The Many-Worlds Interpretation and Local Causality

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HPS/Pl 125, WI '25

March, 2025

1 Introduction

Thanks to the famed Bell-EPR theorem, quantum mechanics is often described as an inherently non-local theory. The theorem provides us with a mystery — two particles are entangled in such a way that they must have opposite spins, but the outcome of each spin measurement cannot be pre-determined before measurement. As a result, it seems that measuring the spin of one particle instantly impacts the spin of the other particle, even if they are separated by vast distances, which seems to violate the principle of locality and make our fundamental physics mind-bendingly non-local. However, the Bell-EPR methodology makes one hidden assumption about the outcomes of quantum measurements: that there is only one outcome per measurement. The Many-Worlds Interpretation (MWI) of quantum mechanics challenges this assumption by positing that all possible outcomes of a quantum measurement actually occur, each in its own separate "world." This begs the question: if the MWI is true, is quantum mechanics a local theory?

In response to questions about locality in quantum mechanics, most physicists are quick to point to no-signaling theorems, which show that quantum non-localities cannot be hijacked to send information faster than the speed of light. As Maudlin puts it, "One prominent suggestion for… [a] proper and important sense of 'local' has to do with *signaling*. In this sense, a physical theory is non-local just in case one can specify how to use the physics to send useful, interpretable signals fast than light" (Maudlin, 2014). However, as Marc Lange points out, "Nevertheless, the left measurement event apparently helps to cause something to happen on the right (namely, the right particle acquiring some definite spin component) with no causes in between" (Lange, 2002). Despite the no-signaling theorem, it seems that quantum mechanics allows causal influences to propagate faster than the speed of light, a disturbing prospect for our fundamental understanding of the universe.

In this paper, I will argue that the MWI resolves the locality problem in quantum mechanics in a way that salvages local causality. I will defend the claim that the MWI is a local theory regardless of whether branching events propagate faster than the speed of light. I will also show that concerns about locality due to separability for the MWI do not pose a threat to causality, and argue that the MWI's ability to resolve the locality problem in quantum mechanics serves as a reason to select the MWI over competing interpretations.

This paper will proceed as follows. I will first present a brief overview of the Bell-EPR theorem, and defend why the non-locality it implies is a threat to our understanding of causality despite the no-signaling result. I will then present the MWI of quantum mechanics, motivated by a brief description of the measurement problem it is designed to solve. I will discuss two branch propagation schemes, the light-cone branching of David Wallace and global branching, and show why both schemes are compatible with local causality. I will then describe the issue of separability for the MWI, and show that it does not pose a threat to local causality. Finally, I will conclude by arguing that the MWI's ability to resolve the locality problem in quantum mechanics serves as a strong reson to favor the MWI over other interpretations of quantum mechanics.

2 The Bell-EPR Paradox and Local Causality

The Bell-EPR theorem is the quintessential evidence of non-locality in quantum mechanics. I will begin with a careful presentation of the theorem, so that I can later show how the MWI undermines the non-locality it implies.

2.1 Bell-EPR

In 1935, Einstein, Podolsky, and Rosen (EPR) published a paper which attempted to prove that quantum mechanics and the quantum wave function provide an incomplete description of reality (Einstein et al., 1935). They ask the reader to imagine two particles entangled in such a way that they must have opposite spins along some axis Z. Prior to any measurement, each particle has a 50% chance of being Z spin-up or Z spin-down. When one of the particles is measured using a Stern-Gerlach apparatus, quantum formalism allows us to immediately predict the outcome of a measurement performed on the other particle. EPR assume locality, and conclude that the measurement on the first particle could not have influenced the second particle, and therefore the outcome of the measurement must have been fixed from preparation. They conclude that some hidden variable of each particle not included in the wave function must have encoded the spin of the particle for the duration of the experiment, and that the wave function therefore did not provide a complete description of the state of the particle.

This conclusion was challenged by John Bell in 1964, when he published a paper which showed that the type of hidden variable demanded by EPR could not exist (Bell, 1964). Bell's theorem can be most easily grasped by considering a 3 particle state known as the Greenberger-Horne-Zeilinger (GHZ) state. The GHZ state is a three-particle entangled state with the following properties:

- If spin is measured along the x-axis for all three particles, the number of particles with spin up will always be odd.
- If spin is measured along the z axis for two particles, and along the x-axis for the third particle, the number of particles with spin up will always be even.

