The Argument from Locality for Many Worlds Quantum Mechanics

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Abstract: One motivation for preferring the many worlds interpretation of quantum mechanics over realist rivals, such as collapse and hidden variables theories, is that the interpretation is able to preserve locality (in the sense of no action at a distance) in a way these other theories cannot. The primary goal of this paper is to make this argument for the many worlds interpretation precise, in a way that does not rely on controversial assumptions about the metaphysics of many worlds.

1. Introduction

One reason that is often given for preferring the many worlds interpretation of quantum mechanics over rival interpretations is that if one adopts an ontology of many worlds, then one avoids the kind of "spooky" action at a distance that is supposed to be a consequence of quantum entanglement, according to other approaches. This argument seems to be straightforward and obvious to many advocates of the many worlds interpretation (Deutsch and Hayden 1999, Kuypers and Deutsch 2021, Tipler 2014, Vaidman 2021, Wallace 2012) and yet it is rarely spelled out in precise detail. When it is, it can sometimes seem to rely on controversial assumptions about the metaphysical interpretation of the many worlds interpretation itself; including the nature of physical states, observers, the fundamental space of the theory, and the branching process.

The central aim of this paper is to achieve a clear and defensible formulation of this argument from locality for the many worlds interpretation of quantum mechanics that is as neutral on these meta-interpretational issues as possible. Although I am optimistic that this can be accomplished, to show this is not as straightforward as one might like. Indeed, showing that the many worlds interpretation avoids action at a distance, in a way rival interpretations do not, does require wading into metaphysical discussions about change, persistence, and fundamentality that many working in the foundations of physics might prefer to ignore. Nonetheless, although a consideration of the metaphysics of many worlds is important if we are to evaluate and defend an argument for that interpretation from locality considerations, what I show in what follows is that there is a clear formulation of the argument that avoids any particularly controversial metaphysical commitments (e.g. to wave function realism, facts about the multi-location of individuals, ad hoc stipulations about the branching process, or the superiority of the Heisenberg representation).

I begin here with a brief overview of the many worlds interpretation, as well as a simple and naïve statement of the argument from locality for the interpretation. I then consider why one might have concerns about the validity about this argument, and worry that it cannot, as it stands, show that the many worlds theory is local in a way its rivals are not. To foreshadow, although one may argue from naïve considerations that the many worlds interpretation implies that the states of localized quantum systems will be unchanged as the result of measurements conducted far away, the many worlds interpretation also appears to bring with it a new kind of action at a distance. In particular, it looks like a measurement conducted by an observer of one part of an entangled quantum system can immediately cause objects separated at arbitrary distances away to branch into multiple objects in distinct worlds. Although this point has motivated some advocates of the many worlds theory (e.g. Sean Carroll and Charles Sebens (2018)) to reject the argument from locality, it has motivated others to modify the way we understand the many worlds interpretation itself. Here I focus primarily on two ways of modifying the many worlds interpretation to save some version of the argument from locality, one due to Kelvin McQueen and Lev Vaidman (2019), and another due to David Wallace (2012). I raise concerns for both of these approaches, along the way showing why an appeal to a higher-dimensional metaphysics for the many worlds interpretation also would not succeed to underwrite a promising argument for the interpretation from locality considerations.[1] Ultimately however, all of these maneuvers can be avoided. This is because, as I will show, the branching of distant systems does not in any way undermine the locality of the many worlds interpretation. And one can see this without bringing

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[1] Another maneuver worth mentioning is that of Kuypers and Deutsch (2021), who argue that one needs to move from the Schrödinger representation of quantum mechanics (what will mainly be used here) to the Heisenberg representation to see the locality of the many worlds interpretation. A similar assumption motivates the arguments in Deutsch and Hayden (1999) and Tipler (2014) that the many worlds interpretation is best because it is straightforwardly local. Nothing I will say in what follows is intended to indicate any deep disagreement with these authors. But I do intend to show in what follows that one doesn't need to move to the Heisenberg representation to see the locality in the many worlds interpretation. The naïve argument that I will present in Section 2.3 is formulated in the (more familiar and arguably clearer, from an ontological point of view) Schrödinger representation, and yet as I will argue, it is basically sufficient to demonstrate the locality of the many worlds interpretation, so long as one doesn't make the mistake to think that branching involves nonlocal action (to be argued in Section 6).

in any controversial assumptions. I conclude this paper by comparing the locality-based argument for the many worlds interpretation with the other main argument for the interpretation, which comes rather from parsimony considerations.

2. The Many Worlds Interpretation of Quantum Mechanics and the Argument from Locality

2.1 The Many Worlds Interpretation as a Solution to the Measurement Problem

The central puzzle for quantum mechanics that the many worlds interpretation was proposed in order to address is the measurement problem (Albert 1992). This is a paradox that seems to arise from, first, the fact that the Schrödinger equation predicts that observers interacting with systems in quantum superpositions will themselves evolve into quantum superpositions. For example, the Schrödinger equation predicts that observers measuring the z-spin of determinately x-spin up particles will necessarily evolve into superpositions of observing a result of z-spin up and observing a result of z-spin down. The paradox arises because, as a matter of fact, observers do not ever find themselves in such superpositions, but rather always find themselves in determinate states. For example, an observer undertaking a measurement of the z-spin of a determinately x-spin up particle will determinately find a result of either z-spin up or z-spin down.

One way to resolve this paradox is to claim that the Schrödinger equation is sometimes violated, or in any case, does not apply in all circumstances (e.g. von Neumann 1932). In particular situations, such as those we would describe as ones in which an observer measures a system in a quantum superposition of z-spin states, the Schrödinger dynamics do not apply and instead the entire system collapses onto one or another determinate z-spin state, so that the observer, in this case, will determinately find a result of either z-spin up or z-spin down.

Another way to resolve this conflict, between what the Schrödinger equation predicts and what observers find as the result of measurements, is to argue that the Schrödinger equation does not directly describe the behavior of physical systems like particles, measuring devices, or observers, but rather some other thing, the quantum wave function, that may influence but does not constitute these physical systems. One then may introduce additional, "hidden" variables into the quantum description to capture the states of these physical systems, and stipulate that these systems, unlike the wave function, never enter into superpositions, but are always in determinate states (e.g. Bohm 1952).

Following Hugh Everett (1957), advocates of the many worlds interpretation argue that there is no need to either add hidden variables (determinate values) or modify the dynamics (e.g. by adding a collapse law) in order to reconcile the predictions of the Schrödinger equation with facts about human observations. To see this, consider our quantum system, which is assumed to be a particle that is determinately x-spin up, and so is in a superposition of z-spin states:

(1) $|\uparrow_x\rangle = \frac{1}{\sqrt{2}}|\uparrow_z\rangle + \frac{1}{\sqrt{2}}|\downarrow_z\rangle$

We can consider this particle to be part of a larger system, which involves an observer (O) with a Stern-Gerlach device (D) who is ready to measure the z-spin of that determinately x-spin up particle (P):

(2) $\psi = \frac{1}{\sqrt{2}}|ready\rangle_O|ready\rangle_D|\uparrow_z\rangle_P|E_0\rangle_E + \frac{1}{\sqrt{2}}|ready\rangle_O|ready\rangle_D|\downarrow_z\rangle_P|E_o\rangle_E$

The last parts (kets) in each term in (2) denote the state of the larger environment (E).

Now, consider the quantum state that results, according to the Schrödinger equation, from this observer using their Stern-Gerlach device to measure the z-spin of the particle:

(3) $\psi = \frac{1}{\sqrt{2}}|\uparrow\rangle_O|\uparrow\rangle_D|\uparrow_z\rangle_P|E_1\rangle_E + \frac{1}{\sqrt{2}}|\downarrow\rangle_O|\downarrow\rangle_D|\downarrow_z\rangle_P|E_2\rangle_E$

Here, '$|\uparrow\rangle_D$' indicates that the detector indicates an up result. And '$|\uparrow\rangle_O$' indicates that our observer sees an up result. A defender of a collapse interpretation will note that observers never seem to be in states like (3). And so, we should believe instead of evolving to (3), the state (2) must collapse onto one or another state in which the observer sees a determinate result. According to the collapse theory proposed by John von Neumann (1932), such a system will evolve to:

(4) $\psi = |\uparrow\rangle_O |\uparrow\rangle_D |\uparrow_z\rangle_P |E_1\rangle_E,$

or

(5) $\psi = |\downarrow\rangle_O |\downarrow\rangle_D |\downarrow_z\rangle_P |E_2\rangle_E,$

with probabilities for each result given by the Born rule.[2] A defender of a hidden variables interpretation will say that the quantum state does indeed evolve to (3), however this only

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[2] In the case of more realistic collapse theories like the Ghirardi-Rimini-Weber (GRW) theory (Ghirardi et. al. 1986), systems do not collapse completely onto eigenstates like (4) or (5), but rather to states like:

(6) $\psi = a|\uparrow\rangle_O |\uparrow\rangle_D |\uparrow_z\rangle_P |E_1\rangle_E + b|\downarrow\rangle_O |\downarrow\rangle_D |\downarrow_z\rangle_P |E_2\rangle_E,$

or:

(7) $\psi = b|\uparrow\rangle_O |\uparrow\rangle_D |\uparrow_z\rangle_P |E_1\rangle_E + a|\downarrow\rangle_O |\downarrow\rangle_D |\downarrow_z\rangle_P |E_2\rangle_E,$

where $|a| \gg |b|$, and $a^2 + b^2 = 1$. The values of a and b are determined by new constants, to be confirmed by experiment. Advocates of the GRW theory, to solve the measurement problem, must argue that a state like (6) or (7) is close enough to an eigenstate so observers in such states will see a determinate result (Ghirardi et. al. 1986, Albert and Loewer 1992). To keep the discussion simple and manageable, and because the differences between the various collapse represents the state of the wave function. It does not represent the physical systems that make up the particle, measuring device, observers, and larger environment, all of which are in determinate states of some variable and not superpositions. For the Bohmian (Bohm 1952, Dürr et. al. 1992), these are always determinate position states.

