Studies in History and Philosophy of Science 106 (2024) 43–53

Contents lists available at ScienceDirect

Studies in History and Philosophy of Science

journal homepage: www.elsevier.com/locate/shpsa

Non-separability, locality and criteria of reality: a reply to Waegell and McQueen

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ARTICLE INFO

Keywords:
Quantum theory
Locality
Non-separability
Many-worlds

ABSTRACT

Using a 'reformulation of Bell's theorem', Waegell and McQueen, (2020) argue that any local theory which does not involve retro-causation or fine-tuning must be a many-worlds theory. Moreover they argue that non-separable many-worlds theories whose ontology is given by the wavefunction involve superluminal causation, as opposed to separable many-worlds theories (e.g. Waegell, 2021; Deutsch and Hayden 2000).

I put forward three claims. (A) I challenge their argument for relying on a non-trivial, unquestioned assumption about elements of reality which allows Healey's approach (Healey, 2017b) to evade their claim. In an attempt to respond to (A), Waegell and McQueen may restrict their claim to theories which satisfy such an assumption, however, I also argue that (B) their argument fails to prove even the so weakened claim, as exemplified by theories that are both non-separable and local. Finally, (C) by arguing for the locality of the decoherence-based Everettian approach (Wallace, 2012) I refute Waegell and McQueen's claim that wavefunction-based ontologies, and more generally non-separable ontologies, involve superluminal causation. I close with some doubtful remarks about separable Everettian interpretations as compared to non-separable ones.

1. Introduction

The locality of the Everett interpretation of quantum theory is often hailed as one of its great merits. Waegell and McQueen (2020) attempt to reinforce this point with an alleged theorem that, supposedly, singles out the Everett interpretation for its particularly local character. In detail, Waegell and McQueen use the GHZ correlations (Greenberger et al., 1989) to argue for the 'Which Way' claim: the claim that any theory which correctly predicts the GHZ correlations must either be a many-worlds theory, or involve at least one of superluminal causation, retro-causation, or fine-tuning. In addition to this, Waegell and McQueen analyse several prominent many-worlds interpretations with respect to the issue of locality and they reach the controversial conclusion that interpretations according to which the ontology is wholly given by the wavefunction involve superluminal causation.

In the present paper, I put forward three claims, criticizing Waegell and McQueen's arguments. First, I claim that (A) *if Which Way is left unqualified, it is false*. I provide evidence for (A) with a counterexample to Which Way: Healey's Pragmatist Interpretation of quantum mechanics (Healey, 2017). This interestingly reveals how Waegell and McQueen's assumptions about predictions and elements of reality may be denied even within a broadly realist attitude towards physics, such as Healey's (Healey, 2020).

There is a natural reply to (A), namely weakening the conclusion of the argument by defining a new Which Way* claim that includes the Criterion of Reality as an explicit assumption. However, I argue that (B) *the argument given by Waegell and McQueen (W&McQ argument) fails to prove Which Way** because it involves a fallacious inference which ignores the possibility for local but non-separable approaches to quantum theory. I will illustrate the fallacy using the decoherence-based Everettian interpretation (Wallace, 2012) as an example. Following Waegell and McQueen, I call this approach Oxford Everettian quantum mechanics.

Waegell and McQueen explicitly deny that there are any non-separable *local* interpretations of quantum mechanics, and thus they would reject (B). In particular, they argue that the Oxford Everettian interpretation involves superluminal causation. I disagree. In order to support (B), I prove that (C) *Oxford Everettian quantum mechanics is non-separable and local* and, consequently, *non-separability does not necessarily involve superluminal causation*. Following Timpson and Brown (2002) and Brown and Timpson (2016), I articulate the details of the crucial role played by non-separability in accounting for all quantum phenomena locally within the Oxford Everettian interpretation.

Finally, in light of the arguments presented in the paper, I briefly compare separable and non-separable Everettian of quantum theory.

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https://doi.org/10.1016/j.shpsa.2024.03.004
Received 25 July 2022; Received in revised form 21 March 2024

Since the points listed above are interrelated, they will not be addressed in a linear fashion. Section 2 summarizes Waegell and McQueen's argument. A discussion of locality in quantum theory cannot do without a discussion of Bell's theorem, therefore, in Section 3 I explore the relationship between Bell's Factorizability condition and statements of locality, as a reference for later arguments. I then briefly argue that Healey's pragmatist interpretation is a counterexample to the Which Way claim in Section 4. In Section 5 I outline the Oxford Everettian interpretation and use it to reveal a mistake in the W&McQ argument, even when Which Way is appropriately weakened. In this same section, I argue that the Oxford Everettian approach does not involve any superluminal causation and therefore that non-separability does not involve superluminal causation. Finally, I briefly compare separable and non-separable Everettian interpretations.

2. The W&McQ argument

In 1989, Greenberger et al. (1989) ingeniously noted that quantum systems of more than 2 particles jointly prepared in the GHZ state generate some surprising correlations. Waegell and McQueen (2020) appeal to these correlations to argue for the Which Way claim:

Which Way. *Any theory which correctly predicts the GHZ correlations cannot satisfy all of the following three principles: Local Causality, No Superdeterminism and One World.*

where the three principles are defined as follows (Waegell & McQueen, 2020, p. 41):

Local Causality. *There can be no cause and effect between space-like separated events.*

No Superdeterminism. *The elements of reality that determine a system's response to interventions do not determine what interventions will occur on that system.*

One World. *There exists a single-world ontology in which every measurement has a single definite outcome.*

While Local Causality[1] and One World are straightforward, No Superdeterminism needs clarification, particularly concerning the nature of the 'elements of reality' that are mentioned in the statement of the principle. Waegell and McQueen do not specify what they mean by 'elements of reality', but, from context, it is clear that an element of reality is an agent-independent physical property, which determines the outcome of the relevant experiment performed on the system. Therefore, No Superdeterminism is meant to ensure that measurement settings are independent of the measured physical properties and 'effectively rules out explanations of the entanglement correlations that appeal to either effects preceding causes or fine-tuning' (Waegell & McQueen, 2020, p. 39).

In order to prove Which Way, Waegell and McQueen develop an argument (W&McQ argument) that is supposed to demonstrate the negation of One World from the assumptions of Local Causality and No Superdeterminism. I will now summarize the argument and clearly divide it into four distinct steps. In step (i), they introduce the following new assumption:

Criterion of Reality. *If a system's response to an intervention can be predicted with certainty, then there is an element of reality which determines that response.*

[1] In this paper, the term 'locality' refers to Local Causality.

This assumption is evidently inspired by the analogous criterion defined in the famous EPR paper (Einstein et al., 1935).

In step (ii), they argue that 'from *local causality* and *[criterion] of reality* we [are] able to deduce *localized [criterion] of reality*' (Waegell & McQueen, 2020, p. 44, emphasis in original), namely the following principle:

Localized Criterion of Reality. *If an intervention and response happen in a finite region of space–time, and the response can be predicted with certainty, then there is an element of reality located only in that region that determines that response.*

The Localized Criterion of Reality defines a sufficient condition for the existence of elements of reality that are in some sense located only in a region. Waegell and McQueen justify this inference as follows:

> The localized element of reality must be confined to this finite region; if it were not, then the response could be affected by causes in a space-like separated region, violating local causality. (Waegell & McQueen, 2020, p. 41)

The reasoning seems clear: if an element of reality determining the outcome of an experiment lies outside of the experimental region, there would be a violation of Local Causality.