Notice that given the measurement of the first two particles along x, x or x, z, we can immediately predict with certainty the outcome of a measurement performed on the third particle along x, just as we could in the original EPR case. However, we now should attempt to assign the outcomes of the measurements prior to measurement, such that the outcomes will always agree with these predictions. The problem: there is no way to assign these outcomes prior to measurement to satisfy the constraints. The outcome of the third measurement must change depending on the the experimenter's choice of measurement axes for the first and second particles measured, and therefore the outcome cannot be fixed prior to measurement. Bell's theorem shows that no hidden variable theory can satisfy the constraints of the GHZ state, and therefore that EPR cannot hold. We therefore obtain a proof by contradiction: If quantum mechanics is local, then there must be a hidden variable which fixes the outcomes of measurements on entangled systems from preparation. There may be no such hidden variables, and therefore quantum mechanics must be non-local.

2.2 Non-local Causality

The Bell-EPR theorem provides us with a puzzling mystery. We have two particles separated from each other, and simply measuring the state of one particle seems to have an immediate impact on the state of the other particle across a space-like separation. Many physicists are happy to accept this non-locality and dismiss it as "non-causal". Take what Griffiths has to say about the subject for example, "Causal influences cannot propagate faster than light, but there is no compelling reason why ethereal ones should not. The influences associated with the collapse of the wave function are of the latter type, and the fact that they 'travel' faster than light may be surprising, but it is not, after all, catastrophic." But on what grounds can we dismiss this non-locality as not causal? What is the difference between a causal and a non-causal influence? To answer this question, we must first define what we mean by a causal influence.

To define a causal influence, I will draw on the dominant theory of causality in contemporary philosophy, know as the counterfactual theory of causation. According to this theory, conditioning on all other relevant features of the environment, an event A is a cause of an event B if and only if, had B no longer occurred, A would not have occurred either. This definition of causality holds a place of prominence in the philosophy of causation as well as in practical scientific applications for inferring causal relationships from correlational data (Lewis, 1973) (Pearl, 1995). This method of causal inference rests on a foundational assumption known as the causal markov condition (CMC), which holds that given all causal parents of a variable, the variable is independent of all of its non-causal ancestors and descendants. This essentially means that if we hold fixed all potential causes of an event, then any statistical independence we observe between the event and other variables must be due to causal relationships (Geiger and Pearl, 1990).

Now, we can apply this definition of causality to the Bell-EPR theorem. We have two particles, A and B, which are entangled in such a way that measuring the state of A will immediately determine the state of B. We are able to condition on the preparation of the particles, and we know that there are no unobserved confounding variables which could be causing the correlation between them — this is what Bell's theorem shows us. This means that despite conditioning on the possible causal parents of the two particles, we still observe a statistical independence between the two particles. Therefore we have two options: either the particles are causally related (meaning we have non-local causation) or fundamental physics demonstrates that the causal markov condition is false. This is a difficult pill to swallow — either option implies that we will have to revise our fundamental understanding of causality and reckon with unfortunate consequences for our understanding of the universe. As a result, an alternative that would allow us to avoid this conundrum would be very welcome. The MWI will provide just such an alternative.

3 The Many-Worlds Interpretation

Quantum mechanics suffers from a fundamental issue known as the measurement problem. The measurement problem can be understood as the fundamental puzzle of how quantum superpositions evolve to definite measurement outcomes. This problem is often illustrated by the famous thought experiment of Schrödinger's cat, in which a cat is placed in a box with a radioactive atom and a vial of poison. The atom has a 50% chance of decaying in the next hour, and if it does, the cat will be poisoned and will die. If the atom does not decay, the cat will live. The Copenhagen interpretation of quantum mechanics tells us that the atom will be in a superposition of decayed and not decayed until we open the box and look inside. Does this mean that the cat is also in a superposition of dead and alive until we open the box and look? Several interpretation of quantum mechanics have been proposed to solve the measurement problem, but one of the most popular is the Many-Worlds Interpretation (MWI), which posits that all possible outcomes of a quantum measurement actually occur, each in its own separate "world." In this way, the MWI solves the measurement problem by eliminating it — superpositions do not evolve to definite outcomes, because all outcomes of a quantum measurement actually occur in separate worlds. For Schrödinger's cat, there are therefore some worlds in which the cat is dead, and some worlds in which the cat is alive, and there is no sense in which one definite outcome must occur (Wallace, 2012).

If we are to accept the MWI, we need to develop a sharp account of the branching of worlds. Modern approaches to the MWI have considered branching as a result of quantum decoherence, a phenomenon in which the wave function of a system becomes entangled with its environment, causing it to separate into distinct non-interacting branches. David Wallace describes this approach as giving rise to a natural, emergent universe from the structure of ordinary unitary quantum mechanics, "there is an *emergent* branching structure realised by the underlying unitary dynamics. In that emergent theory, the configuration space can be taken to be the space of instantaneous decoherence selected projectors [of the system's density matrix in the pointer basis]" (Wallace, 2012).