An advocate of the many worlds interpretation, by contrast, will choose to interpret a quantum state as both an accurate and complete description of all physical systems, and take it to evolve always according to the Schrödinger equation (or relativistic variant), including in situations involving measurement. The measurement paradox, they will argue, seems to arise because it is natural to think of (3) as including the representation of a single observer who is in an indeterminate perceptual state. However, we should resist that interpretation. Rather, we should interpret (3) as including a representation of two observers: one who determinately observes an up result, and another, who determinately observes a down result.

Everett's idea was that we interpret states like (3) as involving one total or "absolute" quantum state, but also at the same time multiple "relative states," states that are relative to the experiences of observers. However, rather than using this language of relative states, most followers of Everett today regard the evolution of systems like the one we are describing as a process wherein a system branches into two or more distinct worlds. And so in (3), an advocate of the many worlds interpretation will say not only that, as Everett proposed, we find a description of two observers, but also that in (3), we find a state describing two different worlds

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approaches won't make a great difference to the arguments that follow, I will use the von Neumann theory to illustrate key points below, and intend these points to carry over to more realistic collapse theories like GRW.

or branches.[3] A quantum state like (3) describes the existence of two worlds in virtue of the fact that the systems captured by the two terms are to a sufficient degree causally isolated from one another (Wallace 2010). And so, the metaphysical framework is one of a single universe (or multiverse) with a complete description given by the quantum state, that has as components sufficiently causally isolated systems that we may legitimately refer to them as many worlds.

It is crucial here to emphasize that not every system that is correctly represented by a quantum state involving a superposition of terms counts as one in which there are many worlds, according to the many worlds theorist. There must at the very least be a sufficient degree of causal isolation. In the many worlds framework, there is today a very standard account of the kind of physical process that brings this causal isolation about, namely decoherence. It will be useful to dwell on this momentarily, as the nature of decoherence and how it leads to the branching of a quantum system into multiple distinct worlds will play an important role in the discussion of locality that follows. And more importantly, that the two parts of the quantum state are causally isolated from each other is absolutely essential for advocates of the many worlds interpretation's resolution of the measurement problem. For the fact that the observer getting a result of z-spin up determinately sees that result, and not the result of spin down on the other branch, is what grounds the fact that measurements appear to have determinate results.

2.2 Decoherence and Branching

[3] See Barrett and Byrne (2012) for the history of the many worlds interpretation, from Everett's original idea of relative states described in his PhD dissertation to the version of the theory commonly endorsed today.

It is the coherence of quantum states that leads to the kind of interference phenomena that are characteristic of quantum mechanics and that, for example, we observe in the two-slit experiment. In this case, it is helpful to think of the coherence of the quantum state as what is allowing the parts of the quantum field going through the first slit and the parts going through the second slit to interfere with each other and result in an interference pattern on a fluorescent screen. Mathematically, physicists represent the coherence of a quantum state using the tool of a density operator, which for pure states directly corresponds to the outer product of a system's wave function.

(8) $\rho = |\psi\rangle\langle\psi|$

A system in a coherent state will have a density operator that contains the presence of interaction (or "cross-") terms that track the interaction between the parts of the quantum state. For example, in the case we considered in Section 2.1, before our observer conducts their measurement, we may write down the reduced density matrix for our system involving the particle, detector, and observer. The reduced density matrix is arrived at from the overall density matrix for the total system by the partial trace operation. In this case, we start with the state in (2) and trace out the state of the environment to arrive at:

(9) $$\rho = \frac{1}{2}|ready\rangle_O|ready\rangle_D|\uparrow_z\rangle_P\langle ready|_O\langle ready|_D\langle\uparrow_z|_P +$$
$$\frac{1}{2}|ready\rangle_O|ready\rangle_D|\uparrow_z\rangle_P\langle ready|_O\langle ready|_D\langle\downarrow_z|_P +$$
$$\frac{1}{2}|ready\rangle_O|ready\rangle_D|\downarrow_z\rangle_P\langle ready|_O\langle ready|_D\langle\uparrow_z|_P +$$
$$\frac{1}{2}|ready\rangle_O|ready\rangle_D|\downarrow_z\rangle_P\langle ready|_O\langle ready|_D\langle\downarrow_z|_P$$

This is a coherent state. In (9), the second and third terms indicate the interference between the two parts (the "up" and "down" parts) of the overall quantum system.

So, if this is what it is for quantum states to be coherent, that there be interference between the different terms in a quantum superposition, what the advocate of the many worlds interpretation needs to achieve the causal isolation between branches they are after is that the entangled states that result from measurements, like (3) above, to a large extent exhibit decoherence. They want it to be the case that even if there is a part of the quantum system correctly described as an observer seeing result z-spin up, and another part correctly described as an observer seeing z-spin down, that these two parts of the total system do not interfere or interact with one another.[4] In a series of papers, by Zeh (1970) and then later, Saunders (1993), Zurek (1993, 2003), and Wallace (2010), it was argued that in cases of quantum measurement like that considered in Section 2.1, this is precisely what happens. Zurek, in particular, argued that when a system in a microscopic superposition interacts with an observer (so that we would say the observer has measured the system), this process generates sufficient traces in the larger environment so that the following interesting thing happens. For a particular way of representing the quantum state (what Zurek called "the pointer basis," in which the basic states correspond to the locations of physical systems), the cross-terms in its corresponding reduced density matrix are essentially eliminated. That this decoherence is achieved depends on the environmental states that result from the measurement being roughly orthogonal, in other words, $\langle E_1|E_2\rangle \approx 0$. In our

[4] At least to a great extent. The quantum states and density matrices we will consider here are rather idealized, in what is intended to be a harmless way. As such, they will seem to suggest that there is complete isolation between the branches, by way of a complete suppression of cross-terms. A more realistic representation of the quantum states in question would show that interference/interaction is not completely eliminated, but only largely and for the most part.

case, a universe in which an observer measures the z-spin of a determinately x-spin up particle will be described by a wave function whose density matrix may be written as:

(10) $\rho = \frac{1}{2}|\uparrow\rangle_O|\uparrow\rangle_D|\uparrow_z\rangle_P\langle\uparrow|_O\langle\uparrow|_D\langle\uparrow_z|_P + \frac{1}{2}|\downarrow\rangle_O|\downarrow\rangle_D|\downarrow_z\rangle_P\langle\downarrow|_O\langle\downarrow|_D\langle\downarrow_z|_P$

In effect, the result of a quantum system in a microscopic superposition interacting with a measuring device, observer, and larger environment leads to a quantum system that is accurately, if approximately, described as one in which there are a multiplicity of systems with determinate locations that do not interfere or interact with one another. In short, in situations like the measurements of systems in a quantum superpositions, we have a physical process of decoherence in the overall system that makes it the case that there are parts of the total quantum system correctly described as many worlds.

2.3 The Argument from Locality

We now turn to the argument from locality for preferring the many worlds interpretation over other interpretations of quantum mechanics (collapse theories and hidden variables interpretations). The main claim here is that if we adopt a collapse theory or hidden variables interpretation, then the phenomenon of quantum entanglement will require one to accept instantaneous action between spatially distant systems (nonlocality). However, such nonlocality is removed when one instead adopts the many worlds interpretation. Here, for the sake of space, we will just compare the many worlds theory with the simple, von Neumann collapse theory, where, upon measurement, the quantum state collapses onto an eigenstate of the measured observable. However, the argument straightforwardly carries over to more sophisticated collapse theories, like the GRW theory, as well as to hidden variables theories, including Bohmian mechanics. Indeed, it is widely accepted, including by advocates of hidden variables interpretations of quantum mechanics, that the main lesson of Bell (1964) is that hidden variables theories are nonlocal in this sense of implying action at a distance.

