warton & Argaman, 2020). However, in the interpretation presented here, only the heads of the biphotons are capable of nonlocal transmission of information. This points to an obvious suggestion for future research. Rather than treating the head and tail as Parity transformations of each other, we could treat them as CT transformations of each other. This would yield a retrocausal interpretation where the head of each biphoton actually originates at its respective detector. That is, population A1 photons originate at detector A1 and travel backwards in time, etc. Alternately, treating the head and tail as CT transforms of each other might just be a useful way of treating the biphoton mathematically, without asserting that retrocausality is what actually happens. In the delayed choice case, for example, there is no need to suppose actual retrocausal effects. However, in the nonlocal case, treating the head of the biphoton as a CT transform of the tail is certainly an attractive idea. At the very least, it behaves as if this were true.

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[14] (Fankhauser, 2017) goes into extensive detail here.

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Let us take stock of what we claim to have accomplished here. If this analysis is correct, the single hidden variable interpretation will replicate all results of quantum mechanical experiments just as well as any standard interpretation. This would make choosing between interpretations mostly a philosophical matter. However, now we turn to the issue of the measurement problem where we believe the single hidden variable interpretation has a distinct advantage.

5. The measurement problem

Let us now complete a classical observation. After the photons measure each other, we have a couple more steps. First, one of the photons, let us say Bob's, must become entangled with Bob's measuring device and then with Bob. We then have, from the point of view of an outside observer, not entangled with the system:

$$|\psi_B\rangle \otimes |Device\rangle \otimes |Bob\rangle \quad (22)$$

Obviously, however, Bob does not experience himself in a superposition, so what is happening from the inside perspective? From the inside perspective, something important happens in each of these steps. 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. More on this is discussed below in this section.

Finally, Bob looks at the measurement. Let us say that he finds that the photon took path 1. Now, we can finally write:

$$|\psi_B\rangle = |B1\rangle \quad (23)$$

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. The wave function still persists and describes the outside perspective; all that has happened is that Bob is now allowed to take the inside perspective, which has existed all along. Bob can now see the formerly hidden variable.

Micro-observations remove objective uncertainty on some measurement basis and convert it into subjective uncertainty when viewed from the outside perspective. Then, once the human observer becomes part of the system, the subjective uncertainty is eliminated as well. However, the removal of objective uncertainty by micro-observers is only a partial solution to the measurement problem. 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. Micromeasurements can be erased, and objective uncertainty can be reintroduced. To complete the journey 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 us return to our initial situation where Alice happens to measure on the preexisting measurement basis and have Bob set the angle to $\pi/4$.

$$P(B1) = P(A1, B1) + P(A2, B1) = \frac{1 + cos(\pi/4)}{4} + \frac{1 + cos(\pi/4 + \pi)}{4} = 0.43 + 0.07 = 0.5 \quad (24)$$

$$P(B2) = P(A2, B2) + P(A1, B2) = \frac{1 + cos(\pi/4)}{4} + \frac{1 + cos(\pi/4 + \pi)}{4} = 0.43 + 0.07 = 0.5 \quad (25)$$

$$P_T(B1) = P_S(A1) * P_?(B1|A1) + P_S(A2) * P_?(B1|A2) \quad (26)$$

$$P_T(B1) = 0.5 * 0.85 + 0.5 * 0.15 = 0.5 \quad (27)$$

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 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, any positional information they acquire will be distinctly different than any positional data that would be acquired at the other detector. Thus, even if an individual micromeasurement does not completely localize the photon, it will definitively identify which detector it has arrived at. And, while each micromeasurement might erase a small portion of the information gained by the previous micromeasurement, most of the information from each micromeasurement will be preserved, and there will be a myriad of separate, perhaps slightly imperfect, records of the event, each with little objective uncertainty.

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. Nonerasability is the defining feature of macroscopic observations when compared to micro-observations.