We are now equipped to think about the MWI in the context of local causality. Consider the EPR experiment. We know that EPR gives rise to a decoherence when each of the anti-correlated particles is entangled with its measurement apparatus, giving rise to an emergent branching structure as Wallace describes. Before, the observation of one particle instantly informed us of the state of the other particle. But how has that changed in the MWI?

3.1 The Locality of the MWI

Consider two experimenters, Alice and Bob, who are each measuring the spin of one particle of an entangled pair in the EPR state, each at a vast space-like separation from each other. As EPR typically proceeds, Alice measures the spin of her particle along some axis Z, and Bob measures the spin of his particle along the same axis. As soon as Alice measures the spin of her particle, she knows beyond a doubt that Bob's particle will have the opposite spin. But in the MWI, the picture changes significantly. Before measuring her particle, Alice knows that both possible outcomes of both her measurement and Bob's measurement will obtain. The only uncertainty Alice has is which world she will find herself in — the one in which she sees up or the one in which she sees down. Once she finds herself in one of those worlds, *nothing has changed about Bob's state or her knowledge of it.* Alice still knows that Bob's world will branch into two branches, one in which Bob's particle is spin up and one in which it is spin down, regardless of the result Alice has seen. The only knowledge Alice has gained about Bob is that when she later meets with him to compare notes, she meet the version of Bob who measured the opposite spin that she did.

If we now wish to reconsider our causal picture that we previously developed, we see that the MWI has resolved our concern — we no longer are forced to accept non-local causality or reject the Markov condition. Given that both outcomes of each measurement will obtain, we can now happily conclude that there is no statistical dependence between the two measurement events, and therefore no reason to believe that the outcome of one measurement has any causal impact on the other. The MWI has saved us from the non-local causality of the Bell-EPR theorem, and allowed us to maintain a local causal picture of the universe.

One should be careful, however, not to prematurely overstate the case, and to carefully think through any new causal issues that may arise as a result of the MWI. For example, we have a fundamental question about the branching of the universe. When Alice makes her measurement, the universe must branch into two distinct branches, one in which Alice sees spin up and one in which she sees spin down. But when this happens, what is happening in Bob's location? Does Alice's measurement cause an instantaneous global branching such that as soon as Alice's particle decoheres, the entire universe branches? If so, does this lead to a new violation of local causality?

3.2 Branch Propagation in the MWI

First, we will consider the favored branch propagation scheme of David Wallace, known as light-cone branching. In this scheme, the universe branches fully locally, such that the branching of the universe only moves across space within the light cone of the event which caused the branching. When Alice makes her measurement, the universe first branches at the location of the particle measured. The two branches then diverge across space at a rate no faster than the speed of light. Alice realizes the result of her measurement in no less than the time it takes for the light from her measurement device to reach her eyes. If Alice wants to tell Bob the result of her measurement, she can only communicate this information to him at a speed no faster than the speed of light, not only due to her own limitations, but also because the branching event itself cannot propagate faster than the speed of light. In this way, the light-cone branching scheme of the MWI is fully local, and does not violate any local causal principles.

This type of light cone branching fully and naturally resolves all of our concerns regarding the locality of branching, but notice that we pay a price for it. While Wallace likes to describe the MWI as "just quantum mechanics itself, taken literally as a description of the universe" (Wallace, 2012), this is no longer totally true if we accept the light-cone branching scheme. There is nothing about unitary quantum mechanics itself or Schrödinger evolution that requires the propagation of branching events to be limited in this way — it requires an additional assumption or postulate about the universe. As a result, we should also consider other possible branch propagation schemes that could be consistent with the MWI.

A less straightforwardly local branch propagation scheme, known as global branching, is a very simple concept — at the time of a measurement event, the entire universe branches into multiple worlds instantly, regardless of the distance or connection to the measurement event. In this scheme, when Alice measures her particle, Bob branches into two distinct worlds, one in which he *will* observe spin-up and one in which he *will* observe spin-down. This leaves us with the unintuitive result that there are temporarily two identical Bobs who have not yet been differentiated in any way, but will be in the future. Sebens and Carroll (2018) describe the unintuitive consequences of this branching scheme, "the globally-branching view might cause some discomfort. It implies that observers here on Earth could be (and almost surely are) branching all the time, without noticing it, due to quantum evolution of systems in the Andromeda Galaxy and elsewhere throughout the universe." Does this apparently non-local interaction violate our local causality and undo the good work done by the MWI in resolving the Bell-EPR non-local causality?