Start with a system of two particles (a) and (b) in the spin singlet state. These particles are sent to two observers, Alice (A) and Bob (B), separated at great distance from each other, who are each ready to measure the z-spin of their particles with Stern-Gerlach devices (D_A) and (D_B). The initial state of the system may be written as:

(11) $$\psi = \frac{1}{\sqrt{2}}|ready\rangle_A|ready\rangle_B|ready\rangle_{D_A}|ready\rangle_{D_B}|E_0\rangle_E\left(|\uparrow_z\rangle_a|\downarrow_z\rangle_b - |\downarrow_z\rangle_a|\uparrow_z\rangle_b\right)$$

Now suppose that Alice measures the z-spin of her particle, but Bob does not. According to the many worlds interpretation, the system will now evolve into the following state that is correctly described as having as parts two branches or worlds: one in which there is a successor of Alice, an observer who determinately observes an up result, and another, in which there is a successor of Alice[5] who determinately observes a down result:

(12) $$\psi = \frac{1}{\sqrt{2}}|ready\rangle_B|ready\rangle_{D_B}\left(|\uparrow\rangle_A|\uparrow\rangle_{D_A}|\uparrow_z\rangle_a|\downarrow_z\rangle_b|E_1\rangle_E - |\downarrow\rangle_A|\downarrow\rangle_{D_A}|\downarrow_z\rangle_a|\uparrow_z\rangle_b|E_2\rangle_E\right)$$

The crucial thing to note is that although Alice's measurement has caused her to change, has caused each of her successors to come to have a determinate belief about the measurement's result, Alice's measurement has not caused any change in the state of either Bob, his measuring device, or his particle, which are all some distance away. This is straightforward in the case of Bob and his detector, which are still, according to (12), each in the ready state. As for Bob's particle, this is shown by noting first that the intrinsic states of subsystems are captured by their reduced density matrices (Wallace and Timpson 2010, p. 709). For Bob's particle, this is:

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[5] Is Alice herself numerically identical to both or either of these successors? This is a question we will postpone answering for now.

(13) $\rho_b = \frac{1}{2}|\uparrow_z\rangle\langle\uparrow_z| + \frac{1}{2}|\downarrow_z\rangle\langle\downarrow_z|$

This reduced density matrix is the same whether we start from state (11) or start from state (12) and trace out the state of the other subsystems and larger environment. Since the reduced density matrix ρ_b remains unchanged in the evolution from (11) to (12), this means that Alice's measurement produces no change in the state of Bob's particle. Thus, according to the many worlds interpretation, there is no action at a distance involved when an observer interacts with one part of an entangled system.

However, compare this to what happens when Alice measures her particle according to a collapse interpretation, like the von Neumann theory. According to this theory, measurements trigger a collapse of the quantum state onto one or another eigenstate with probabilities given by the Born rule. According to such an interpretation, when Alice measures the z-spin of her particle, the system as a whole collapses onto either of the states in (14) or (15), with probabilities ½ each:

(14) $\psi = |ready\rangle_B |ready\rangle_{D_B} |\uparrow\rangle_A |\uparrow\rangle_{D_A} |\uparrow_z\rangle_a |\downarrow_z\rangle_b |E_1\rangle_E$

or:

(15) $\psi = |ready\rangle_B |ready\rangle_{D_B} |\downarrow\rangle_A |\downarrow\rangle_{D_A} |\downarrow_z\rangle_a |\uparrow_z\rangle_b |E_2\rangle_E$.

In this case, again, we can see that Alice's measurement affects neither the state of Bob nor Bob's Stern-Gerlach device. However, Alice's measurement has affected the state of Bob's particle. Her measurement has caused it to collapse onto a determinate state of being either z-spin up or z-spin down.[6] Thus, the argument goes, while the many worlds interpretation does not involve action at a distance, collapse theories do. And, although it has not been demonstrated here, hidden variables theories involve action at a distance as well. For this argument, one may consult Bell (1964). For this reason, it argued, we should prefer the many worlds interpretation.

3. Branching and Nonlocal Action

3.1 Putative Nonlocal Action in the Many Worlds Theory

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[6] Again, there is no great change if we instead consider the GRW theory. According to that theory, when Alice measures her particle, it is overwhelmingly likely that the system will collapse onto either:

$$\psi = |ready\rangle_B |ready\rangle_{D_B} \left[a|\uparrow\rangle_A |\uparrow\rangle_{D_A} |\uparrow_z\rangle_a |\downarrow_z\rangle_b |E_1\rangle_E + b|\downarrow\rangle_A |\downarrow\rangle_{D_A} |\downarrow_z\rangle_a |\uparrow_z\rangle_b |E_2\rangle_E\right],$$

or:

$$\psi = |ready\rangle_B |ready\rangle_{D_B} \left[b|\uparrow\rangle_A |\uparrow\rangle_{D_A} |\uparrow_z\rangle_a |\downarrow_z\rangle_b |E_1\rangle_E + a|\downarrow\rangle_{D_A} |\downarrow_z\rangle_a |\uparrow_z\rangle_b |E_2\rangle_E\right].$$

where $|a| \gg |b|$, and $a^2 + b^2 = 1$. As in the von Neumann theory, the state of Bob and his detector are unchanged. However, we may now note that unlike in the case of the many worlds theory, the state of Bob's particle has changed as the result of Alice's measurement. For its reduced density matrix is no longer given by (13), but now rather by:

$$\rho_b = a^2 |\uparrow_z\rangle\langle\uparrow_z| + b^2 |\downarrow_z\rangle\langle\downarrow_z|,$$

or:

$$\rho_b = b^2 |\uparrow_z\rangle\langle\uparrow_z| + a^2 |\downarrow_z\rangle\langle\downarrow_z|.$$

Thus, arguably, there is action at a distance, on both the von Neumann and the GRW collapse theories.

While the main goal of this paper is to show that the argument I have just presented in Section 2.3 is basically correct, not all advocates of the many worlds interpretation will be satisfied with that argument.[7] To see why, consider again the case in which Alice and Bob are each sent their particles, and then Alice alone conducts her measurement. We are thus interested in the transition from:

(11) $$\psi = \frac{1}{\sqrt{2}}|ready\rangle_A|ready\rangle_B|ready\rangle_{D_A}|ready\rangle_{D_B}|E_0\rangle_E\left(|\uparrow_z\rangle_a|\downarrow_z\rangle_b - |\downarrow_z\rangle_a|\uparrow_z\rangle_b\right)$$

to:

(12) $$\psi = \frac{1}{\sqrt{2}}|ready\rangle_B|ready\rangle_{D_B}\left(|\uparrow\rangle_A|\uparrow\rangle_{D_A}|\uparrow_z\rangle_a|\downarrow_z\rangle_b|E_1\rangle_E - |\downarrow\rangle_A|\downarrow\rangle_{D_A}|\downarrow_z\rangle_a|\uparrow_z\rangle_b|E_2\rangle_E\right)$$

In order to ensure locality, one might think we need to be careful about how we understand the resulting state (12). To see this, note that Alice's interaction with her particle, according to the many worlds interpretation, will result in a process of decoherence in which the total system branches into two distinct worlds. It is worth emphasizing here that decoherence results in a

[7] To my knowledge, the argument for the many worlds interpretation from locality has never been explicitly presented in the simple form I outline in Section 2.3. So, I do not want to give the misleading impression that other advocates of the many worlds interpretation have explicitly considered the argument in that form and then rejected it. My assertion that not all will be satisfied with that argument is based on the fact that those who discuss the issue of locality in print have either (a) thought they have needed to engage in various more tendentious maneuvers to show that the many worlds interpretation is local (Deutsch, Hayden, Kuypers, McQueen, Tipler, Vaidman, Wallace) or (b) rejected the claim that it is local (Sebens and Carroll). And this is for the reasons to be presented in this section. My aim here is to show that an attention to uncontroversial metaphysical considerations shows that both (a) and (b) are unnecessary.

branching of the *total* system, not just the "Alice" parts. We can underscore this point by noting that (12) is mathematically equivalent to:

(16) $$\psi = \frac{1}{\sqrt{2}}|ready\rangle_B|ready\rangle_{D_B}|\uparrow\rangle_A|\uparrow\rangle_{D_A}|\uparrow_z\rangle_a|\downarrow_z\rangle_b|E_1\rangle_E + \frac{1}{\sqrt{2}}|ready\rangle_B|ready\rangle_{D_B}|\downarrow\rangle_A|\downarrow\rangle_{D_A}|\downarrow_z\rangle_a|\uparrow_z\rangle_b|E_2\rangle_E,$$

in which there are two terms, with Bob, his detector, and his particle represented in each.

