Chapter 7

On time, causation and explanation in the causally symmetric Bohmian model of quantum mechanics*

Joseph Berkovitz

University of Toronto

0 Introduction/abstract

Quantum mechanics portrays the universe as involving non-local influences that are difficult to reconcile with relativity theory. By postulating backward causation, retro-causal interpretations of quantum mechanics could circumvent these influences and accordingly increase the prospects of reconciling quantum mechanics with relativity. The postulation of backward causation poses various challenges for the retro-causal interpretations of quantum mechanics and for the existing conceptual frameworks for analyzing counterfactual dependence, causation and causal explanation, which are important for studying these interpretations. In this chapter, we consider the nature of time, causation and explanation in a local, deterministic retro-causal interpretation of quantum mechanics that is inspired by Bohmian mechanics. This interpretation, the so-called 'causally symmetric Bohmian model', offers a deterministic, local 'hidden-variables' model of the Einstein-Podolsky-Rosen experiment that poses a new challenge for Reichenbach's principle of the common cause. In this model, the common cause – the 'complete' state of particles at the emission from the source – screens off the correlation between its effects – the distant measurement outcomes – but nevertheless fails to explain it.

Plan of the chapter:

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1 The background

The arrow of time and the time-asymmetry of causation are closely related. Yet, the exact relation between them is a matter of ongoing discussion and controversy. Some authors maintain that causal symmetry is related to temporal asymmetry by definition. They define causation in terms of temporal asymmetry, so that causes precede their effects by definition. David Hume's characterization of causation in terms of constant conjunction is a famous example: "We may define a cause to be *an object, followed by another, and where all the objects similar to the first are followed by objects similar to the second*" (Hume 1777, Section VII, Part II). Hume also related the time-asymmetry of causation to two other asymmetries: time-asymmetry of counterfactual dependence and a corresponding asymmetry in our experience. Thus, he added:

> "Or in other words where, if the first object had not been, the second never had existed. The appearance of a cause always conveys the mind, by a customary transition, to the idea of the effect. Of this also we have experience. We may, therefore, suitably to this experience, form another definition of cause, and call it, an object followed by another, and whose appearance always conveys the thought to that other." (ibid.)

Other authors argue that temporal asymmetry supervenes upon causal asymmetry (Reichenbach 1956, Mellor 1981, 1998)[1], though there is a controversy as to whether the causal asymmetry is primitive (Mellor 1981, 1998) or supervenes on the thermodynamics asymmetry (Reichenbach 1956).[2] Reichenbach (1956) proposes that the direction of time could be reduced to the causal asymmetry that is reflected in the 'fork' asymmetry in macroscopic phenomena – namely, the fact that in such phenomena all the open v-shaped causal forks seem to be in the same direction (see Fig. 1a) – and that this asymmetry could be reduced to the thermodynamic asymmetry. By a cause, Reichenbach meant a

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[1] Cover (1997, p. 306) thinks that it is "not unreasonable to read Kant's Second Analogy as expressing a causal theory of time."

[2] For discussions of attempts to relate the direction of time to the thermodynamic asymmetry, see for example Price (1996), Albert (2000), Kutach (2001, 2002, 2007), Loewer (2007), Price and Weslake (2009) and Frisch (2013).

probabilistic cause, i.e. a cause that raises the probability of its effects (for more details see Section 9).[3]

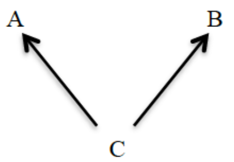

Figure 1a: Causal fork open toward the future, constituted by a common cause, *C*, and its joint effects, *A* and *B*. Arrows denote causal connections.

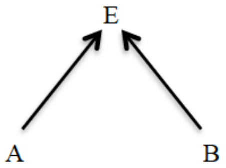

Figure 1b: Causal fork open toward the past, constituted by two causes, *A* and B, and their joint effect, *E*.