No further characterization of such *localized elements of reality* is offered by Waegell and McQueen, but I will briefly attempt to define the notion more precisely. Given a spacetime region R, consider an object O which, at some points along its worldine, is wholly spatially contained in R. Then, a localized element of reality in R is a property instantiated as an intrinsic property[2] by such an object O at least at some points of its worldline at which it is wholly spatially contained in R. Two examples illustrate that my characterization appropriately classifies between localized and non-localized properties. Consider a particle O_1 of mass M such that, at some times, it is wholly spatially contained in R. Its mass is correctly classifies as a localized element of reality in R, since, at least prima facie, it is an intrinsic property of O_1 as it goes through R. On the other hand, *being-at-a-distance-D-from-*O_2, where O_2 is outside R, is correctly excluded from being a localized element of reality in R, since the property *being-at-a-distance-D-from-*O_2 is not an intrinsic property of O_2.

In step (iii), Waegell and McQueen prove that three systems jointly prepared in the GHZ state individually possess localized elements of reality corresponding to spin-X and spin-Y measurement outcomes. Consider the correlations that three systems in the GHZ state exhibit:

$$XXX = -1, \quad YYX = +1, \quad XYY = +1, \quad YXY = +1$$

where X and Y refer to the outcomes for a spin measurement in the X or Y direction. Given the outcomes of experiments on two systems (say A and B), one may predict with certainty the outcome for the third (C), and therefore one can deploy the Localized Criterion of Reality to deduce that, prior to any measurement, C must possess a localized element of reality determining the measurement outcome. If the experiments are performed at space-like separation, one may deploy Local Causality to argue that the interventions on A and B cannot generate or modify the localized elements of reality at C and therefore the localized element of reality determining the outcome at C is present independently of the interventions at A and B.

Evidently, this argument can be deployed for possible scenarios involving different measurement directions on all three of the systems. No Superdeterminism ensures that the choice of measurement direction is independent of the elements of reality of the systems, which in turn

[2] For the purposes of this paper, we may take *intrinsic* properties to be properties 'such that having them does not consist in being related, or failing to be related, in any way to any external object or objects' (Rodriguez-Pereyra, 2022, p. 28).

ensures that switching from one possible measurement scenario to another does not change which localized elements of reality are present. Waegell and McQueen conclude that all three systems possess localized elements of reality corresponding to spin-X and spin-Y outcomes, prior to their measurement and independently of the measurements on other systems.

Finally, Waegell and McQueen use different counterfactual measurement scenarios to deduce a contradiction with the One World axiom (step (iv)). Consider three systems A, B and C jointly prepared in the GHZ state, and suppose that three observers at spacelike separated points (Alice, Bob and Charlie) choose and perform spin-X measurements on their system. From above, we know that each individual system possesses localized elements of reality determining the results of such experiments. By taking into account the GHZ correlations mentioned above, one can constrain the values of these elements of reality as follows:

$$\lambda_X^A = l \in \{1,-1\}, \quad \lambda_X^B = m \in \{1,-1\}, \quad \lambda_X^C = -\lambda_X^A \lambda_X^B = -lm \in \{1,-1\}$$

where λ_i^j is the element of reality for spin-i measurement on system j, and λ_X^C has been deduced using the GHZ correlations.

Consider now the counterfactual scenario in which everything is kept equal until the choice of measurement type is taken, and suppose that Alice and Bob decide to perform spin-Y measurements, rather than spin-X. Via a reasoning analogous to the one provided for step (iii), thanks to No Superdeterminism and Local Causality we know the elements of reality of A, B and C are unchanged from the previous measurement scenario. In particular, λ_X^C is unchanged and we can place the following constraints on the elements of reality of A, b and C:

$$\lambda_Y^A = n \in \{1,-1\}, \quad \lambda_Y^B = -lnm, \quad \lambda_X^C = -lm$$

where λ_X^C is left unchanged and λ_Y^B is deduced using the GHZ correlations. Waegell and McQueen repeat the argument twice over, and obtain the following sets of localized elements of reality:

$$\lambda_Y^A = n, \quad \lambda_X^B = m, \quad \lambda_Y^C = mn$$

and:

$$\lambda_X^A = -l, \quad \lambda_Y^B = -lnm, \quad \lambda_Y^C = mn$$

In this last set, λ_Y^B and λ_Y^C are kept unchanged from, respectively, the second and third sets of elements of reality, and the value of λ_X^A is deduced using the GHZ correlations. An apparent contradiction is reached: λ_X^A is l according to the first set of elements of reality, while it is $-l$ according to this last set.

It appears that a system possesses two different localized elements of reality which are meant to determine the outcome of one and the same experiment. Waegell and McQueen conclude that both experimental outcomes occur, and therefore the One World principle is violated. Hence, they claim they have given a proof of non-uniqueness of experimental outcomes from the principles of No Superdeterminism and Local Causality, or, equivalently, they have proven the Which Way claim.

In the rest of the paper, I criticize two steps of the argument. The unquestioned introduction of the Criterion of Reality in step (i) clearly stands out as a weak point. The non-triviality of the Criterion of Reality is overlooked by Waegell and McQueen, as they do not seem to consider the possibility of such a substantive assumption failing. This oversight is the reason behind my claim that (A) if Which Way is left unqualified, it is false, which I prove in Section 4. Secondly, I argue in Section 5 that the inference from the conjunction of Local Causality and Criterion of Reality to the Localized Criterion of Reality (step (ii)) is wrong. I appeal to the Oxford Everettian interpretation to substantiate my criticism.

3. Locality and Bell's Factorizability

In order to prove (A), (B), and (C) I will need to establish that Healey's Pragmatist Interpretation of quantum mechanics and Oxford Everettian quantum mechanics satisfy Local Causality. For obvious reasons, in arguing for these claims I cannot go without discussing Bell's theorem. I will now lay the groundwork for such a discussion by clarifying some aspects of the relationship between Bell's different statements of locality, and Local Causality.

Bell (1990) starts from the following locality condition, which I have named Bell's Intuitive Local Causality:

(BILC). *The direct causes (and effects) of events are nearby, and even the indirect causes (and effects) are no further away than permitted by the velocity of light.*[3]

Bell notes that it is difficult to deduce a mathematical condition from a principle such as (BILC) which only talks about causes and effects, therefore from (BILC) he infers a different principle, which I named Bell's Probabilistic Local Causality (BPLC):

(BPLC). *A theory will be said to be locally causal if the probabilities attached to values of local beables in a space–time region 1 are unaltered by specification of values of local beables in a space-like separated region 2, when what happens in the backward light cone of 1 is already sufficiently specified, for example by a full specification of local beables in a space–time region 3.*[4]

where regions 1, 2 and 3 are depicted in Fig. 1. Just as Waegell and McQueen use the notion of *elements of reality*, Bell employs the notion of a *beable*. A beable of a theory (Bell, 1976) is an (agent-independent) physical entity postulated by a theory and a *local* beable is a beable that is confined to a limited region of space. Finally, from (BPLC), Bell infers the famous Factorizability condition (Bell & Aspect, 2004, p. 243) and shows that it is violated by quantum-mechanical predictions.

While (BILC) is evidently related to Local Causality, the mathematical condition of Factorisability is not. Why should we then care about a violation of Factorizability? Because if Factorizability follows from (BPLC), and (BPLC) follows from (BILC), then from a violation of Factorizability follows a violation of (BILC), leading to worries of non-locality. Nonetheless, it is apparent that some assumptions are needed to infer (BPLC), which is a condition about *probabilities*, from (BILC), which is a condition about *causes and effects*. In this paper, I am interested in two assumptions which are not met by Healey's approach and Oxford Everettian quantum theory.

The first of such assumptions is Reichenbach's Common Cause Principle. Such a principle, or a principle substantially similar, is widely accepted as needed to justify the inference from (BILC) to (BPLC).[5] Roughly speaking, the Common Cause Principle states that if α and β are correlated, then either α is a cause of β, or β is a cause of α, or they have a common cause such that, conditional on the common cause their correlation must disappear (call it a *decorrelating* common cause).