When the total system was described by quantum state (11), we had a coherent quantum state, that was not yet split into multiple branches or worlds. However, once the state has evolved to (12), or equivalently (16), there are now two distinct worlds. And so, as a result of Alice's measurement, it looks like it is not only she, her particle, and detector that have branched, but also Bob, his particle, and his detector as well. Alice's measurement at her location thus seems to have caused an immediate change in all of the objects at Bob's location, far away though it is.

In their work, McQueen and Vaidman (2019) and McQueen and Waegell (2020) argue that this a kind of nonlocality that should not be tolerated by the defender of the many worlds interpretation. As McQueen and Vaidman put it, "it goes against the spirit of the many worlds interpretation, which involves removing as much nonlocality as possible" (2019, p. 17). For this reason, they insist that although (12) and (16) are mathematically equivalent, they actually describe two distinct physical situations (see also Sebens and Carroll (2018), pp. 33-34). And we must resist the physical interpretation suggested by (16), in which Alice's measurement has caused Bob, his detector, and particle to branch. McQueen and Vaidman's preference is to say, we can have locality in the many worlds interpretation, but only if we insist that branching occurs locally. And so, for this reason, the simple argument I outlined in 2.3 is too quick. We also have to note that in the case in which Alice alone measures her particle, Alice branches, but Bob does not. There are indeed two worlds that result from Alice's measurement. However, there is only a single Bob that is located in both of these worlds.

According to McQueen and Vaidman, if we are to preserve locality in the many worlds interpretation, then we must adopt a metaphysical interpretation of the transition from (11) to (12) according to which Alice's measurement does not cause Bob or the objects in his vicinity to branch. If Alice's measurement causes the objects at Bob's location to branch, then the many worlds interpretation is not local. For the next couple of sections, I will focus, as McQueen and Vaidman do, on the situation for Bob. We will return to what turns out to be the more interesting (and thus more complicated) case, the effect of Alice's measurement on Bob's particle, in Section 6.[8]

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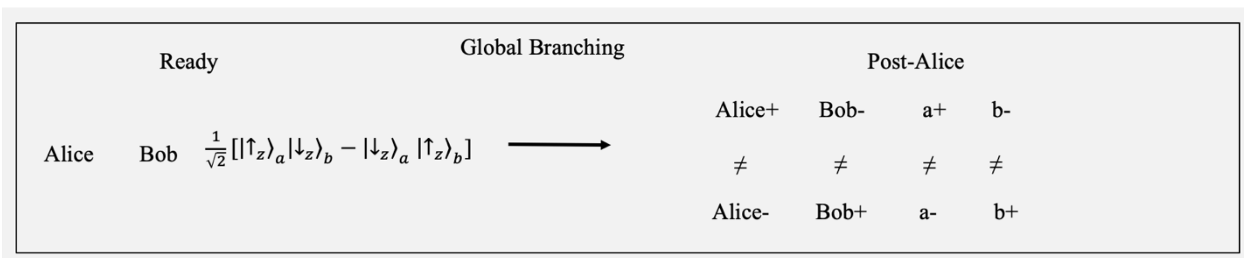
[8] At this point, I am sometimes asked why we are making such a fuss about whether Alice's measurement causes Bob (or his detector or particle) to branch. After all, doesn't the many worlds theorist think that fundamentally, there is just the total quantum state? And since it (the total quantum state) evolves unitarily according to the Schrödinger equation, doesn't the many worlds theorist think that there isn't really fundamentally any action at a distance? I have more to say about this maneuver, the one that appeals to a more fundamental ontology in which everything is local, in Section 5. However, the basic point is that even if one thinks the total quantum state is more fundamental than localized subsystems like Alice and Bob, these localized subsystems do exist. And, moreover, one should care about whether there is action at a distance, and more specifically, superluminal influence between them. For such influence would be straightforwardly in tension with special relativity. It is for this reason that we will continue to

3.2 Global Branching vs. McQueen-Vaidman Branching

McQueen and Vaidman's proposal is very subtle, so it will pay to look at it more carefully. What they object to is what Sebens and Carroll (2018, p. 35) call the "global branching" model. According to the global branching model, when decoherence leads to a branching into distinct worlds, all objects in the world branch. Figure 1 illustrates the global branching process. In this figure and those that follow, to keep things manageable, we will omit representation of the detectors and larger environment.

Figure 1



Here, we start with Alice and Bob in the ready states, while their particles are entangled in the spin singlet state. According to the global branching model, when Alice measures her particle, this causes all four subsystems to branch. So there are now two successors each of Alice, Bob, Alice's particle, and Bob's particle.

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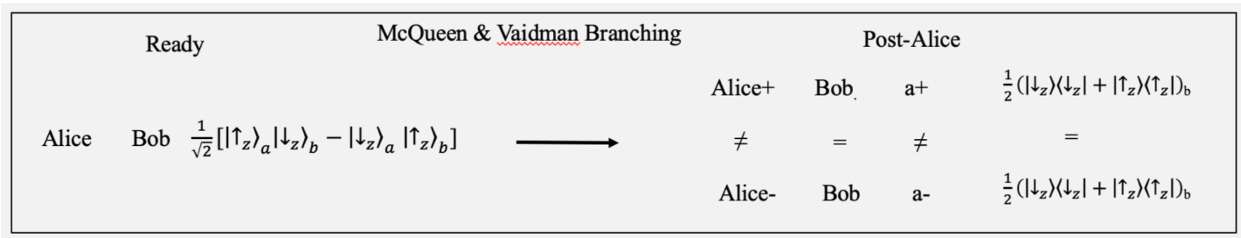
investigate this question about whether it is true that according to the many worlds interpretation, Alice's measurement has no immediate effect on Bob or the other subsystems in his vicinity.

I will call McQueen and Vaidman's different model of the branching process "McQueen-Vaidman branching."[9] They refer to it as "semi-local branching." This is illustrated by Figure 2.

Figure 2



Notice the two main differences. First, in the global branching model, Alice's measurement has caused Bob to branch. Although earlier there was just one Bob, who we may assume existed in just one world, now there are two "Bobs," one in the world where Alice observes an up result, and one in the world where Alice observes a down result. By contrast, in the McQueen-Vaidman model, after Alice conducts her measurement, there are now two worlds, where there was one earlier. But there remains only a single Bob. That Bob is now bi-located in the two worlds.[10] The

[9] McQueen and Waegell (2020) argue for a different way of achieving locality in the many worlds interpretation. It is a bit more complicated and will not be considered here.

[10] The idea of "bi-location" here is subtle, and deserves more discussion. The core idea is that after Alice's measurement, Bob is bi-located in the sense that he exists both in the Alice+ world and the Alice- world. Since there is no reason to think that Alice's measurement causes Bob to move around in space, there is no reason to think that McQueen and Vaidman's view requires that after Alice's measurement, the single Bob will become bi-located in the sense of having two distinct *spatial* locations. For this reason, I concede, the language of "bi-location" is a bit strained, nonetheless I think we can grasp its meaning: one object in two worlds. One might wonder, why we shouldn't think that when the universe branches, it isn't only the objects (like

second main difference is that in the global branching model, Alice's measurement also causes Bob's particle to branch. Although previously, there was a single particle b whose intrinsic state was described by the density matrix (17), there are now two particle b's.

(17) $\rho_b = \frac{1}{2}|\downarrow_z\rangle_b\langle\downarrow_z|_b + \frac{1}{2}|\uparrow_z\rangle_b\langle\uparrow_z|_b$

And it appears (though this may have to be reconsidered below) that one of these particles determinately has z-spin down (the one in the world where Alice's particle has z-spin up), and the other of these particles determinately has z-spin up (the one in the world where Alice's particle has z-spin down). By contrast, in the McQueen-Vaidman model, there remains still just the one particle b. And its intrinsic state is still characterized by the reduced density matrix in (17). Its state has not changed, although it is now bi-located in two worlds.