Accounts of causation, like Hume's, that define the direction of causation to be the same as the direction of time exclude the possibility of backward causation, i.e. causation from present to past events or from future to present events. While our experience seems to suggest that backward causation does not exist, it is commonly thought that this kind of causation is conceptually, metaphysically and, perhaps, physically possible. Indeed, in the physics literature, there have been proposals to interpret classical electromagnetism and quantum mechanics (henceforth, QM) as involving backward causation. Wheeler and Feynman (1945, 1949) introduced the absorber theory of electromagnetism as a time-symmetric alternative to conventional electromagnetism, which, unlike the latter, imposes no *ad hoc* time direction on electromagnetic processes (for a discussion of this theory, see Crammer 1983). And there have been various retro-causal interpretations of quantum mechanics[4] (henceforth, RCIQM) that postulate the existence of backward causation in an attempt to circumvent the non-local influences that the more conventional interpretations of QM postulate, and accordingly increase the prospects of reconciling QM with relativity theory.

In what follows, our focus will be on RCIQM. We shall analyze the causal structures that models of RCIQM predict in Bohm's (1951) version of the Einstein-Podolsky-Rosen experiment (henceforth, the EPR/B experiment) and some variants of it (see Section 2). In the EPR/B experiment, pairs of particles are emitted from a source and when they are far away from each other undergo measurements. The distant (space-like) measurement

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[3] To simplify things, in what follows in Sections 1-8 we shall not discuss the exact characterization of probabilistic causation, though the approximate contours of the concept of causation we have in mind will become clearer as we go. In Section 9, we shall characterize probabilistic causation more precisely and discuss Reichenbach's view in the context of a deterministic, retro-causal interpretation of QM.

[4] See, for example, Costa de Beauregard (1953, 1977, 1979, 1985), Cramer (1983, 1986, 1988), Sutherland (1983, 1998, 2008), Price (1984, 1994, 1996, 2012), Reznik and Aharonov (1995), Miller (1996, 2008), Berkovitz (2002a, 2008, 2011), Gruss (2000), Kastner (2012) and Price and Wharton (2017).

outcomes are curiously correlated, and these correlations suggest the existence of non-local influences between the outcomes, which are difficult to reconcile with relativity theory. The RCIQM we shall discuss provide local common-cause models of this experiment: the measurement outcomes are the effects of a common cause – the 'complete' pair-state at the emission from the source – which occurs in the intersection of their backward light cones (see Fig 4).

We shall consider the nature of the backward causation that these interpretations postulate and the closed causal loops that they predict, as well as the predictive and explanatory challenges that these causal patterns raise. Here, and henceforth, by a causal loop we mean a sequence of events (or facts) that loops back in such a way that each event (fact) in the loop is an indirect cause of itself (Horwich 1995, p. 259) (for an example of such a loop, see Fig. 2).[5] We shall assume for the sake of consideration that backward causation is metaphysically possible and, moreover, that our universe might comprise such causation if any RCIQM were an appropriate interpretation of QM. This assumption excludes theories of time and theories of causation that prohibit backward causation.

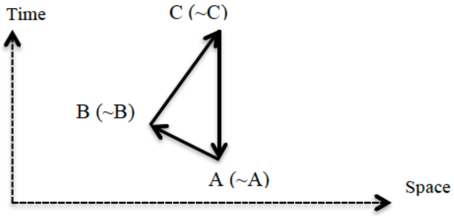

Figure 2: A space-time diagram of a causal loop that involves backward causation, where arrows denote causal influences. In this loop, *A* is forward cause of *B*, *B* is a forward cause of *C* and *C* is a backward cause of *A.* An alternative possible loop is one in which ~*A* causes ~*B*, ~*B* causes ~*C* and ~*C* causes ~*A*.[6]

In the philosophical literature, there are various arguments for the impossibility of backward causation. Further, as we shall see, the backward causation that RCIQM postulate gives rise to causal loops, and there are various arguments for the impossibility of such loops. There are also some arguments for the inconsistency of RCIQM. We shall argue that all these arguments are based on disputable premises and that backward causation, causal loops, and RCIQM could be consistent. We shall then analyze the nature of time, causation, probability and explanation in the context of a deterministic RCIQM.

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[5] In the philosophical literature, the nature of causation is controversial. It is common to think of causation as a relation. Different accounts explicate causation in terms of different relations (for a discussion of whether causation is a relation, see Hausman 1998, Section 2.3), though there is a controversy about whether the relata are events or facts. There are also process theories of causation that explicate causation in terms of certain kinds of processes (see Section 5). For a review of the metaphysics of causation, see Schaffer (2003/2016) and references therein.