It is easy to see how the common cause principle may support an inference from (BILC) to (BPLC). Consider the local beables in regions 1 and 2 of Fig. 1 with their attached probabilities, and name them α and β. Given that they lie in space-like separated regions, (BILC) forbids any direct causal link. Suppose α and β are correlated, then using the Common Cause Principle one derives that there must be a common cause which gives rise to such a correlation and that, conditional on this common cause, the correlation must disappear. (BILC) warrants that the common cause and all its effects that can be causally relevant to α are contained in the past-lightcone of 1. Therefore, conditional on

[3] Bell and Aspect (2004, p. 239).

[4] Bell and Aspect (2004, p. 239–240).

[5] See, for example, Myrvold et al. (2021, Section 3.1).

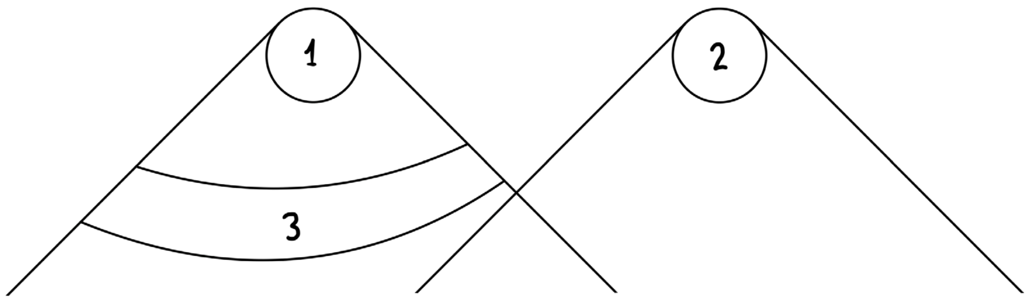

Fig. 1. Regions 1, 2 and 3 mentioned in (BPLC).

a complete characterization of the beables in the past-light cone of 1, the correlation between α and β must disappear, and the probabilities attached to α must not depend on the probabilities attached to β. In other words, we have derived (BPLC), from (BILC) using the common cause principle. Thus, I hope to have illustrated[6] why the common cause principle, or an assumption essentially similar, are necessary in deriving (BPLC) from (BILC).

The second assumption I will be interested in concerns the type of probabilities that Bell's theorem involves. Brown and Timpson (2016, p. 14) correctly note that in order to make a clear-cut connection between probabilities and causal influence, Bell must assume that quantum probabilities are objective chances, and their objectivity must be motivated by them representing, or being grounded in, some localized element of reality.

Now that the preliminary groundwork has been laid down, I can proceed to argue for (A), namely that Which Way is false, if left unqualified.

4. HPI contradicts Which Way

I will now present a counterexample to Which Way: Healey's pragmatist interpretation (HPI) (Healey, 2017). HPI evades the argument's conclusion by denying the Criterion of Reality assumed in the W&McQ argument. More importantly, HPI reveals an interesting way in which the Criterion of Reality may be false even within the context of a broadly realist attitude towards physics. In particular, HPI highlights that two key assumptions seem to underlie the way in which Waegell and McQueen apply the criterion. Firstly, that predictions about an event offer information which is not relative to the predicting agent.[7] Secondly, that it is meaningful to speak of elements of reality even in situations in which decoherence has not obtained. HPI rejects both assumptions and the Criterion of Reality with them, thus illustrating that they are not necessary parts of (broadly) realist accounts of physics (Healey, 2020). In this sense, it highlights the non-triviality of the Criterion of Reality and thus forces a restriction of the scope of the Which Way claim to theories which satisfy such a criterion.

According to HPI 'it is not the function of quantum states, observables, probabilities or the Schrödinger equation to represent or describe the condition or behaviour of a physical system with which they are associated' (Healey, 2016, p. 184). Rather than serving a descriptive or representational role, quantum mechanics is a source of objectively good advice on how to apportion credences to claims about values of physical magnitudes (call these *magnitude claims*) from a given physical situation.

In Healey's view, quantum states are relational entities: they hold between a system and an agent-situation, i.e. the physical situation of a *possible or actual* agent from the perspective of whom the quantum state is assigned. Albeit relational, quantum states are objective. From quantum states, one may obtain quantum probabilities for certain magnitude claims using the Born Rule. Such probabilities are objective advice on what degrees of belief to assign to specific magnitude claims from the agent-situation relative to which the quantum state is assigned.

In Healey's view, although the formalism of quantum mechanics in itself does not represent the world, HPI still provides a non-relational physical ontology on which agents in all situations can agree upon. *Such a non-relational ontology is described by meaningful, true magnitude claims*. Thus HPI is not simply a form of scientific anti-realism (Healey, 2020). Nonetheless, HPI offers only a "gappy" (Healey, 2020, p. 135) ontology, because *claims about magnitudes are only meaningful if they refer to the decoherence basis of a stably decohered system* (Healey, 2017, Chapter 12). For example, in the two-slit experiment, one may meaningfully talk about the position of the particle only when it encounters the screen, because the quantum state of the particle will be decohered in the position basis only when the particle hits the screen (Healey, 2012). A fortiori, predictions are only meaningful when they refer to meaningful magnitude claims.

Healey (2016) offers detailed arguments to show that HPI is compatible with Local Causality. Although I will not get into the details here, one can easily ascertain that, in the context of HPI, from the violation of Bell's Factorizability it does not follow that (BILC) is violated, and thus no worries of locality arise, for the following reason. In section 3, I noted that the inference from Bell's intuitive principle of locality (BILC) to Factorizability is justified only if quantum probabilities represent, or are grounded in, localized elements of reality, since only then the link between probabilities and causation is justified. However, in HPI, probabilities do not serve a representational role, rather they are objective advice relative to an agent-situation. Further, their relational nature prevents probabilities from representing a localized entity. Hence, in the context of HPI, one may not derive Factorizability from (BILC) and, consequently, from a failure of Factorizability it does not follow that (BILC) is violated. Hence, no worries of non-locality are raised by the failure of Factorizability.

Therefore, HPI satisfies Local Causality. Moreover, Healey assumes One World. Finally, No superdeterminism is also satisfied, as there is no mechanism in the theory which constrains the choices of experiment types. Therefore, HPI is a counterexample to the Which Way claim.

As anticipated, HPI circumvents the W&McQ argument because it denies the Criterion of Reality (step (i)). An analysis of Healey's conception of quantum probabilities immediately reveals friction between HPI and the application of the criteria of reality by Waegell and McQueen. Firstly, neither probabilities nor quantum states describe the physical world and, a fortiori, neither describes elements of reality which determine experimental outcomes. Secondly, Healey's quantum probabilities (together with the quantum state) are relational, and they are informative only with respect to a specific agent-situation, as reflected in the fact that, relative to different agent-situations, different, but *objectively and equally correct* probabilities may be assigned to the same magnitude claim. On the other hand, Waegell and McQueen's criteria of reality assume that a certain prediction is informative on

[6] Even though I have not *proven* it.

[7] An analysis of the criteria of reality from Oxford EQM's perspective will also highlight a similar assumption (section 5.3).

the existence of an (agent-situation-independent) element of reality. Given Healey's conception of probabilities, it is not clear that this latter assumption is warranted.

However, ultimately, the Criterion of Reality fails in HPI because it assumes that it is meaningful to talk about elements of reality, prior to the experiment, and thus prior to decoherence. On the other hand, according to HPI, predictions about magnitudes (and thus elements of reality) are only meaningful when referred to the decoherence basis of a stably decohered system. Therefore, one may not use quantum theory to claim the existence of a magnitude or element of reality if decoherence has not occurred. Hence the Criterion of Reality does not hold in HPI.