Now, hopefully wearing our metaphysician hats, we can see that there is a difference between the global branching model, which is essentially what Sebens and Carroll (2018) assume, and what I would argue is the most natural, default way to understand what is happening

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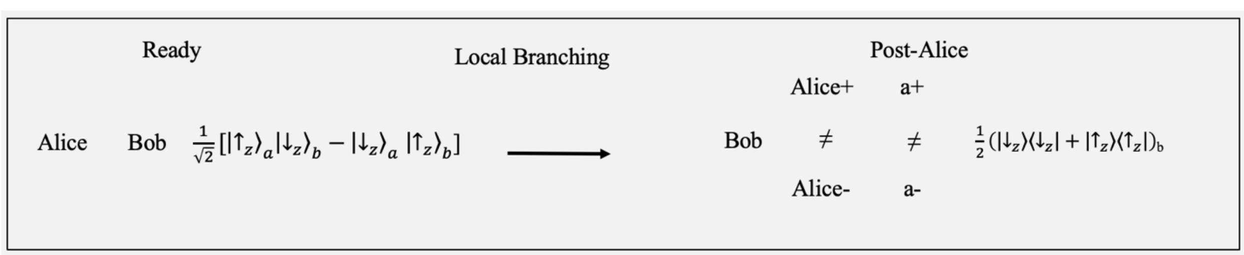
Alice, Bob, and their particles) that branch, but spacetime as well. In that case, Bob would become bi-located also in the sense of existing in two distinct spacetimes. The answer to this question is that, even if we should think that spacetime can branch, here we are just confining our discussion to particle quantum mechanics, a theory in which the background spacetime is fixed and does not enter into superpositions. Again, this is to keep things manageable. Ultimately, if there is good reason to believe that spacetime itself enters into superpositions, then the many worlds theorist will think that just as people and particles branch, so does spacetime. But theories in which spacetime itself may enter into superpositions are quantum theories of gravity, and are beyond the purview of this paper.

when branching is brought on as a result of decoherence, and McQueen-Vaidman branching. In particular, in the global branching model, but not the McQueen-Vaidman model, Alice's measurement at one location has instantly caused Bob, at a distant location to branch. And so it seems to involve nonlocality. In my view, McQueen and Vaidman are correct to be drawing attention to the metaphysics involved in the branching process. But, at the same time, one might naturally raise the following objection to their resolution of the puzzle. Sure, it is true that in the global branching model, Alice's measurement causes an immediate change in Bob: he branches. But in the McQueen-Vaidman branching model, Alice's measurement also causes an immediate change in Bob. In their model, he doesn't branch, but he does become bi-located. And this too, is a change.

Continuing with this objection, one might point out that if McQueen and Vaidman really wanted to ensure that Alice's measurement caused no immediate change in Bob, a distance away, then they should really defend what I will here call "local branching," illustrated in Figure 3.

Figure 3



In local branching, although Alice's measurement immediately causes a branching event to take place in her vicinity, it does not immediately effect a branching into worlds at distant spatial locations. So, in the local branching model, Alice's measurement does not (at least not immediately) cause either Bob or his particle to branch. And in the local branching model, Alice's measurement does not (at least not immediately) cause either Bob or his particle to become bilocated. So, if McQueen and Vaidman really want to make sure there is no action at a distance in the many worlds interpretation, it seems they should prefer local branching, rather than their own "semi-local" branching model.

4. Local Branching

What I am here calling 'local branching' is effectively the model of the branching process proposed by Wallace in his work (2012). In his discussion of the way the many worlds interpretation achieves locality, Wallace notes, following e.g. Zurek (2003, p. 718), that decoherence takes time. So, he argues, this means that we can expect the branching process to ripple out across spacetime at a rate determined by the processes leading to the decoherence:

> When some microscopic superposition is magnified up to macroscopic scales (by quantum measurement or by natural processes) it leads to a branching event which propagates outwards at the speed of whatever dynamical interaction is causing decoherence – in practice, it propagates out at the speed of light. (Wallace 2012, p. 307)

If we adopt Wallace's position, then we should say that when Alice measures her particle, this immediately causes branching at her location. But it will take about $\frac{\textit{the distance between Alice and Bob}}{c}$ seconds for this branching to ripple out to Bob's location. And so even though yes, Alice's measurement does cause Bob to branch, there is no violation of locality. This causal process isn't instantaneous, nor does it involve any superluminal influence.

Wallace's picture is bringing out a point that I haven't explicitly mentioned yet, but is important to emphasize. This is that the central reason why one should care about locality isn't that action at a distance is intrinsically problematic or unintuitive (although that may be the case as well). Rather, it is that some forms of action at a distance are incompatible with relativity. If we want our interpretation of quantum mechanics to play nicely with relativity, then we should not allow it to involve signaling or causal influences that travel faster than the speed of light. By claiming that branching occurs first at a source location and then ripples out across spacetime subluminally, Wallace thereby ensures that the many worlds theory will be compatible with special relativity.

Let's be clear: Wallace is absolutely correct to insist on an interpretation of the many worlds theory that makes it compatible with special relativity. However, there are reasons to be cautious about Wallace's account of how this happens. In particular, one could be concerned that Wallace's claim that the branching in the many worlds theory ripples out subluminally is ad hoc, and not well-motivated. Let's take a bit of time to see this clearly.

First, one could imagine a collapse theorist saying an exactly analogous thing to save locality in their interpretation: "Your argument in Section 2.3, in which you claimed that the collapse theory was nonlocal, relied on the assumption that the collapse of the quantum state occurs throughout space instantaneously. However, this is not how I understand the collapse process. Rather, although the collapse is triggered at a location (e.g. where Alice does her measurement), it ripples out through spacetime at the speed of whatever dynamical interaction is causing the measurement to take place – in practice, it propagates out at the speed of light." In fact, we don't have to imagine a counterfactual collapse theorist here; Wayne Myrvold (2002, 2003) argues that the collapse process is local in this way.

Wallace will likely not be impressed with this move because, he could argue, the collapse theorist has no justification for saying that collapses spread through spacetime at rates equal to or lower than the speed of light, except to make the theory compatible with relativity. And this makes the move ad hoc. However, Wallace can say that in the case of branching, we do have a reason to think the branching process ripples out subluminally. To put it extremely crudely, the argument is:

1. Branching is caused by decoherence.

2. Decoherence takes time.

Therefore,

3. Branching takes time.

The reason decoherence is a dynamical process that takes time is because it requires the environmental states E_1 and E_2, associated with different components in the superposition, to become roughly orthogonal, i.e. $\langle E_1 | E_2 \rangle \approx 0$. In practice, this amounts to the distinct measurement outcomes characterized by distinct terms in the superposition leaving distinct kinds of traces in the environment. This is straightforwardly a process that takes time. So, there is an argument, based on independent facts about the process of decoherence that justifies us in the conclusion that branching spreads through spacetime subluminally. Since collapse theorists do not similarly use decoherence to explain the collapse of the wave function, they cannot appeal to this same justification to underwrite the analogous conclusion for the collapse process.[11]

[11] This isn't to say that decoherence plays no role in a collapse theory. On the GRW theory, absolutely decoherence plays an essential role. However, it is not in triggering the collapse. According to the GRW theory, collapse is a spontaneous process that for every microscopic system always has a tiny chance of occurring. Rather, the role of decoherence in the GRW theory is to explain why, although collapses do not evolve systems onto eigenstates of position, observers do not ever gain information about the low-amplitude parts of the quantum state.

The problem, however, is that even if one accepts the soundness of the above argument, without some additional stipulations, we have not ensured that branching involves no superluminal influence. To see this, let's follow Zurek and Wallace in noting that Alice's measurement will leave traces in the environment, and that only when there are sufficient such traces will decoherence result. Already at this point, one might ask, why does this imply that branching itself takes time? After all, we might allow that it takes time for the states of the environment to become close enough to orthogonal, but once they do, then why not think branching occurs instantaneously and everywhere? Just that this is consistent means that the above argument is invalid.

I don't want to hang anything on this logical point, however. The important issue, after all, is whether sufficient time elapses between Alice's measurement and Bob's branching to avoid superluminal influence. And even if, strictly speaking, only decoherence takes time, but branching is instantaneous, still Wallace will be right to claim that time will have elapsed between Alice's measurement and Bob's branching. So, the main point I want to make is not that the above argument is invalid. Rather my point is that, even if we allow that branching takes time because decoherence takes time, this doesn't ensure that *enough* time will have elapsed between Alice's measurement and Bob's branching to avoid superluminal influence.

Remember, Bob (and his particle) can be very far away from Alice. Alice can be in New York; Bob on Earendel, for all we know. Now one can just stipulate that even after $\langle E_1 | E_2 \rangle \approx 0$ and decoherence has been achieved, still it will take more time for the complete quantum state to branch, and in particular, for the branching to ripple out to Bob, if he is very far away. But now, this would need additional justification.

All this said, although the fact that decoherence takes time does not imply that the branching process spreads subluminally through spacetime, this does not mean that Wallace cannot just stipulate that it does. He can, just as a collapse theorist can stipulate that the collapse process is subluminal. But since the collapse theorist can do the same thing, this undercuts any argument for the many worlds interpretation based on locality considerations. For this reason, we will, for the remainder of this paper, compare the two interpretations of branching we introduced in Section 3: global branching, and what McQueen and Vaidman offer us, the "semi-local" branching model. However, I will also note that if one's interest is not so much with using locality to make an argument for the many worlds interpretation over other approaches, but one just wants to ensure that the many worlds interpretation is local, then one can follow Wallace and stipulate the branching process is local.

5. Carroll and Sebens on Global Branching

In the next section, I will explain why even if Alice's measurement does cause distant systems to branch, even at a superluminal rate, this does not involve action at a distance, and how one can say this without invoking any ad hoc or metaphysically tendentious assumptions. However, first it would be good to consider what two prominent many worlds advocates, Carroll and Sebens, have to say about the fact that on the global branching model they prefer, the many worlds interpretation appears to be nonlocal. In fact, they do not regard this as much of a problem:

> The non-local nature of 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. We take this to be one among many

> psychologically unintuitive but empirically benign consequences of Everettian quantum mechanics. (Sebens and Carroll 2018, p. 35)

This is a rather stunning admission. As I mentioned above, and as McQueen and Vaidman also note, the locality of the many worlds interpretation is commonly regarded as one of the main points in its favor. It is not clear on what basis Sebens and Carroll can say it is empirically benign.