[6] Whether event causation could exist between 'events' which are absences of other events is a matter of controversy (see, for example, Schaffer 2003/2016).

In the next section, we present the main ideas of RCIQM. In order to prepare the ground for the study of the backward causation that RCIQM postulate and the causal loops that they predict, in Section 3 we discuss the challenges that analyses of backward causation and causal loops encounter. In Section 4, we review the main arguments for the impossibility of backward causation and causal loops and argue that they have all been challenged. In Section 5, we present the block universe, arguably the dominant ontological framework for understanding space and time in contemporary physics and metaphysics, and consider the representation of backward causation and causal loops in this framework. In Section 6, we discuss indeterministic RCIQM and argue that the causal loops that these interpretations predict pose serious challenges for their predictive and explanatory power. The question arises as to whether deterministic RCIQM fare better. Sutherland (2008) proposes a deterministic RCIQM that is based on Bohmian mechanics (henceforth, BM), 'the causally symmetric Bohmian model' (henceforth, CSBM). In Section 7 we briefly review BM and in Section 8 we present and analyze CSBM.

In Section 9, we consider Reichenbach's Principle of the Common Cause (henceforth, PCC). There have been various objections to PCC. However, as we shall see, none of them apply to the common-cause models that CSBM predicts. In Section 10, we argue that CSBM presents a new challenge for PCC. In the common-cause models that this interpretation predicts for EPR/B experiments, the common-cause screens off the correlation between its effects: the probability of each of the effects given the common cause is independent of the other effect. Thus, it is natural to expect that in such models the correlation between the effects be explained by the common cause. But, as we shall see, this is not the case. In the model that CSBM predicts for the EPR/B experiment, the correlation between the effects has no causal explanation: it is a matter of a brute fact.

That CSBM postulates causally unexplained correlations might not come as a surprise to some students of causal loops. Indeed, it has been argued that causal loops involved causally inexplicable correlations (Horwich 1995). Yet, this argument has been contested (see Section 10), and in any case the causally unexplained correlations that CSBM predicts are of a different kind.

In Section 11 we conclude by considering whether the backward causation that CSBM postulates is compatible with causal theories of the direction of time, and whether the failure of PCC in the common-cause models that CSBM predicts is due to the backward causation that it postulates.

2 The main idea of retro-causal interpretations of quantum mechanics

RCIQM postulate backward causation. The state of a measured system before the measurement is influenced by the state of the measurement apparatus during the measurement or the outcome of the measurement (or some corresponding event/state that carries the same relevant information).[7] These backward influences are a radical deviation from the mainstream metaphysics of science and they pose challenges for the predictive and explanatory power of RCIQM (Berkovitz 2001, 2002a, 2008, 2011). So why bother with such interpretations of QM? The main reason is that RCIQM are supposed to overcome one of the main foundational problems that the mainstream and more conventional interpretations of QM encounter. The mainstream and more conventional interpretations of QM portray the quantum realm as non-local (Bell 1987, Redhead 1987, Butterfield 1992, Berkovitz 2007/2016), and it is very difficult to reconcile this non-locality with relativity theory (Maudlin 1994/2011, Berkovitz 2007/2016, Section 10). By postulating backward causation, RCIQM could avoid this kind of non-locality and consequently increase the prospects of reconciling QM with relativity theory. Further, orthodox QM encounters the infamous measurement problem (Myrvold 2016, Section 4), and some RCIQM, including the retro-causal Bohmian model, also address this problem.

The main idea of RCIQM could be illustrated by a simple example. Consider the EPR/B experiment. Pairs of particles are emitted from a source in opposite directions in the singlet state for spin.[8] When the particles are far away from each other, they encounter apparatuses that can be set to measure spin properties along various directions. Each of the measurements occurs outside the backward light cone of the other measurement, so that there could not be any ('direct') subluminal or luminal influences between them (see Fig. 3). According to orthodox QM, the quantum realm is indeterministic and the outcome of each of the distant measurements is a matter of sheer chance. Yet, the measurement outcomes are curiously correlated: the probability of spin 'up' along the direction n in one wing of the experiment depends on whether the measurement outcome in the other wing is spin 'up' or spin 'down' along the direction m. This correlation suggests the existence of a curious influence or connection between the distant (space-like separated) measurement outcomes, and indeed the 'more conventional' interpretations of QM seem to predict the existence of such non-local influence or connection (see Fig. 3). In the reference frame of the source, the pair-state at the emission and the setting of the left-wing measurement apparatus jointly determine the outcome or the probability of the outcome of the left-wing measurement, and the pair-state at the emission, the setting of the right-wing measurement apparatus and the outcome of the left-wing measurement jointly determine the outcome or

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[7] For an example of such corresponding events/states, which are not effects of the measurement outcomes, see Sections 8 and 10.