Waegell and McQueen do not comment on HPI, but they do offer a comment regarding another interpretation denying the Criterion of Reality, namely QBism[8]:

> the question of locality is not a question of personal experience, it is a question of physical ontology. But a physical ontology is something that QBists have yet to provide. (Waegell and McQueen, p. 49)

They argue that QBists cannot address the question of non-locality because they do not offer a physical ontology. Regardless of whether Waegell and McQueen's criticism of QBism hits the mark, one should note that it does not apply to HPI. As remarked above, HPI does provide a physical ontology, albeit a "gappy" one, since 'there is a meaningful story to be told about the values of various magnitudes in circumstances when the content of claims about them is well enough defined.' (Healey, 2020, p.135). Hence HPI may not be brushed away as quickly.[9]

In this section, I have demonstrated (A) Which Way is false and the W&McQ argument fails to prove Which Way because it relies on the non-trivial assumption of the Criterion of Reality. Waegell and McQueen may naturally reply to (A) by narrowing the scope of their argument to theories which satisfy the Criterion of Reality, and, instead, claim that the W&McQ argument proves Which Way*, namely the claim that any theory that can correctly predict the GHZ correlations has to give up (at least) one of Local Causality, One World, No Superdeterminism, *or Criterion of Reality*. In the rest of this paper, I show that (B) the W&McQ argument does not even prove Which Way*.

5. Non-separability and the Localized Criterion of Reality

Waegell and McQueen claim that theories whose ontology is fully specified by the wavefunction, such as what I denote as Oxford Everettian Quantum Mechanics (Oxford EQM), violate Local Causality. Interestingly, they reject appeals to non-separability to save such theories from non-locality (Waegell & McQueen, 2020, pp. 44–47).

Contrary to their claims, I will show that (C) Oxford EQM satisfies Local Causality and thus issues of separability are independent of Local Causality. The analysis of Oxford EQM will demonstrate that Waegell and McQueen's inference from the conjunction of the Criterion of Reality and Local Causality to the Localized Criterion of Reality (step (ii) of the W&McQ argument) is wrong. Hence (B): the W&McQ argument fails to prove Which Way*.

I start by offering a brief outline of Oxford EQM. I then prove (C) by arguing that Oxford EQM is local. Finally, I show that step (ii) of the W&McQ argument fails, and thus demonstrate (B).

[8] See, for example, Fuchs et al. (2014).

[9] I would like to thank an anonymous reviewer for their help in clarifying this point.

5.1. Oxford Everettian Quantum Mechanics

I use 'Oxford EQM' to refer to the decoherence-based Everett interpretation traditionally associated with Oxford-affiliated philosophers, most famously outlined in Wallace (2012). Oxford EQM leaves from the assumption that unmodified unitary quantum theory tells a literally true story of what the physical world is like. In line with this principle, Oxford EQM takes the density operator of a given system to represent the (intrinsic) physical state of the system and the unitary evolution of the density operator to describe the dynamical change of this physical state.[10] An important consequence of this assumption is the non-separability of the ontology: in general the density operator of a composite system does not supervene on the density operators of its subsystems, due to entanglement. This in turn means that, according to Oxford EQM, *the intrinsic properties of a joint system do not supervene on the intrinsic properties of its subsystems*. Entanglement involves relations between systems that are not reducible to the intrinsic properties of the parts.[11]

Although Oxford EQM is concerned with *unitary* quantum mechanics without collapse, the apparent collapse of the wavefunction must be explained, in order to solve the problem of measurement. In short, the appearance of collapse is explained by the branching of worlds. In Oxford EQM measurement interactions are a particular class of unitary interactions which involve entanglement between the quantum state of the system and the quantum state of the apparatus, such that environmental decoherence of the system's quantum state obtains. Roughly speaking, environmental decoherence is a dynamical process which results in the approximate diagonalization of the density operator of the system with respect to a specific basis such that each diagonal term evolves independently.[12] Then, expressed in the decoherence basis, the quantum state is a superposition of terms – the so-called branches – which are mutually dynamically isolated and approximately obey classical equations. These robust patterns in the wavefunction are understood as suggesting the emergence of many 'worlds', in each of which a different measurement outcome obtains.[13]

The following example is instructive. Suppose a spin-$\frac{1}{2}$ particle is prepared in the following state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$

and then sent through a spin detector. Assign a quantum state $|up\rangle$ and $|down\rangle$ to the apparatus measuring up or down. Suppose that, before the particle goes through, the measurement device is in the state $|up\rangle$ and ready to measure. The measurement interaction is a unitary entanglement interaction of the following form:

$$|+\rangle|up\rangle \rightarrow |+\rangle|up\rangle$$

$$|-\rangle|up\rangle \rightarrow |-\rangle|down\rangle$$

and therefore the overall joint state of the particle and apparatus evolves as:

$$\frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)|up\rangle \rightarrow \frac{1}{\sqrt{2}}(|+\rangle|up\rangle + |-\rangle|down\rangle)$$

As remarked above, environmental decoherence in the appropriate spin basis must obtain for the interaction to be called a *measurement* interaction. Decoherence makes the above transition irreversible for all practical purposes and, therefore, for all practical purposes, a definite

[10] Whenever I use the terms 'quantum state' without qualification, I refer to both pure and impure quantum states, mathematically represented by density operators.

[11] For more details on the ontological picture summarized here, see Wallace and Timpson (2010).

[12] For more details, see: Schlosshauer (2007).

[13] Wallace (2010), Saunders (2021).

state of the measuring apparatus is irreversibly paired with a definite eigenstate of the system in the appropriate spin basis. The measurement interaction has magnified the microscopic superposition of states into a macroscopic superposition that includes the measurement apparatus, generating a branching event which propagates outwards at the speed of the dynamical interaction that is causing decoherence. Each branch of this superposition defines a distinct world in which only one of the outcomes obtains[14] and the apparent collapse of the wavefunction in each branch is explained.

Since the branching of worlds is a dynamical process, it does not happen in the whole of spacetime at the same time. Rather, starting from the localized branching event, local decohering interactions involve more and more parts of the physical world in the superposition. Somewhat picturesquely, one could say that the worlds 'expand' at the speed of the dynamical interaction that is causing decoherence. This feature prevents branching itself from involving any superluminal causation.

5.2. Oxford EQM, non-separability and locality

5.2.1. Oxford EQM is local: positive arguments.

I will now show that Oxford EQM satisfies Local Causality. Following Timpson and Brown (2002) and Brown and Timpson (2016) I argue that the peculiar features of Oxford EQM, such as non-uniqueness of measurement results and non-separability, allow for an explanation of all quantum-mechanical phenomena and predictions without superluminal causation. I then illustrate the point with an example relevant to Waegell and McQueen: the GHZ scenario.

Recall that Local Causality consists in the denial of the possibility for causation to occur between spacelike separated *events*. Thus, in order to evaluate Local Causality within Oxford EQM, one must first clarify the nature of events and their location in the world as described by such a theory.

As explained in the previous section, Oxford EQM represents the world via the quantum state.[15] At least in principle, all features of the world *as represented by Oxford EQM* supervene on the quantum state (although there may be features of the world which are not described by Oxford EQM and thus might not supervene on the quantum state). Hence, all events described by Oxford EQM supervene on the density operator being or changing in some way.[16]

A rough account of event locations goes as follows. Consider an event represented by (or supervenient on) the density operators of a system S being or changing in a certain way at a point P along its worldline. Roughly, we may claim that the event is located in the spacetime region R if and only if the system at point P of its worldline is located in R. A better account of event locations may be given by avoiding any mention of the location of a system, and relying instead only on the quantum state and spacetime: *an event located in a spacetime region is represented by (or supervenient on) the density operator of such spacetime region being or changing in a certain way*. The density operator of a spacetime region may be determined in the way detailed by Wallace and Timpson (2010).