Let us suppose, for example, that after many entanglements, an attempt at a hypothetical measurement of a macroscopic system on a basis orthogonal to a previous measurement basis is made, such as is done in the new Wigner's friend thought experiment. For example, see (Ormrod, Vilasini, & Barrett, 2023). It cannot be on a basis orthogonal to all the bases used for all the existing micromeasurements, however. So, although perhaps it can partially erase them, it cannot do so completely. Let us suppose an original value of "1" is recorded in a quantum experiment rather than an alternative "0". Initially, a myriad of micromeasurements on nearly parallel bases all record it as "1". After an attempt at erasure, suppose the typical particle or "micromeasurement device" only retains a small degree of correlation with the initially measured particle. As in (24) and (25), 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 micromeasurement would now only give us only 51% certainty that the initial result was "1", we can repeatedly use Bayes's formula[15] for probability

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[15] $P(H_i|E) = P(H_i) P(E|H_i) / P(E)$

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updates across a macroscopic number of micro-observations. The result will be (almost) 100% certainty that the initial result was "1". If we treat the universe as a hypothetical "observer" entangled with the system, with access to all the micromeasurements, there is essentially zero uncertainty regarding 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" (Schrodinger, 1937). 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. (So hopefully the cat is still alive).

6. A brief taxonomy of this interpretation.

In recent years, a new, more complex version of 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 the logical possibilities. For example, (Bong, Utreras-Alarcón, & Ghafari, et al., 2020) and (Ormrod, Vilasini, & Barrett, 2023). This provides a couple of different taxonomical systems with which to classify interpretations. Working through the possibilities on these lists, let us start by saying what this interpretation is not.

1. Events are absolute. Two macroscopic observers don't disagree on the result of a measurement.[16]

2. There is only one world; no multiworld hypothesis is needed.

3. Bell nonlocality is a fact.

4. There is no superdeterminism. Choices are possible.

5. There is no superluminal signaling or superluminal dynamics.

Using the taxonomy provided in (Bong, Utreras-Alarcón, & Ghafari, et al., 2020), the implication of these assumptions 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 microrecords of the event now add up to a permanent macroscopic record of the event.

Our solution to the paradox does not pick just one of the possible resolutions to the puzzle but a bit of two options:

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where:

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

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

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

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1) Micro-observations are not absolute because they can be erased.
2) Macroscopic observers cannot be treated as quantum objects because their observations are thermodynamically irreversible and nonerasable.

In short, in the thought experiment (Ormrod, Vilasini, & Barrett, 2023), Alice and Charlie have a spacelike separation from Daniella and Bob. All perform measurements. Daniella has an inside perspective and precedes Bob, who has an outside perspective. 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 simple quantum micromeasurement and not an observation by a macroscopic observer, in which case Bob will not be able to perform a completely orthogonal measurement.

Let us now discuss classifying our interpretation with the taxonomy provided by (Ormrod, Vilasini, & Barrett, 2023). There, the assumptions we have made of "Bell nonlocality" and "no superluminal dynamics" would imply that our only remaining choices are "nonabsolute events" and "information loss". We do not argue that micro-observations are absolute, so we have no problem there. However, we do argue that macroscopic observations are absolute. The argument from (Ormrod, Vilasini, & Barrett, 2023) would then be that if from the perspective outside of the system, all interactions inside the system are viewed as unitary, as we have stipulated, then it must be possible for Bob to perform a measurement orthogonal to Daniella's. And, if we stipulate that such a measurement is impossible, then this implies information loss.

However, we do not have just one macromeasurement. Rather, we have a myriad of micromeasurements. In theory, yes, each of them could be measured on a basis orthogonal to their unique original measurement basis, and the original information that had been recorded would then be erased. However, in practice, thermodynamic chaos will render such measurements impossible. We would have to, in effect, reassemble then dead version of Schrödinger's cat one subatomic particle at a time. Thus, we would argue that even though Bob cannot perform an orthogonal measurement, information is not lost in the absolute sense since orthogonal measurements are still possible, at least in theory.