[8] In Dirac's notation, the singlet state for spin is expressed as follows: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|n+\rangle_1|n-\rangle_2 - |n-\rangle_1|n+\rangle_2\right)$, where the indexes '1' and '2' denote the first and the second particle respectively, and $|n+\rangle_1$ ($|n+\rangle_2$) and $|n-\rangle_1$ ($|n-\rangle_2$) are the states of the first (second) particle having respectively spin 'up' and spin 'down' along the direction n.

the probability of the outcome of the right-wing measurement.[9] This kind of non-local influences between the measurement events is difficult to reconcile with relativity theory.

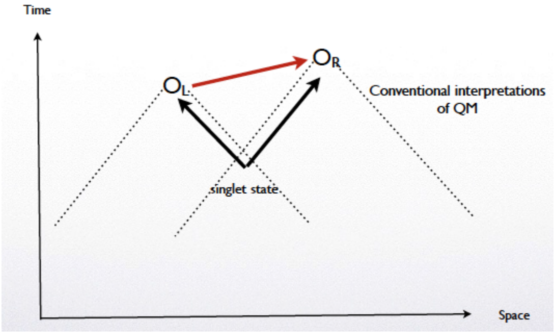

Figure 3: A Space-time diagram of the non-local influences in the EPR/B experiment in 'conventional' interpretations of QM. In the reference frame of the source, the left-wing measurement outcome influences the right-wing measurement outcome. O_L (O_R) denotes the left- (right-) wing measurement outcome.

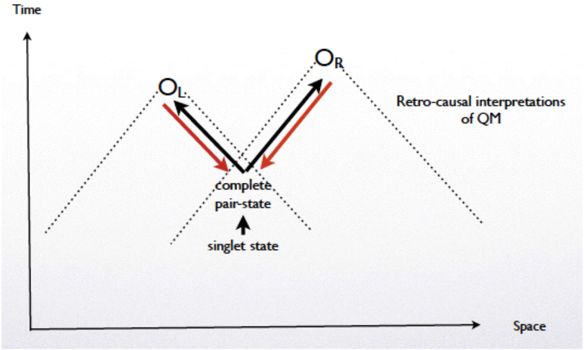

Figure 4: A space-time diagram of the causal influences in local retro-causal interpretations of QM. The probability of each of the measurement outcomes is determined by the 'complete' pair-state at the emission from the source, and this state is influenced by the settings of the measurement apparatuses or the measurement outcomes, depending on the model.

RCIQM provide very different models of the EPR/B experiment (see Fig. 4). These interpretations of QM are in effect 'hidden-variables' theories, and accordingly in the models that they prescribe for the EPR/B experiment the 'complete' state of the particle pair is different from its QM wavefunction. In these models, the probability of each of the measurement outcomes is determined by the 'complete' pair-state at the emission from the source, and this state is influenced by the settings of the measurement apparatuses or the

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[9] Some hidden-variables interpretations of QM, like Bohmian mechanics, postulate the existence of 'parameter dependence', i.e. the dependence of the probability of the distant measurement outcome on the setting of the nearby measurement apparatus in the EPR/B experiment. But, as Berkovitz (1998, Sections 2.3-2.4, 2007/2016, Section 8.4) argues, Bohmian mechanics involves ('specific') outcome dependence, and parameter dependence is the result of this outcome dependence.

measurement outcomes, depending on the model. In Section 8, we shall discuss the nature of the complete pair-state in the CSBM model of the EPR/B experiment.

3 Backward causation and causal loops: the complications

The study of backward causation poses serious challenges for the existing conceptual frameworks for analyzing causation. Let us consider, for example, two of the main asymmetries that are presupposed in analyses of causation: the asymmetry of manipulation and the asymmetry of counterfactual dependence.