One thing they might be thinking is that perhaps we can tolerate nonlocal interactions between Alice and Bob or us and systems in the Andromeda Galaxy because, after all, localized systems like these are not fundamental, according to the many worlds theorist. In other work, Carroll, for example has defended a particularly radical fundamental ontology for the many worlds interpretation, what he calls 'Mad Dog Everettianism' (Carroll and Singh 2020, Carroll forthcoming). According to this interpretation, fundamentally, all that is real is the quantum wave function, properly understood as a vector or ray in Hilbert space. In this fundamental ontology, there is no nonlocal action. All there is is a ray evolving smoothly over time according to the Schrödinger equation (or its relativistic variant). I am not sure if this is what Sebens and Carroll are thinking here: that the nonlocality they find to be a consequence of global branching is unobjectionable because it is ultimately just an emergent manifestation of a more fundamental ontology that is entirely local. But there are at least two reasons why this response would not be satisfactory.

First, pointing to a more fundamental ontology in Hilbert space does nothing to address the tension between quantum nonlocality and relativity. Since the Mad Dog Everettian is not denying that Alice and Bob are real, only that they are fundamental, he still has to address the appearance of superluminal influence between them, which would be in conflict with relativity.

Now, one might think that if these subsystems in spacetime are only real, but not fundamental, then perhaps since they are ultimately grounded in a higher-dimensional Hilbert space ontology, the higher-dimensional behavior might effectively screen off any causal influences between subsystems in spacetime. In this case, there wouldn't be any action at a distance in spacetime, and so, there would be no conflict with relativity. Alice's measurement wouldn't cause Bob to branch. Rather, all causation would take place at the fundamental level. Bob's branching really and truly isn't caused by Alice's measurement, rather it's just determined by the wave function that grounds it.

Alyssa Ney (2021) considers this possibility in recent work. However, as she argues, this is an extremely tendentious move:

> I … find such a position unsatisfactory. The reason is that if one wants to argue in this way that there is no immediate causation across spatial distance because such causal relations are undercut or screened off by the behavior of the wave function, then one must similarly do so for all other causal relations in the low-dimensional framework. For there will always be a wave function explanation available at the more fundamental level. So, unless we are to be causal nihilists about what happens in the derivative low-dimensional space or spacetime, we should not argue that the behavior of the wave function undercuts the reality of derivative nonlocal action. (Ney 2021, p. 111)

So, even if there is a more fundamental ontology that is local, this does not remove the existence of nonlocal connections in spacetime, and so, the conflict with relativity, unless we want to reject causality in spacetime altogether.

But even if one wants to bite this bullet, there is another reason why an appeal to Mad Dog Everettianism does not help. This is that the ray-in-Hilbert-space view, like the more commonly defended version of wave function realism, which takes the fundamental ontology to be a field in a high-dimensional configuration space, is an ontological position available not just to those adopting the many worlds interpretation, but also to those defending collapse and hidden variables theories.[12] As Ney (2021, pp. 105-113) has shown, even if an advocate of the many worlds interpretation might argue that the nonlocality in the spacetime ontology may be explained as a manifestation of a more fundamental ontology that is local in higher dimensions, so too can an advocate of these other solutions to the measurement problem. This is straightforward for hidden variables theories like Bohmian mechanics. It requires more argument in the case of collapse theories, but here too things are more or less clear (Ney 2021, pp. 105-110). Even if there may be nonlocality in what one might regard as the less fundamental spacetime metaphysics, a wave function realist or "Mad-Dog" collapse theorist could see all of this nonlocality removed in what they regard as the more fundamental, higher-dimensional ontology. And this means then that, without arguing that the many worlds theory implies that locality is preserved in the nonfundamental spacetime ontology, one can't use a locality-based argument to support the many worlds interpretation over its main rivals.

It is my view that Sebens and Carroll are giving up on the locality-based argument for the many worlds interpretation too easily when they allow the nonlocality they perceive to be a consequence of global branching to be "psychologically unintuitive but empirically benign." The

[12] Albert (1996) defends wave function realism as an ontological interpretation of Bohmian mechanics. Valia Allori et. al. (2008) describe the view they call 'GRW_0,' which is an ontological interpretation of the GRW collapse theory according to which all there is fundamentally is a wave function in configuration space.

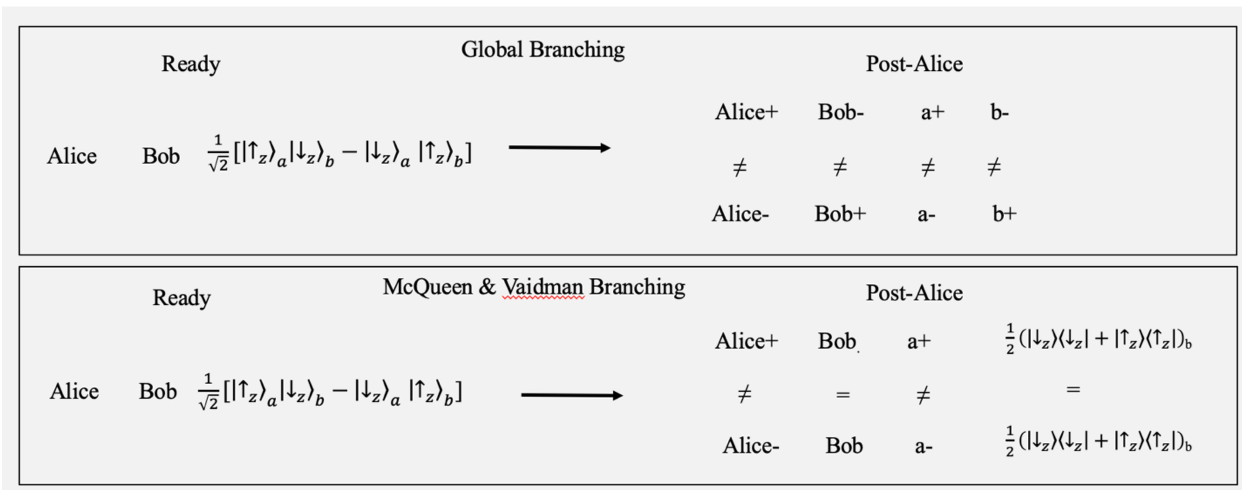
locality of the many worlds interpretation can be straightforwardly defended against the threat posed by global branching. Moreover, this does not require appeal to a more fundamental ontology in a high-dimensional space.

6. Resolving the Appearance of Nonlocality in the Global Branching Model

6.1 Semi-Local Branching is Not an Improvement on the Global Branching Model

First, let's recall the two models of branching we are considering.

Figure 4



According to the global branching model, when Alice measures her particle, this triggers a branching event in which at the same time as she and her particle branch, so also do Bob and his particle. As we saw above, there is a concern that this model involves action at a distance, because Alice's measurement immediately causes Bob to branch. To avoid this consequence, McQueen and Vaidman insist on a semi-local branching model according to which at the time Alice and her particle branch, Bob and his particle do not. However, Bob and his particle do become "bi-located." In summary, in the McQueen-Vaidman branching model, although Alice's measurement causes the world to branch, Alice' measurement does not cause Bob or his particle to branch. There is still just one Bob, and one particle b.

In Section 3, I argued that the semi-local branching model is not much of an improvement on the global branching model because even though we thereby avoid the consequence that what Alice does immediately causes Bob to branch, still there is instantaneous change in that what Alice does immediately causes Bob to come bi-located. If we are metaphysically sophisticated enough to see the difference between branching and bi-location, then we should be metaphysically sophisticated enough to see that they are both in some sense instantaneous changes to Bob.