Information is *effectively* lost, however, in the sense that it becomes irretrievable. As with other thermodynamically irreversible events, we cannot "put the genie back into the bottle", 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.

7. Philosophical discussion.

Some readers may be uncomfortable with the idea of intrinsic uncertainty. The idea that every effect has a physical cause is deeply ingrained in physics. We have two ways to address this issue. First, we can make philosophical arguments in favor of nondeterminism. Second, we can provide a way around nondeterminism.

First, while we cannot disprove determinism, we can argue that it is a poor fit for the universe we experience. Most obviously, of course, we as humans experience choice. However, also consider, for example, evolution, which needs random mutations in order for creatures to adapt. Additionally,

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consider AI, which needs (pseudo)random numbers in order to learn. Additionally, consider that if we only ever use deductive logic, we ourselves can never learn. All the information in Euclidian geometry, for example, is already contained in its axioms. All deductive logic does is shuffle that information around. A fully deductive or deterministic universe never loses information, but it never gains information either. It just moves information around and "restates it" in a different form. It cannot "learn". It's sterile and unchanging from the point of view of the information needed to describe it.

Finally, nondeterminism fits much more easily with the existence of an arrow of time than determinism does. Rather than fully deterministic laws that operate equally well running backward in time as they do running forward in time, in a nondeterministic universe, paths diverge moving forward in time, whereas they would merge in the reverse direction. A direct connection from this proposed quantum arrow of time to the thermodynamic arrow of time might be possible as well, by noting that well-ordered systems are easier to erase than disorderly ones. Disorderly systems, then, are more likely to achieve permanent status. None of these considerations prove that determinism is impossible. However, they do argue that it is a poorer fit for the universe we experience than nondeterminism.

We can present a potential way around intrinsic uncertainty, however. Rather than supposing that the "objective uncertainty" as we have presented it here is truly random, we can suppose that it is merely pseudorandom. The definition of objective uncertainty we have used here is that it is the uncertainty that must be present for any observer, even if they are entangled with the system. We can suppose that there is a completely unobservable field that can be sampled to generate a random number when needed. The "universal computer" simply calls the "Rand()" function. On the downside, this is a whole new theoretical object that adds nothing observable to the theory and solves no problem. However, on the plus side, it does eliminate nondeterminism for those who insist on it.

8. 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 values on other potential bases of measurement objectively undetermined. This transformation of uncertainty is invisible from outside the system. If we look again at equation (4):

$$|\psi_{AB}\rangle = \frac{|A1\rangle|B1\rangle + |A2\rangle|B2\rangle}{\sqrt{2}} \quad (4)$$

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. Alternately, it may represent completely objective uncertainty for an experimenter measuring on a basis orthogonal to the premeasurement basis. Alternatively, it may represent a combination of both if they measure on some other basis. We also suggest that in cases where neither experimenter measures on the preexisting basis, the biphoton reorients itself to match one of their measurement bases, and this process involves nonlocality. The head of the biphoton will rotate to match the new basis of measurement and this information will be communicated nonlocally. The tail, if needed, in response to a micromeasurement, will rotate its counterpart to anti-correlate with the final measurement. This information is only communicated at luminal or subluminal speeds.

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The wave function represents the total probability, objective plus subjective, and 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 entanglements accumulate and become thermodynamically irreversible, we are left with only subjective uncertainty and results that cannot be erased.

This gives us an interpretation of quantum mechanics that avoids difficult ideas such as nonabsolute macroscopic events, many-world hypotheses, superdeterminism and superluminal dynamics. It also avoids the idea of wave function collapse. It refines and extends a proposed solution to the measurement problem; it explains the results of the quantum eraser experiment without difficulty, and it provides an arrow of time. Finally, it also makes the order of events in nonlocal situations slightly less of a concern.

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