In discussions of causation, it is common to presuppose that manipulations of causes result in changes in (the probabilities of) their effects but that manipulations of effects do not result in changes in (the probabilities of) their causes. This *asymmetry of manipulation* is motivated by the idea that causes are means of bringing about their effects – whenever an effect is an end, its causes automatically supply means of achieving it[10] – but that effects are not means of bringing about their causes. Relatedly, it is common to presuppose that (the probability of) an effect is counterfactually depended on its causes, but that (the probability of) a cause is not counterfactually depended on its effects.[11] Counterfactual accounts of causation take this *asymmetry of counterfactual dependence* to reflect the essential characteristics of causal relations, namely, that they are necessary and asymmetric (Hume 1777, Section VII, Lewis 1973a, Lewis 1986) (for a review of counterfactual accounts of causation, see Menzies 2001/2014).

It is difficult to account for these asymmetries in the context of backward causation. First, the standard understanding of the counterfactuals that are involved in causation seems to exclude backward causation. The most influential analysis of such counterfactuals is due to Lewis (1973b, 1986, Chapters 16-18). According to this analysis, the explication of causal dependence should not be in terms of 'backtracking' counterfactuals, i.e. counterfactuals that state that if things had been different at a certain time, some things would have been different at earlier times.[12] Accordingly, Lewis' account of causation, and any other account that explicates causal dependence in terms of non-backtracking counterfactuals, is inapplicable to backward causation. Thus, if causation is to be explicated in terms of counterfactuals, we need to look for a different analysis of counterfactuals. Since non-backtracking counterfactuals are also central to analyses of manipulation, the same difficulty also reflects on the prospects of explicating the

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[10] See Mellor (1995, p. 79) and Menzies and Price (1993, p. 187).

[11] More precisely, it is common to assume that (probabilities of) effects are counterfactually dependent on their causes or that there is a chain of counterfactual dependencies that connect the effects to the causes (see, for example, Lewis 1986, Chap. 21).

[12] In resolving the vagueness of 'non-backtracking' counterfactuals, we typically hold the past fixed until the time in which the antecedent of the counterfactual is supposed to obtain.

asymmetry of manipulation. Berkovitz (1998, Section 2.6) proposes a sketch of an account of causation in which causal dependence is analyzed in terms of backtracking counterfactuals, and such an account is applicable to backward causation.

It is noteworthy that Lewis motivated the *time asymmetry of counterfactual dependence* by the *asymmetry of overdetermination*; where the time *asymmetry of counterfactual dependence* obtains when future events might be counterfactually dependent on past events, but past events could not be counterfactually dependent on future events.[13] A *determinant* of an event is any set of conditions that are jointly sufficient, given the laws of nature, for the event's occurrence. Thus, determinants of an event may be its causes or its effects (i.e. 'traces of its occurrence'). Lewis held that it is contingently true that events typically have very few earlier determinants but very many later determinants. As Price and Welsake (2009) comment, Lewis believed originally that the asymmetry of overdetermination is not statistical, in which case it should be distinct from the thermodynamic asymmetry. As Elga (2000) argues, though, the dynamical properties of thermodynamic irreversible processes show that in many ordinary cases Lewis' deterministic asymmetry of overdetermination fails.

In Sections 6, 8 and 10, we shall argue that backward causation could give rise to causal loops, and in such loops the asymmetry of manipulation, the asymmetry of counterfactual dependence, and the time asymmetry of counterfactual dependence do not obtain. Yet, even if we abandoned the idea of explicating causation in terms of these asymmetries, counterfactual dependence and manipulation would still be important concepts for the analysis of backward causation and causal loops. Thus, we would still face the challenge of developing accounts of counterfactual dependence and manipulation that are applicable in these contexts.

Backward causation raises some additional challenges. In a universe in which backward causation exists events might be caused by both forward and backward causes and accordingly be much more constrained. This is the case in causal loops. In such circumstances, the behavior of physical systems and the relations between events are expected to be very different from linear causation. Yet, while the heavy constraints on events in causal loops pose serious challenges for the study of such loops, they also provide a key for analyzing the causal loops that RCIQM predict; for, as we shall see in Sections 6 and 8, these constraints help identify the range of possible causal loops (Berkovitz 2001, 2008, 2011). But first we need to counter the arguments for the impossibility of backward causation and causal loops.