It seems hardly possible to reject this localization schema. Some doubts may stem from a misled feeling that density operators of systems (or of spacetime regions) do not offer a complete account of the states of systems (regions), because they cannot predict entanglement correlations. However, as already noted, within Oxford EQM, entanglement correlations are accounted for by relational properties holding between the entangled systems, which cannot be reduced to intrinsic properties of the individual entangled systems, due to non-separability (see section 5.1 above). One should not expect the descriptor of the state of a system (or of a spacetime region) to include also its non-intrinsic (relational) properties, and thus it is natural that density operators of individual systems do not account for entanglement correlations between the systems, which are accounted for instead by the quantum state of the joint system.[17]

Moreover, it is evident that when defining a notion of the location of an event, it is only intrinsic properties that matter. This was also recently argued by Ney (2023), through the following old example. When Socrates drinks the hemlock and dies, Xanthippe instantly becomes a widow. Plausibly, Socrates drinking the hemlock causes Xanthippe to become a widow. Although Socrates and Xanthippe may be spacelike separated, the scenario evidently involves no violation of Local Causality because the change in Xanthippe only involves extrinsic properties, namely the extrinsic property of *being a widow*, and thus it is not localized in Xanthippe's region.[18]

With a clear understanding of events and their location in Oxford EQM, it is easy to see that the nature of the dynamics in Oxford EQM ensures that Local Causality is satisfied. First, recall that Oxford EQM involves only unitary dynamics. Secondly, Oxford EQM uses only local unitaries, ultimately arising from the local interactions in the underlying field theory. With these assumptions, the no-signalling theorem (Ghirardi et al., 1980) proves that applying unitary dynamics to the density operator of a system (or spacetime region) will not affect the density operator of any other space-like separated system (region), even if they are entangled. Moreover, given the local, unitary, and thus deterministic nature of the dynamics, the quantum state of a spacetime region is determined by the quantum state of a cross-section of its past-light cone.[19] Therefore, in Oxford EQM there is a clear sense in which events depend only on events in their past light-cone and spacelike separated events cannot influence each other.

It is intuitively clear that such features imply that there is no superluminal causation in Oxford EQM. Depending on one's favourite account of causation, one may explicate such intuition in different ways. For example, it is often noted that causation is accompanied by counterfactual dependence or co-variation[20] in some form or another.[21] Since density operators of spacelike separated systems (or regions) are independent of one another, it is evident that, in Oxford EQM, spacelike separated events do not counterfactually depend on or co-vary with one another, nor they are linked by a chain of events which

[14] With respect to a coarse-grained choice of discretization of phase-space and time. The branching structure emerging from a measurement-like interaction has no natural count of worlds and is not discrete (Wallace, 2010, 2012, Chapter 3).

[15] Together with an algebra of operators and a preferred one (the Hamiltonian). All of these elements are necessary to make sense of how quantum theory represents the world (according to Oxford EQM). However, as we are working in the Schrodinger's picture, these latter elements are unchanged over time and there is no need to include them in our discussion.

[16] Note, there may well be events more easily described without reference to the density operator, but, if they are accounted for by Oxford EQM, they must ultimately supervene on the density operator.

[17] Note that a density operator encodes all the expectations values for outcomes of measurements on that system (alone); another reassurance that the density operator describes the (intrinsic) state of a system *completely*.

[18] Waegell and McQueen might want to object to the strong intuitive pull of the Socrates example and, instead, claim that in a world with entanglement and non-separability the change or establishment of an extrinsic, (non-separable) property of a region might constitute an event localized in such a region. However, it is not clear how an argument to this effect would go and no such argument can be found in Waegell and McQueen (2020), apart from some related considerations (Waegell & McQueen, 2020, p. 46) which I analyse at the end of section 5.2.3.

[19] Wallace (2012, pp. 302–303).

[20] Define co-variation as follows: 'E counterfactually covaries with C just in case (and to the extent that) variation in the manner of C's occurrence would be followed by corresponding variation in the manner of E's occurrence' (Paul & Hall, 2013, p. 17).

[21] For some famous counterfactual accounts of causation, see Lewis (1973, 2000) among others.

counterfactually depend on or co-vary with each another, i.e. there is no set $\{C, D_1, \ldots, D_n, E\}$ such that E counterfactually depends on or co-varies with D_n, D_n counterfactually depends on or co-varies with D_{n-1}, ... and D_1 counterfactually depends on or co-varies with C.

Moreover, one may easily ascertain that the locality of Oxford EQM would be confirmed under accounts of causation which instead appeal to the intuition of lawful sufficiency, for example Mackie (1965), since any event outside of the past-light cone of E is going to be redundant in any set S of events which is sufficient for E's occurrence.[22] Ultimately, it is clear that our key intuitions on causation converge on the claim that Oxford EQM satisfies Local Causality.[23]

Although I have already established that Oxford EQM does not involve superluminal causation, more can be said about *how* the ontology of Oxford EQM is such that it accounts for all quantum phenomena without involving superluminal causation. As Brown and Timpson (2016) note, there are four interrelated features that make it possible for Oxford EQM to explain empirical predictions without superluminal causation. First, the absence of collapse obviously deals with possible sources of nonlocality. Second, the dynamics of Oxford EQM involves only local unitaries. Third, the non-separability of the fundamental states of the theory, which allows for irreducible relations, i.e. relations which are not reducible to the intrinsic properties of the relata. Finally, the fact that all measurement results occur.

How these four qualities act together can be summarized as follows. Firstly, as I illustrated above, measurement interactions are just *local* unitary interactions that pair the (possibly superposed) states of the system to different states of the measuring apparatus. Secondly, since all measurement outcomes are realized, there is no need for any superluminal causation to enforce entanglement correlations. The irreducible relations that hold between entangled systems take care of this issue via local processes only. Non-uniqueness of outcomes and non-separability together allow for the key feature which ensures the locality of the Everettian account of quantum theory, namely that within Oxford EQM entanglement correlations arise in virtue of an appropriate joining/splitting of branches in the overlap of the future light-cones of measurement events.

Suppose two branching events happen at different spacetime points due to measurements on two entangled systems. At each branching event the superposition is magnified to generate distinct macroscopic (somewhat localized) worlds which expand through local decohering interactions. The irreducible relational properties that held between the systems now hold between the worlds in the two different locations. At the meeting point of the expanding branching processes, which is within the overlap of the future light-cones of the measurement events, these relational properties determine how branches split and/or join each other in such a way as to enforce entanglement correlations. The process does not involve superluminal causation because, while the relations hold between systems which are spatially separated, they are only causally active through local interactions at the meeting points, where they are localized intrinsic properties of the system involved in the interaction.

To illustrate in detail the process just described, I will present an example in the following section.

[22] I would like to thank an anonymous reviewer for helpful comments on this point.

[23] I cannot rule out the possibility that there might be an account of causation which disagrees with my conclusions on the locality of Oxford EQM. However, the arguments I have provided show that such an account would have to deny widely-held intuitions about causation. It is also worth noting that Waegell and McQueen (2020) do not develop or discuss any such account of causation.