At this point, McQueen and and Vaidman might give the following response. "Yes," they might say, "it is true that after Alice's measurement, Bob becomes bi-located, where he wasn't earlier. But this is just a "metaphysical" difference to Bob. In other words, it is a difference that doesn't have any empirical consequences. On the other hand, the change to Bob that occurs on the global branching model, as the result of Alice's measurement is an empirical change. For, before Alice's measurement, Bob had a 50% chance of finding his particle to have z-spin up, were he to measure it. But on the global branching model, after Alice's measurement there are two Bobs, call them "Bob+" and "Bob-". And these Bobs have different chances of finding their particle to have z-spin up, were they to measure them. Bob+ has a 100% chance of finding his particle to be z-spin up, while Bob- has a 0% chance of finding his particle to be z-spin up. By contrast, on our picture, there is still just one Bob after Alice's measurement. And since there is only one Bob in these two worlds, the chance of him finding his particle to have z-spin up is just the same as it was before Alice did her measurement, 50%."[13]

But to this, the defender of global branching should give the following response. Let's allow that in a sense it is true that the chances of Bob+ or Bob- finding his particle to have z-spin up are 100% or 0%. And these chances are different than those the original Bob had for finding his particle to have z-spin up. Still, this doesn't imply any intrinsic change to Bob. And for this reason, these changes don't imply any action at a distance. To see this, consider a simple analogy. Suppose at the time that Socrates is drinking the hemlock in prison, his wife, Xanthippe is located elsewhere, perhaps very far away from Athens, perhaps in the Andromeda Galaxy. It is

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[13] As a side note: this is one of McQueen and Vaidman's (2019) main objections to Sebens and Carroll's (2018) account of probability in the many worlds interpretation as self-locating uncertainty. Sebens and Carroll argue that after Alice's measurement, but before Bob (Bob+ or Bob-) knows the result, he can be uncertain about where in the quantum multiverse he is located, i.e. which world he is in. And since things would look the same to Bob (Bob+ or Bob-), whether he were in the world where Alice measured up or the world where Alice measures down, he should assign probability ½ to each. McQueen and Vaidman agree that probability in the many worlds interpretation should be understood in terms of self-locating uncertainty, but want to say that in a case like this, Bob himself hasn't branched, and so there is no basis for self-locating uncertainty. Bob can reason that the probability he would find his particle spin-up is ½, but this isn't because he himself has split and the Bob who is consider the probabilities (Bob+ or Bob-) is unsure about which world he is in. According to McQueen and Vaidman, if we are to avoid locality, we must insist there is only one Bob and he is located in both worlds!

certainly true that the instant Socrates dies, Xanthippe becomes a widow. But does this imply a violation of locality, action at a distance? Of course not. There is nothing troublesome or problematic about this change to Xanthippe, from being a wife to being a widow. This is, because, to use Peter Geach's phrase (1969), this change to Xanthippe is a "mere Cambridge change." Important though this change is, it is not a change intrinsic to Xanthippe, but a merely a change in the world around her, a change in her extrinsic properties. Similarly, this change to Bob, that according to the global branching model, he first has a 50% chance of measuring his particle to have z-spin up, but then after Alice's measurement, he has either a 100% or 0% chance, is a mere Cambridge change. It is a change to his extrinsic properties, not an intrinsic change to Bob. And as such, it poses no threat of action at a distance.[14]

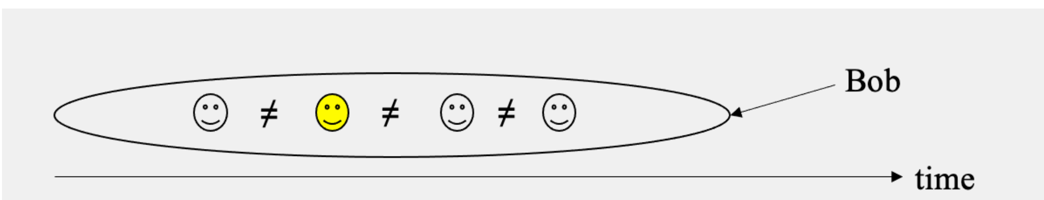
But, one might press, even if this change in his extrinsic properties, in what Bob would measure, isn't an intrinsic change to Bob, isn't his branching an intrinsic change? This will require more discussion, but ultimately again, the answer is "No." The quick and dirty response the defender of global branching can give is that the property of being a twin is an extrinsic property. Whether or not you are a twin is not an intrinsic feature of you, but concerns whether there exists another person of a certain type. To address this issue more fully however, we need to get clear on the metaphysics of persistence.

[14] It is worth noting that not all intrinsic changes to an object are changes to its intrinsic properties. For example, if Socrates's death caused Xanthippe to change her location, this would be an intrinsic change to Xanthippe, and one that would legitimately raise questions about action at a distance. However, in the case we are considering, Alice's measurement neither causes a change to Bob's intrinsic properties nor a change to his location.

6.2 Branching and Persistence

Following David Lewis (1976, 1986) and Ted Sider (2001), the metaphysics of persistence that can best accommodate special relativity is some version of four-dimensionalism, or the doctrine of temporal parts. According to the more common form of this position, perdurantism, material objects like persons persist over time by being four-dimensional spacetime worms that have different temporal parts at different times.[15] Moreover, according to the perdurantist, objects undergo intrinsic change over time in virtue of having a temporal part at one time that has an intrinsic property and a temporal part at another time that lacks that property.[16]

Figure 6



Now let us consider the case in which Bob branches as the result of Alice's measurement. Here there will be two spacetime worms, as in Figure 7.

[15] Not much would change in the present discussion if we considered the main four-dimensionalist rival to perdurantism, the stage theory (defended in Sider 2001). However, the language that we would have be use if we assumed the stage theory is more complicated, and so I shall confine myself in the text to discussing what is the case according to perdurantism.

[16] Following the clarification made in footnote 14, we can also allow that objects can change their location over time by having a temporal part at one spatial location and another temporal part that is not at that location.

Figure 7

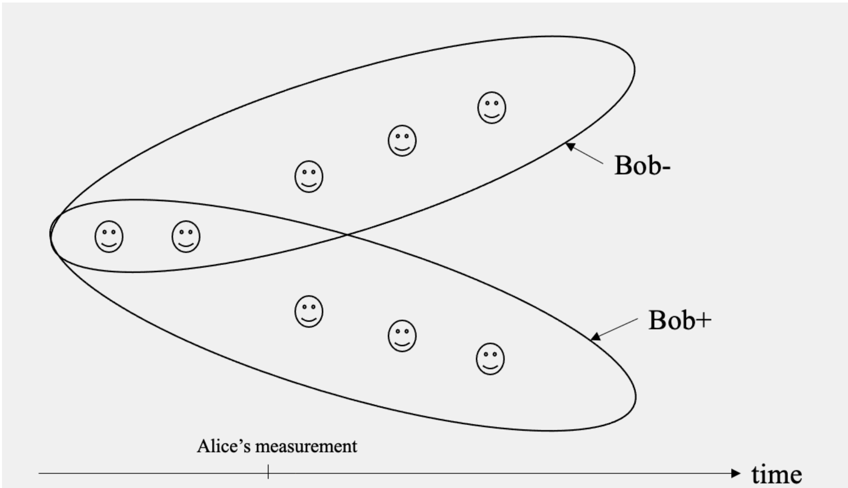


Figure 7 is misleading in at least one respect. This is that there is no reason to think that Alice's measurement should lead to a difference in Bob's location. For example, we have no reason to think that after Alice's measurement, the Bob in the world where Alice gets an up result will move to the left, while the Bob in the world where Alice gets a down result will move to the right. So, strictly speaking, these spacetime worms will overlap in their spatial locations for at least a time after Alice measures her particle. Nonetheless, I have drawn Figure 7 in this way, so we can see clearly that there are two worms.[17]

Now we can see why Bob's branching fails to imply that he undergoes an intrinsic change. For what it means to say that Bob branches is that there are actually two Bobs, Bob+ and

[17] A related point is that, for the purposes of this paper, we are assuming that although material objects like Alice, Bob, and their particles branch as a result of decoherence, we are assuming that spacetime itself does not branch. This was discussed already in footnote 10. Recall, this is because this paper is operating for the most part in the context of particle quantum mechanics. We are not assuming a quantum theory of gravity.

Bob-. Before Alice measures her particle, these two Bobs shared common temporal parts. However, after Alice measures her particle, these worms diverge and no longer share common temporal parts. Bob+ is in the world in which Alice measured spin-down for her particle and Bob- is in the world in which Alice measured spin-up for her particle. And the crucial point is that neither Bob+ nor Bob- undergoes any intrinsic change as a result of Alice's measurement. This is because there is no intrinsic property that either Bob+ or Bob- has at the time before Alice's measurement and then lacks as a result of her measurement, nor does either Bob+ or Bob- change their position as a result of that measurement. And this is just what was argued in Section 2.3 In the many worlds interpretation, unlike in collapse and hidden variable theories, the intrinsic properties of objects spatially separated from Alice are not immediately affected by her measurement.

Therefore, focusing on the effect of Alice's measurement on Bob, there is no reason to think that the global branching model implies action at distance. In a way, there is a change to Bob in the global branching model, just as there is a change to Bob in the McQueen-Vaidman semi-local branching model. In the former model, Alice's measurement immediately causes Bob to branch. In the latter model, Alice's measurement immediately causes Bob to become bi-located. However, in neither case is this an intrinsic change to Bob that raises legitimate concerns about action at a distance. In both cases, what we have is a mere Cambridge change. It is like the case where Socrates's death causes Xanthippe immediately to become a widow.