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[13] The time asymmetry of counterfactual dependence is the same as the asymmetry of counterfactual dependence in forward causation. But in backward causation the asymmetry of counterfactual dependence may obtain while the time asymmetry of counterfactual dependence is violated.

4 Arguments for the impossibility of backward causation and causal loops

In the literature, there are various arguments for the impossibility of backward causation. Some arguments for the impossibility of backward causation are based on accounts of causation that exclude its possibility by definition. As we have seen above, such accounts are out of favor. Other arguments are based on accounts of causation that do not exclude backward causation by definition. For example, if causation requires that the cause and the effect both exist (as it is commonly assumed), backward causation cannot exist according to tensed theories of time. According to these theories, the future does not exist, and accordingly backward causation would require that effects exist when their causes are absent. In what follows, we shall assume the 'block universe' framework of space and time (see Section 5), and this ontological framework does not exclude the possibility of backward causation.

A more neutral line of argument for the impossibility of backward causation is the so-called 'bilking argument' (Flew 1954, Black 1956, Dummett 1964, Fay 2001/2015). The Bilking argument attempts to demonstrate that backward causation is impossible or, at least, that a belief in its existence can never be justified. The main idea is that if an effect E occurred before its cause C, one could observe E and then try to prevent C and thus 'bilk' the alleged backward causation from C to E. If C could be prevented, then it cannot be a cause of E. And if it is never possible to prevent C when E occurs, then there is no ground to claim that C is a backward cause of E.

Bilking arguments have been challenged (see, for instance, Dummett 1964, Horwich 1987, Tooley 1997, pp. 48-52, Dowe et al. 1998). Moreover, the common view is that backward causation is conceptually, metaphysically, and perhaps also physically possible. Yet, in RCIQM backward causation may lead to causal loops and there are various arguments for the impossibility of such loops. The most popular arguments attempt to show that if such loops were possible, paradoxes would follow. For example, it is argued that if a person could travel to the past, she could kill her grandfather even before her mother is conceived, thus making her birth impossible (for a causal analysis of such a scenario see Section 10). Another argument for the inconsistency of causal loops, put forward by Mellor (1995, Chapter 17.3, 1998, Chapter 12), is based on a probabilistic account of causation, where causation is explicated in terms of the single-case probabilities that an effect has with its cause and would have had without it.[14] Mellor argues that these probabilities are supposed to constrain the long-run frequencies of the effect with the cause and without it, but in causal loops they fail to do so (for an analysis of this argument, see Berkovitz 2001).

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[14] For such interpretations of probability, see Mellor (1971, 1995), Giere (1973a,b), Lewis (1986, Chap. 19), Humphreys (1989), Popper (1990), Suarez (2013) and Berkovitz (2015).

Other arguments are more modest. Rather than striving to establish the impossibility of causal loops, they aim to demonstrate that such loops would involve anomalies, such as improbable or inexplicable coincidences. For instance, no matter how many times a time traveller attempts to kill her grandfather before her mother is conceived, she is destined to fail because of some commonplace reasons, like slipping on banana skins. But, it is argued, the coincidences between the time traveller's attempts and such commonplace causes of the attempts' failures would be causally inexplicable because the coincidences would be due to neither 'direct' causal connections nor common causes (Horwich 1987, Chap. 7, 1995).

In reply to such impossibility/improbability/inexplicability arguments, one may point out that causal loops impose heavy consistency constraints on the events that occur in them, whereas the above arguments overlook these constraints (Lewis 1986, Chap. 18, Horwich 1987, Chap. 7, 1995, Smith 1997, Berkovitz 2001, 2002a, 2008, 2011, Dowe 2003). Once we take account of these constraints, we find that causal loops are neither impossible nor necessarily improbable, though they may appear paradoxical, counterintuitive, or inexplicable (see Sections 6, 8 and 10 for some of the curious characteristics of causal loops). Another reply, which we shall consider in Section 10, is that the apparent improbable or inexplicable correlations between events that are involved in causal loops do have causal explanations.