5.2.2. The GHZ scenario

I will now spell out Oxford EQM's account of the GHZ scenario, which was employed by Waegell and McQueen in their argument.[24] The GHZ scenario involves three spin-$\frac{1}{2}$ particles prepared in the following entangled superposition:

$$|GHZ\rangle = \frac{|+z\rangle_1|+z\rangle_2|+z\rangle_3 - |-z\rangle_1|-z\rangle_2|-z\rangle_3}{\sqrt{2}}$$

where $|+z\rangle_n$ and $|-z\rangle_n$ refer to eigenstates of particle n for, respectively, spin up and spin down in the Z direction. The W&McQ argument involves different measurement scenarios where Alice, Bob and Charlie measure the spin of, respectively, particles 1, 2 and 3, in several combinations of directions. The measurement interaction $U_i(\theta)$ for system n with its measuring apparatus i is defined as follows:

$$|+\theta\rangle_n|+\theta\rangle_i \xrightarrow{U_i(\theta)} |+\theta\rangle_n|+\theta\rangle_i$$

$$|-\theta\rangle_n|+\theta\rangle_i \xrightarrow{U_i(\theta)} |-\theta\rangle_n|-\theta\rangle_i$$

and it is such that the system is stably decohered in the spin-θ basis.

I start by considering the scenario where Alice, Bob and Charlie all measure the spin of their particle in the X direction at space-like distance. Once the measurement devices are prepared to measure in the X direction and, before the measurement, the joint state of the particles and measurement apparatuses is the following:

$$\begin{aligned}|before\rangle = \ &\frac{1}{2}(|+x\rangle_1|+x\rangle_2|-x\rangle_3 + |+x\rangle_1|-x\rangle_2|+x\rangle_3 + \\ &+|-x\rangle_1|+x\rangle_2|+x\rangle_3 + |-x\rangle_1|-x\rangle_2|-x\rangle_3)|+x\rangle_A|+x\rangle_B|+x\rangle_C \quad (1)\end{aligned}$$

Note that, at this stage, the states of the measuring devices are independent of the state of the particles. The measurement interactions pair states of the apparata to states of the particles:

$$\begin{aligned}|after\rangle = \ &\frac{1}{2}(|+x\rangle_1|+x\rangle_2|-x\rangle_3|+x\rangle_A|+x\rangle_B|-x\rangle_C + \\ &+|+x\rangle_1|-x\rangle_2|+x\rangle_3|+x\rangle_A|-x\rangle_B|+x\rangle_C + \\ &+|-x\rangle_1|+x\rangle_2|+x\rangle_3|-x\rangle_A|+x\rangle_B|+x\rangle_C + \\ &+|-x\rangle_1|-x\rangle_2|-x\rangle_3|-x\rangle_A|-x\rangle_B|-x\rangle_C) \quad (2)\end{aligned}$$

In each branch of the superposition, a state of the particle is irreversibly paired to a state of the measuring apparatus: the superposition has been magnified to macroscopic scales. The evolution of the joint quantum state describes the emergence of a multiplicity of worlds where four specific combinations of outcomes obtain, out of the 8 that are mathematically possible.

To answer the question of locality, consider how the process unfolds in spacetime, represented in Fig. 2 (inspired by (Wallace, 2012, p. 309)): At the locations of each experiment, a branching event begins, and, over time, local decohering interactions involve more and more parts of the physical world in this magnified superposition, thus *make irreversibly definite* the outcome of the experiment with respect to more and more parts of the physical world, by branching out such parts of the world. Evidently, such local branching avoids any superluminal causation.

Interestingly, since measurement outcomes are determined only for systems that are involved in the superposition, they are not absolutely nor immediately determined across spacetime. For example, consider the situation from Alice's point of view, in the interval of time between after having performed the experiment and before being reached by the decoherence interactions from another experiment. It is useful to re-express the quantum state $|after\rangle$ differently[25]:

$$|after\rangle = \frac{1}{2}(|+x\rangle_1|+x\rangle_A(|+x\rangle_2|+x\rangle_B|-x\rangle_3|-x\rangle_C + |-x\rangle_2|-x\rangle_B|+x\rangle_3|+x\rangle_C) +$$

[24] A recent paper (Drezet, 2023) appeals to the GHZ scenario to discuss locality in Everettian quantum theory. Much of what I will say here is highly relevant to Drezet's discussion.

[25] For convenience I am swapping the order of the tensor products.

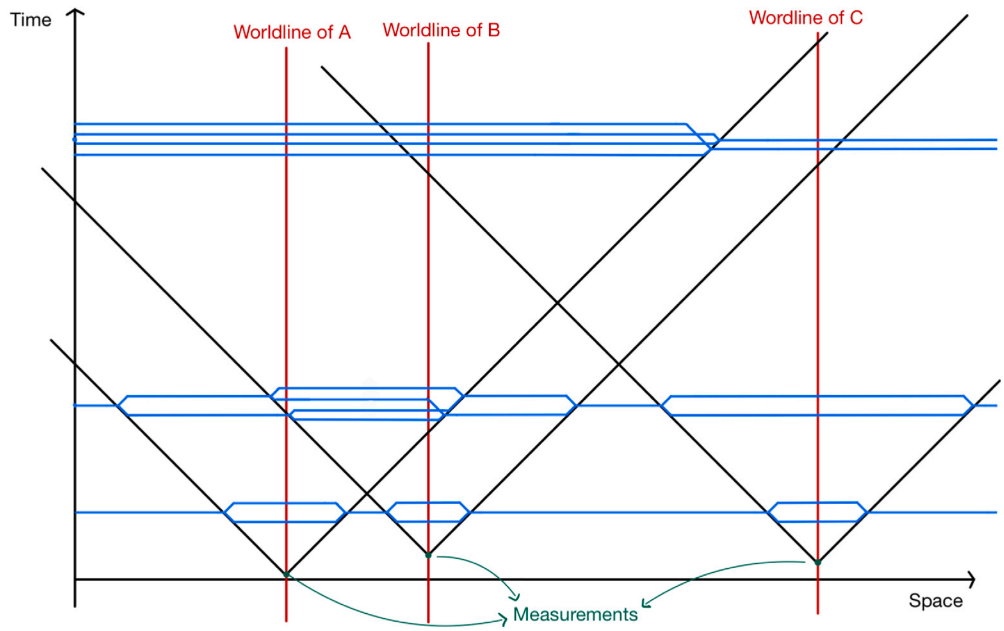

Fig. 2. GHZ scenario in Oxford EQM. The diagonal lines represent the branching processes expanding through decohering interactions, while the horizontal lines schematically indicate the number of branches (note: their separation on the y-axis *does not* indicate a difference in time).

$$+|-x\rangle_1|-x\rangle_A(|+x\rangle_2|+x\rangle_B|+x\rangle_3|+x\rangle_C + |-x\rangle_2|-x\rangle_B|-x\rangle_3|-x\rangle_C)) \quad (3)$$

Based on the outcome of her experiment, Alice can predict that she will experience one of two possible permutations of outcomes for Bob's and Charlie's experiments. However, it is not the case that one of the two permutations of Bob's and Charlie's outcomes obtains, but Alice simply does not know which one. If one were to assume so, one would end up making wrong predictions, because Bob's and Charlie's joint state is an entangled superposition, and therefore, if measured in the appropriate basis, it will produce coherence effects that cannot be accounted for if it was only in one of the two states. On the contrary, *there is no fact about what the outcome of Bob's and Charlie's experiments is with respect to Alice, until she is branched again by the decoherence interactions from another experiment*. Before then, Bob's and Charlie's outcomes are *ontologically* undetermined with respect to Alice. Note that, as there are no correlations to be enforced yet, there cannot be any suspicion for superluminal causation.