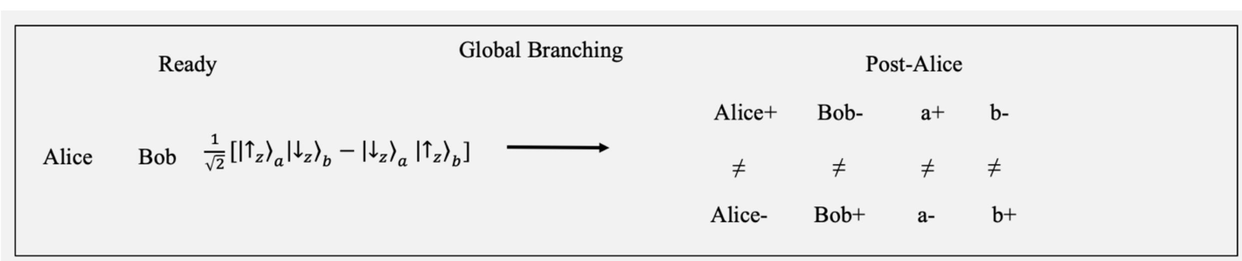
6.3 What About Bob's Particle?

The conclusion of the last section is that the global branching model, the model I take to be the default, most natural way to understand branching in the many worlds interpretation, does not undermine the locality of that interpretation. And so, we do not need to undertake any metaphysical contortions, interpreting branching as a semi-local process, one in which we have to say strictly speaking that Bob doesn't branch but merely becomes bi-located after Alice does her measurement. Nor need we add an ad hoc stipulation that branching spreads through spacetime at a subluminal rate. Nor need we give up altogether on the locality of the many worlds interpretation.

But while the case of Bob is rather straightforward, and the same points about Bob can be extended to apply to the case of Bob's Stern-Gerlach detector, the case of Bob's particle is a bit more complicated. Nonetheless, it is clear, without invoking any tendentious assumptions, that locality is preserved.

So then, let's ask, what happens to Bob's particle as a result of Alice's measurement? Recall the pictorial representation we earlier saw describing what happens according to the global branching model. This reproduced in Figure 8.

<u>Figure 8</u>



Just like Bob, Bob's particle b branches, as a result of Alice's measurement. So there are now two particles, which we may label b+ and b-.

Now recall that for Bob, we acknowledged that although before the measurement, Bob had a 50% chance of measuring his particle to have z-spin up, there are now two Bobs, Bob+ and Bob-. And Bob+ has a 100% chance of finding his particle to have z-spin up, while Bob- has a 0% chance. And although this is clearly a change to Bob's situation, we noted that this was not an intrinsic change to Bob, but rather a mere Cambridge change, since it concerns facts about other systems, not merely Bob+ or Bob- himself.

At least prima facie, it is not clear that this response carries easily over to the case of Bob's particle. To say the same thing, we would have to say although before Alice's measurement, b had a 50% chance of being found z-spin up, if measured, there are now two particles, b+ and b-. The particle b+ has a 100% chance of being found z-spin up if measured, and b- has a 0% chance. So far so good, but the puzzle is whether we can say all of this, while also saying that this is not an intrinsic change to this particle. This seems prima facie wrong just because it can seem that if b+ comes to have a 100% chance of being found z-spin up if measured, that this just means that b+ comes to have the intrinsic property of being z-spin up. And mutatis mutandis for b-. It seems that as a result of Alice's measurement, because of these new chances, b- comes to have the intrinsic property of being z-spin down.

The advocate of the many worlds interpretation with global branching can and should reject these inferences. There are two ways that they can do so. The first way is to apply the same lessons from the Bob case to the case of Bob's particle b. One can insist that strictly speaking, this fact about what a measurement on b+ or b- would result in is not an intrinsic fact about b+ or b-; it involves a relation between b+ or b- and some laboratory apparatus. One can then say that b itself hasn't changed intrinsically. Again, we have two spacetime worms, b+ and b-, and the intrinsic properties of each have not changed as a result of Alice's measurement. Indeed, the particles' spin states may still be given by the reduced density matrix: $\frac{1}{2}|\downarrow_z\rangle_b\langle\downarrow_z|_b + \frac{1}{2}|\uparrow_z\rangle_b\langle\uparrow_z|_b$.

This requires a bit more explanation to see why it is satisfactory. Let's focus on particle b-, Bob's particle in the branch in which Alice has found her particle to have z spin-up. One might ask, if Bob's particle on that branch does not determinately come to have z spin-down as the result of Alice's measurement, then how can we be sure that when it is measured, it will in fact be found z-spin down. Couldn't it, since its intrinsic state continues to just be what's given by the reduced density matrix $\frac{1}{2}|\downarrow_z\rangle_b\langle\downarrow_z|_b + \frac{1}{2}|\uparrow_z\rangle_b\langle\uparrow_z|_b$, come out, when measured, z-spin up? The answer to this question is "No." The particle we have labeled 'b-' is certain to be found z-spin down. But this is not because of anything intrinsic about it. Rather it is because of extrinsic facts about the branch it is on. It is the same fact that makes it a decoherent state that ensures that any future measurements will not conflict with the fact that Alice's particle was found z-spin up. Since an observation on this branch that Bob's particle is z-spin up would conflict with this fact about Alice's particle and the Pauli exclusion principle, this implies that Bob's particle must be found z-spin down.

Although this response is adequate to address any concerns about Bob's particles, there is also a second response available; however, I confess to not finding it is as satisfactory as the first. This is to deny that microscopic systems like particles ever undergo branching. In this case, although the macroscopic systems represented by the quantum state after Alice's measurement branch into distinct successors, the microscopic systems involved do not. This strategy is motivated by the idea that strictly speaking, in order to solve the measurement problem, the advocate of the many worlds interpretation only needs the macroscopic systems (people, pointers, other measuring devices) to have determinate values. The microscopic systems themselves need not, and so they need not branch either. To me, this is a less appealing strategy, as it seems to rely on, as Bell (1980) called it, a "shifty split" between the microscopic and the macroscopic.

It should be noted that an appeal to the microscopic/macroscopic distinction is not so problematic in this case in which we are using it to distinguish which systems do and do not branch, as it is standardly thought to be when it is used to solve the measurement problem (e.g. Leggett 2005). There it is used to specify in which cases the Schrödinger equation applies versus some dynamical collapse law. And the idea is that when we are dealing with microscopic systems alone, the Schrödinger equation obtains; when we are dealing with macroscopic systems, the collapse law obtains. Here the trouble is that there is no sharp boundary between the microscopic and the macroscopic, and yet there would need to be for there to be determinate facts in all cases which laws are operative. Most proponents of the many worlds interpretation today, however, do not find there to be determinate facts in all cases about whether branching occurs or not. This is because the branching structure itself is not fundamental, but derivative ontology. So the fact that the micro-macro distinction is not sharp doesn't cause any special trouble for one who wants to claim that branching only occurs in macroscopic systems.

This all being said, I do not find the view that while macroscopic systems branch, microscopic systems do not plausible. For macroscopic systems are composed of microscopic systems. Say what we want of Bob's particle, it is almost incoherent to suppose that Bob branches, but the particles that compose Bob do not. Anyway, there is no need to try to make sense of this, when the first response above is clearly available.

7. Locality and Parsimony

My conclusion is that the many worlds advocate is justified in arguing for their approach to interpreting quantum mechanics based on locality considerations. In fact, I agree with Vaidman (2021) that this is the most compelling case to be made for the many worlds interpretation. It is not the only argument for the many worlds interpretation. In fact, in a fairly recent collection devoted to presenting and grappling with the many worlds interpretation (Saunders et. al. 2010), the argument from locality was not even mentioned. Rather, the typical motivation for the interpretation tends to emphasize considerations of ontological and ideological parsimony. Unlike hidden variables theories, the many worlds theorist doesn't have to posit any additional ontology – there is just the quantum state (however we interpret this) evolving unitarily over time. There is no need to posit additional entities with determinate properties. And unlike collapse theories, one doesn't need to posit any additional laws; a collapse law in addition to the Schrödinger equation.

The parsimony motivation is fine, and I think it is what has actually motivated so many of us to be drawn to Everett's proposal and the development of it that has been accomplished in the past decades by the work of Deutsch (1997), Saunders (2010), Wallace (2012), Vaidman (2021), and many others. But the simplicity of a theory lies in the eye of the beholder and many think that even if the fundamental ontology and ideology of the many worlds interpretation is simple, still its abundance of many (albeit nonfundamental) worlds and the clunkiness with which it has to handle the question of probabilities make it overall less parsimonious than its rivals. So, it is nice to have the locality argument as well, which can be put forward as more of an objective, open-and-shut case for the many worlds interpretation. If you want a theory that is compatible with special relativity and doesn't involve action at a distance, then you should prefer the many worlds interpretation. I aim to have shown here how one can advance this argument in a way that doesn't rely on any ad hoc or contentious assumptions about how the many worlds interpretation is itself interpreted.

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