Finally, there have also been arguments for the inconsistency of RCIQM. In particular, Maudlin (1994/2011) argues that these theories are bound to be inconsistent. However, as Berkovitz (2002, Sections 5.2-5.4, 2008, Section 8) shows, Maudlin's line of reasoning is based on premises that are natural in linear causation but untenable in the context of causal loops.

5 The block-universe, backward causation and causal loops

In current physics and metaphysics, the 'block universe' is the dominant ontological framework for thinking about space and time, and in what follows we shall assume it. We now turn to present this framework and then consider the representation of backward causation and causal loops in it.

In the block-universe framework, the universe is depicted as a four-dimensional block, where three dimensions represent space and the fourth dimension represents time. Events may be thought of as the properties or states of space-time regions in the block, or properties or states of things in space-time regions. All past, present, and future events exist (but not at the same time). There is no ontological difference between past, present and future events, and the division between them is relational to a standpoint. While the four-dimensional events in a block never change, changes are accounted for in terms of the patterns of and the relations between such events. For example, the motion of an object is characterized in terms of the object being at different locations at different times.

It is frequently claimed that the block-universe framework dictates determinism and excludes chancy events and free will. The idea is that if all future events exist, the future is predetermined. That is, if future events exist and it is a fact about the future that an event *E* occurs, then *E* is bound to occur, and no past, present, or future events could cause *E* not to occur. Thus, it is argued that the future is not open to different possibilities, as indeterminism requires, and that free will is impossible and fatalism is unavoidable.

This reasoning is based on a failure to distinguish between 'the impossibility to *change* the actual future from what it is going to be' and the 'impossibility to *influence* the actual future to be what it is going to be'. It is impossible to change the actual future from what it is going to be, but it is possible to influence it to be what it is going to be. The events in the four-dimensional block that represents our universe reflect the actual past, present, and future of our universe. However, our universe could have been different. Had things been different, a different block, i.e. a block with different events, would have represented our universe. In particular, had we taken different choices, our future might have been different. That is, the unrealized possibilities can account for our capacity to make free choices that partly shape the actual future to be what it is going to be. The unrealized possibilities are also a key for explicating causation, indeterminism and probabilities.

Consider causation. In the literature, there are various accounts of causation. A popular account is Lewis's (1986) counterfactual theory of causation. Lewis' theory fits in the block-universe framework. In fact, this is the framework that Lewis had in mind. In Lewis's theory of *deterministic* causation, an actual event *E* in a universe *w* is said to be *causally dependent* on a distinct, actual event *C* in *w* just in case *E* does not occur in the most similar universes in which *C* does not occur. In Lewis's theory of indeterministic causation, an actual event *E* in *w* is *causally dependent* on a distinct, actual event *C* in *w* just in case the single-case objective probability of *E* in *w* is higher than it would have been in the most similar universes in which *C* does not occur.[15] Other accounts of causation could also fit in the block-universe framework. In particular, process theories of causation, which explicate causation in terms of physical processes, such as processes that transport 'marks' (Salmon 1984) or conserved quantities (Fair 1971, Aaronson 1979, Dowe 1992, 1995) fit well within this framework. Yet, pace the arguments of some propronents of these accouts, it is doubtful that explications of causal processes could circumvent the need to appeal to counterfactuals.

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[15] Two comments: (i) Lewis talks about 'worlds' but really mean universes. (ii) In fact, the above definition is a slight modification of Lewis' account, as Lewis (1986, pp. 176-177) requires that the single-case objective probability that the effect has with the cause be much higher than it would have been without the cause; where 'much higher' means by a large factor, though not necessarily by a large difference.

Next, consider indeterminism. Like in a deterministic universe, in an indeterministic universe the actual future cannot be different from what it is going to be. But unlike deterministic universe, the past is compatible with different futures, and things could have been different: the past could have been followed by a different future. Thus, in the block-universe framework, indeterminism is accounted for by multiple blocks, each representing a possible universe that has the same past and laws but a different future.

Single-case objective probabilities of events are also explicated in terms of possibilities. For example, if the single-case probability of 'heads' in a given coin toss is 0.5, the coin will turn either 'heads' or 'tails', i.e. one of these events will be actual. The coin's single-case probability, which is a property of the actual circumstances, is partially explicated in terms of long-run frequencies of 'heads' and 'tails' in the same kind of tosses (i.e., tosses in similar circumstances) in the universes that are the most similar to our universe. In particular, in a long series of independent tosses of the same kind in the most similar universes, the frequency of 'heads' will almost certainly be 0.5.