Another aspect interestingly different from our pre-theoretic intuitions is the role of non-separability, noted by Brown and Timpson (2016, p. 23). Non-separability allows for relations holding between systems which do not supervene to the intrinsic properties of the relata. Call facts about how things are in Alice's/Bob's/Charlie's spacetime region A/B/C-facts.[26] Then it is non-separability (together with the non-uniqueness of experimental outcomes) that allows for the possibility that A-facts, B-facts and C-facts do not determine facts about how A-facts are related to B-facts or C-facts. In particular, facts about how things in Alice's region are correlated with things in Charlie's and Bob's regions are not determined by how things are in the individual regions. In other words, the irreducibility of the relational-ness of entanglement means that how things are in the individual regions does not determine how the experimental outcomes combine, and thus does not determine the correlations. As remarked above, the correlations are instead determined by the entanglement relations which hold between the regions, which causally determine how the branches locally join/split in the overlap of the future light-cones of the experiments, as represented in Fig. 2.

Thus I have offered a local account of the measurement scenario in which Alice, Bob and Charlie measure in the X direction. Obviously, were the observers to measure spins in different directions, the account would be exactly analogous, with the only difference being the basis with respect to which the systems decohere.

Now that I have shown that Oxford EQM satisfies Local Causality, I will defend such a claim from possible criticism.

5.2.3. *Oxford EQM is local: negative arguments*

In this section, I briefly diagnose why Bell's theorem does not threaten Oxford EQM, following the analysis by Brown and Timpson (2016), and I defend Oxford EQM from the specific objections raised by Waegell and McQueen (2020). Once such objections are dismissed, I will consider as conclusively established that (C) Oxford EQM is a non-separable and local theory, and, consequently, that non-separability does not necessarily involve superluminal causation.

Similarly to HPI, Oxford EQM does not satisfy one of the assumptions necessary to derive Factorizability from (BILC), namely Reichenbach's Common Cause Principle. The principle requires correlations to be explained by a direct causal link or in terms of a decorrelating common cause in the past. From the account of the GHZ scenario just offered, it seems clear that Oxford EQM does not offer either a decorrelating common cause or a direct causal link. Thus Reichenbach's common cause principle is not satisfied by Oxford EQM, and, therefore, a violation of Factorizability does not lead to a violation of (BILC).[27]

It is worth noting that, Reichenbach's Common Cause Principle is unmotivated in Oxford EQM. The Common Cause Principle gains its plausibility from the agreeable intuition that 'correlations cry out for explanation' (Bell & Aspect, 2004, p. 152), however it also provides a restrictive on how these correlations ought to be explained. Oxford EQM breaks this guidance, but still offers an explanation of correlations

[26] I take A/B/C-facts to be *intrinsically about* things in the respective spacetime regions: I exclude facts about how things in Alice's/Bob's/Charlie's spacetime regions are related to things in other regions.

[27] Drezet (2023) claims that 'Everettians are probably ready to accept non-separability as a form of nonlocality. However, the difference with Bell nonlocality is not clearly stated by Everettians' (Drezet, 2023, p. 9). I hope to have clarified this issue.

in terms of physical states, and their associated properties, evolving through local unitary dynamics: a local, causal explanation. Therefore 'we can all actually fully agree … that correlations should be explainable, whilst disagreeing with his [Reichenbach's] specific formulation of what causal explanation (or maybe just explanation) in terms of factors in the past must be like' (Brown & Timpson, 2016, p. 24).

I will now turn to Waegell and McQueen's objections. First, they argue that no Everettian theory which takes the quantum state alone to represent the physical state of systems can satisfy No Superdeterminism and Local Causality. They consider a Bell-EPR scenario and they note that:

> After her measurement, Alice branches into descendants with different outcomes. Focus on a descendant that obtained spin up. She can predict with certainty that if Bob measured X and she meets him, then he will have found spin up too. There must therefore be a localized element of reality at their meeting event which determines that the up Alice meets an up Bob (and not a down Bob, who is also present in space–time; the down Bob meets a down Alice). (Waegell & McQueen, 2020, pp. 44–45)

Waegell and McQueen correctly note that a local theory should account for the joining of branches via some localized element of reality. However, they claim that there are no such localized elements of reality in Oxford EQM since 'the reduced density operator local to Alice's region simply fails to describe the entanglement correlation' (Waegell & McQueen, 2020, p. 45).

Waegell and McQueen are right in noting that the joining/splitting of branches is not accounted for by intrinsic properties of the entangled systems. However, contrary to what they claim, this does not imply that joining/splitting of branches is accounted for non-locally, because whether such relation counts as a localized element of reality depends on the location of the relata, the spacetime region considered, and the nature of the relation itself. In the case of joining/splitting of branches, the relata are wholly spatially located in the spacetime region in which the joining/splitting is taking place. Further, the property *having-two-entangled-parts* is an intrinsic property of the *joint* system. For example, once Alice and Bob meet, the interaction involves the system Alice+Bob and the entanglement properties which determine the (local) joining/splitting of branches are intrinsic to Alice+Bob, and thus they are localized elements of reality. Thus the joining/splitting of branches is accounted for locally in Oxford EQM.

The second argument rests on a misinterpretation of a passage in Wallace (2012, p. 304) where entanglement is described picturesquely as a "string" connecting entangled systems. Waegell and McQueen (2020) claim the following:

> When Alice entangles with particle *a*, she entangles with particle *b*, thereby physically affecting the string connecting *a* and *b*. But there is no local chain of cause and effect running down the string at strictly subluminal speeds. The entire string is affected instantaneously by Alice. And since part of the string is in Bob's region, *local causality* is violated. (p. 46)

Evidently, if entanglement correlations were caused or accounted for by a string-like object with parts in both Alice's and Bob's region, then they would involve superluminal action. However, there is no reason why, in general, the obtaining of a physical relation such as the entanglement relation would necessitate the existence of an object spread out between the two relata, such as a "string" (and Waegell and McQueen do not provide an argument to this conclusion).

Alice entangling with particle *a* and therefore entangling with particle *b* brings about physical change in the region constituted by the union of Alice's and Bob's regions. In particular, such a change involves the establishment of certain entanglement relations between Alice and Bob's particle. Surprisingly, and somewhat counter-intuitively, this change cannot be simply reduced to changes in the individual regions, due to non-separability. Nonetheless, all that matters relative to Local Causality is that no change localized in Bob's region occurs, a fact proven by the unchanged quantum state of Bob. Ultimately, it is no surprise that the changing of the state of a part (Alice's region) may change the state of the whole (the union of Alice's and Bob's regions), without changing the state of another part (Bob's region), and without causal action between the parts.[28]

Hence, I consider conclusively established that Oxford EQM does not violate Local Causality, and, consequently, that (C) Oxford EQM is non-separable and local and that non-separability does not necessarily involve superluminal causation. I will now prove (B).

5.3. Oxford EQM, non-separability and the criteria of locality

Recall that, since HPI contradicts Which Way, I turned to a weaker Which Way* claim, namely the claim that any theory that can correctly predict the GHZ correlations has to give up one of Local Causality, One World, No Superdeterminism, or Criterion of Reality. In this section, I show that (B) the W&McQ argument does not prove even this weaker Which Way*. I explain that step (ii) of the argument, namely the derivation of the Localized Criterion of Reality from the conjunction of the Criterion of Reality and Local Causality, fails. I will show that it is possible to meet the Criterion of Reality and Local Causality without satisfying the Localized Criterion of Reality, by offering Oxford EQM as an example of such a possibility.

Consider first the Localized Criterion of Reality. The definition leaves some ambiguity about the meaning of the term 'response' because, in an Everettian context, all outcomes occur. One natural interpretation would be to consider the 'response' to an intervention to be the branching itself and the subsequent emergence of a multiplicity of worlds. After all, according to Oxford EQM this is the physical situation after a measurement. However, this is not the intended interpretation, simply because if one wants to prove many-worlds, one cannot assume the emergence of the multiplicity of worlds. Instead, 'response' must refer to only one of the possible outcomes of the experiment.