Ney (forthcoming) provides us with a way to think about this issue. Ney raises the notion of a Cambridge change, a change that is not intrinsic to an object itself, but rather a change in extrinsic relationships to the environment around it. She uses the example of Socrates and his wife Xanthippe, who is located very far away from Socrates. When Socrates is made to drink hemlock in prison in Greece, he dies, and therefore Xanthippe becomes a widow instantly across whatever distance separates them. Despite the spatial separation between Socrates' death and Xanthippe, there is nothing about this change in Xanthippe that is causal or implies action at a distance. Instead, we merely observe a descriptive change in Xanthippe's relationship to her environment. In the same way, when Bob's universe branches as a result of a decoherence in Alice's location, no intrinsic change has occurred in Bob's state. Bob remains unchanged, and his probability of measuring spin up or spin down remains 50%, just as before. The only change that has occurred is a descriptive one — Bob is now one of a pair or multitude of identical Bobs, each of whom will measure different outcomes. Just as Xanthippe became a widow, Bob has become a member of a collection of Bobs, but this doesn't imply any sort of causal influence or action at a distance exerted over Bob. As a result, even in the global branching scheme, we can maintain a local causal picture of the universe through the MWI.

4 MWI, Separability, and Locality

There is one other sense in which non-locality remains in the MWI, and we should consider it to determine whether it threatens the local causality we have been careful to protect. This non-locality is known as the problem of separability.

Consider again the EPR state. We have two particles with anti-aligned spins, meaning that the spin of one is always opposite the spin of the other. The measurement of one particle will always inform us of the state of the other particle. Regardless of the interpretation of quantum mechanics one chooses, there is a sense in which the specification of this state alone represents a non-locality. I am presented with two particles in two different locations whose states cannot be fully specified independently from each other. For example, I can describe the state of one particle as a reduced density matrix by tracing over the other particle, but I will fundamentally be losing some of the state information about the particle when I do so — notably the correlation of its spin to the other particle. In the MWI, this akin to Alice knowing which version of Bob she can meet once she measures her own particle. Note that this is a fact about the nature of entanglement itself, and so *no* interpretation of quantum mechanics can escape this sort of non-locality.

However, what sort of threat can this variety of non-locality pose to local causality? We have already established that the correlations between the particles in the MWI do not represent causal influences, but how should we think about this intermingling of the state?

The answer is simple — the correlation between the two particles is endowed to them by the preparation of the state. It's true that the we cannot have a fully local description of the state of each particle without reference to the other particle across space, but this is not an issue in our causal picture because the state was prepared this way in a local setting. The preparation of the state is a local event, and after the state is prepared, the correlations between the particles remain fixed in the EPR state. Thus, while this non-locality remains in the MWI and represents a departure from classical intuition, it does not threaten the causality we were seeking to protect.

5 Discussion

In this paper, I have argued that the Many-Worlds Interpretation of quantum mechanics is a local theory in a way that defeats the EPR-Bell theorem and allows us to maintain a local causal picture of the universe. I have defended the claim that the typical picture of quantum mechanics as a non-local theory does threaten our understanding of causality, and demonstrated that the MWI offers us a way out of this predicament, regardless of the branching propagation scheme we choose to adopt and even when considering the non-separability of the quantum state.

A critical result of this argument is that the MWI is unique in its ability to resolve the problem of local causality in quantum mechanics. The competitors to the MWI, such as spontaneous collapse and Bohmian mechanics, do not offer the same caveat to the non-locality of quantum mechanics that the MWI does. Since in these theories, unique results obtain for each measurement, none of these options can successfully escape the threats to causality posed by the EPR-Bell theorem. How strong of a reason is this to prefer many-worlds over the other interpretations? I argue that it increases the unificationist character of the MWI. Already the MWI is the most parsimonious interpretation of quantum mechanics, with the most readily available extensions to relativistic quantum mechanics and quantum field theory. Now, we see that the MWI is also the only interpretation of quantum mechanics that can resolve quantum mechanics with our understanding of causality. In lieu of experimental evidence to adjudicate between the competing interpretations, I believe this is a strong reason to prefer the MWI over its competitors.

One may disagree with this conclusion, and argue that the MWI's ability to resolve the locality problem is not a strong reason to prefer it over its competitors. Some readers may not be convinced that local causality in quantum mechanics poses a broad threat to our understanding of causality and the universe at large, and therefore may not be convinced that the MWI's resolution of this issue is significant. However, this is just one of several ways in which the MWI provides a more unified account of quantum mechanics than its competitors, and as these reasons accumulate, it becomes more difficult to dismiss each individual reason as unimportant. While one may not be convinced that the MWI's resolution of the locality problem is a strong reason to prefer it, it at least adds to mounting evidence that the MWI is a natural and unified interpretation of the theory.

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