This clarification results in some further ambiguity, because, in an Everettian context, which outcome obtains depends on which branch of the global superposition one is on. Therefore, it is crucial to specify with respect to "whom", or better, with respect to what agent-situation the relevant response obtains. This latter ambiguity is a clear reflection of Waegell and McQueen's underlying assumption pointed out in Section 4 and rejected by HPI as well, namely the assumption that predictions offer agent-independent information. Nonetheless, the ambiguity may be easily resolved: it is clear that the relevant response is the one relative to the predicting agent. Given these clarifications, I can more precisely state the Localized Criterion of Reality in the following form:

Localized Criterion of Reality (Oxford EQM). *If an intervention and response happen in a finite region of space–time R, and the outcome of the response with respect to an agent-situation S can be predicted with certainty from the same agent-situation S, then there is an element of reality located only in the region R that determines the outcome of the response with respect to the agent-situation S.*

Note that, to avoid trivialization of the criterion, it is clear that some constraints must be placed on which agent-situations S of the predicting agents are allowed — for example, agent-situations in the future light-cone of the experimental outcome ought to be excluded, as such agents may obviously predict the outcome of the experiment with certainty. For the purposes of the present paper, I will not explore these constraints any further. Moreover, one should note that the Criterion

[28] I would like to thank two anonymous reviewers for their helpful comments on this point.

of Reality is also affected by these same ambiguities, which should be resolved in a similar manner.

Once the Localized Criterion of Reality is expressed as above, it is easy to show that Oxford EQM violates it. Consider the GHZ scenario. If Alice and Bob perform the experiments on their systems together, and thus they are both aware of both outcomes, then they can predict with certainty the outcome of Charlie's experiment with respect to them. Hence, the antecedent of the Localized Criterion of Reality is satisfied. However, according to Oxford EQM, this does not imply that there is a localized element of reality at Charlie's location which determines that such an outcome will occur with respect to Alice+Bob. On the contrary, the result of Charlie's experiment with respect to Alice+Bob is determined by some non-localized, non-intrinsic relation that hold between Alice+Bob's system and Charlie's system. Therefore, due to the non-separability of Oxford EQM, the Localized Criterion of Reality does not hold.[29]

On the other hand, the (similarly disambiguated) Criterion of Reality does hold in Oxford EQM, because, if the outcome with respect to an agent-situation S can be predicted with certainty from the same agent-situation S, then there are some elements of reality which determine it (which may not be confined to the spacetime region in which the experiment takes place).

Hence, both the Criterion of Reality and Local Causality hold in Oxford EQM, while the Localized Criterion of Reality does not hold: Oxford EQM shows the inference in step (ii) is wrong. Hence, (B) the W&McQ argument fails to prove Which Way*.

6. Concluding remarks

In this paper I have proven that (A) *if Which Way is left unqualified, it is false*, and that the W&McQ argument fails because of the non-trivial assumption of the Criterion of Reality. Waegell and McQueen may reply by simply weakening the Which Way claim so that it only applies to theories which satisfy the Criterion of Reality. However, I have also shown that (B) *the W&McQ argument fails to prove the so weakened Which Way** as exemplified by non-separable, local interpretations. In support of this claim, I have shown that (C) *Oxford Everettian quantum mechanics is non-separable and local* and, consequently, *non-separability does not involve superluminal causation*.

It is worth stressing that, while Oxford EQM illustrates that the W&McQ argument does not prove Which Way*, Oxford EQM is not a counterexample to Which Way* because it is itself a many-worlds theory. Thus, one may attempt to complete the argument and prove Which Way*, by proving that all local, *non-separable* interpretations of quantum mechanics are many-worlds theories, a claim already conjectured by Brown and Timpson (2016, p. 23, footnote 35). However, there are potential counterexamples to Which Way* (and thus to Brown and Timpson's conjecture as well) which I did not consider in the present paper, notably, relativistic dynamical collapse theories (Myrvold, 2002, 2016, 2018, 2019). Such theories ought to be given detailed scrutiny in any attempt to prove Which Way*.[30]

Waegell and McQueen may instead decide to restrict further their claim to a Which Way** claim, by including the *Localized* Criterion of Reality as an explicit assumption (and its denial as a possible "way"). Unfortunately, even if true, such a weakened Which Way** would not be nearly as interesting or powerful as their original Which Way or the already weakened Which Way*. Consider the Which Way* claim. At least pre-theoretically, No Superdeterminism, One World and the Criterion of Reality appear to be sound principles and, at least prima facie, Local Causality also appears well-justified by considerations of compatibility with relativistic spacetime structure.[31] Which Way* is interesting because it would force a denial of one or more prima facie sound principles. However, no good reasons have been provided to deny non-separability, and thus no good reasons have been provided to hold the Localized Criterion of Reality (which, as we have seen, is denied by non-separable theories). Therefore the Which Way** claim turns out to be uninteresting, as one may always choose the "easy way" of denying separability and thus denying the Localized Criterion of Reality.

Finally, it is worth spending a few words to compare separable and non-separable Everettian approaches. The reader will now be familiar with a mainstream non-separable Everettian approach, namely Oxford EQM. A separable Everettian approach was first offered by Deutsch and Hayden (2000), and other separable approaches have more recently been developed by Raymond-Robichaud (2017) and Waegell (2017, 2018, 2021). One might wonder which of these two strands are preferable.

Given the arguments articulated here, the principle of Local Causality cannot be a discriminating factor, since both Oxford EQM and separable approaches satisfy such a principle. Waegell and McQueen (2020, pp. 48–49) attempt to offer some grounds to prefer separable models, as they briefly claim that easier explanations of the Born Rule are available in such separable models. I will not discuss their claim here, but it is worth noting that accounts of the Born Rule in non-separable Everettian interpretations are also widely available (e.g. Wallace, 2012, part II and Saunders, 2022).

On the other hand, two considerations count in favour of Oxford EQM. Firstly, the separable approaches seem to suffer from a problem with empirical underdetermination of their physical states. This has been proven by Timpson (2005) for the approach by Deutsch and Hayden (2000) and given that Bédard (2021) proves an equivalence between Deutsch–Hayden and the approaches of Raymond-Robichaud (2017), one expects Timpson's arguments to carry over to such approaches. In regards to Waegell's approach, he is explicit in referring to it as a local *hidden* variable theory (Waegell, 2021). Secondly, while Oxford EQM is an attempt to interpret quantum theory unchanged, at least prima facie, separable approaches are an attempt to change standard quantum theory in order to interpret it. However, if it is necessary to modify quantum theory to offer a plausible interpretation of it, then one might wonder whether it might be preferable to choose options with a less extravagant ontology than multiverse theories, such as de Broglie–Bohm or dynamical collapse theories.

CRediT authorship contribution statement

Paolo Faglia: Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Many thanks are due to Christopher Timpson, for comments, invaluable discussions and extensive guidance. I would also like to thank Chiara Marletto for many useful discussions about locality, the audience at the MWI workshop in Tel Aviv and, finally, Cheng Foo, Catherine Ashworth, Arlene Lo, Travis McKenna and Juliet Shapiro for detailed comments.

[29] Note that, if 'response' is interpreted instead as referring to the branching process resulting from an intervention, the Localized Criterion of Reality does hold in Oxford EQM.

[30] The metaphysical accounts of non-separability in terms of common ground (Ismael & Schaffer, 2020) or ontological dependence (Calosi & Morganti, 2021) will also be relevant.

[31] For more details, see Myrvold (2021).

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