In the block-universe framework, there is no reason to exclude backward causation as a matter of principle. If backward causation existed, causal loops might exist. We may think of causal loops as sets of events that are related to each other in a cyclical way (see Fig. 2). In consistent loops, each event in the loop's set (together with the relevant circumstances) determines the next event in the set or its probability according to the laws governing the situation. That is, in consistent loops, the relevant laws do not lead to inconsistency, i.e. to events that are incompatible with the loop's set.

In the context of backward causation and causal loops, we may still think of causal dependence as implying some kind of counterfactual dependence. Indeed, in Lewis' theory the counterfactuals are non-backtracking, and as we have seen in Section 3 such counterfactuals exclude the possibility of backward causation. But, first, a theory of causation could be based on backtracking counterfactuals (Berkovitz 1998, Section 2.6). Second, while the question of the analysis of counterfactual dependence in the context of backward causation is complicated, we could apply some counterfactual reasoning to analyze the range of the possible causal loops in a given circumstance even without having a general account of counterfactual dependence for backward causation and causal loops. For example, in circumstance S in which A is a forward cause of B, B is a forward cause of C and C is a backward cause of A, the following counterfactuals obtain: if A occurred in S, the causal loop $A \Rightarrow B \Rightarrow C \Rightarrow A$ would occur, where '⇒' denote causal dependence and if $\sim A$ occurred in S, the loop $\sim A \Rightarrow \sim B \Rightarrow \sim C \Rightarrow \sim A$ would have occurred (see Fig. 2).[16]

Process accounts of causation could also be useful in analyses of backward causation and causal loops, though it is doubtful that such accounts are sufficient for analyzing backwards and causal loops.

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[16] Here for the sake of simplicity, we suppose that S is compatible with both loops.

6 On prediction and explanation in indeterministic retro-causal interpretations of quantum mechanics

There are three main kinds of indeterministic RCIQM. The distinction between them could be illustrated by reference to the kind of backward causation they postulate: (I) RCIQM in which the setting of a measurement apparatus during a measurement influences the 'complete' state of the measured system before the measurement; (II) RCIQM in which a measurement outcome influences the complete state of the measured system before the measurement; and (III) RCIQM in which events that correspond to the measurement outcome (but not the outcome itself) influence the complete state of the measured system before the measurement. In this section we shall focus on interpretations of the first and second kind, and in Sections 8 and 10 we shall discuss a deterministic interpretation of the third kind.

In the EPR/B experiment, the first kind of indeterministic RCIQM postulates that the settings of the measurement apparatuses during the measurements influence the complete pair-state at the emission from the source, and the second kind of indeterministic RCIQM postulates that the measurement outcomes influence the complete pair-state at the emission.[17] Both kinds of RCIQM predict the existence of causal loops. An example of a set up in which such loops are predicted is the following EPR/B-like experiment, henceforth the 'contingent EPR/B experiment' (see Fig. 5).

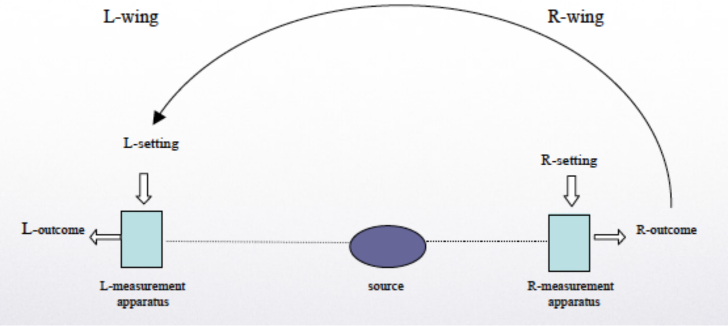

Figure 5: The 'contingent EPR/B experiment', where the R-outcome determines the setting of the L-apparatus by a subluminal signal. For a space-time diagram of the causal connections in this experiment, see Fig. 6.

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[17] In the EPR/B experiment, the measurements are spin measurements. Unless said otherwise, by 'spin measurement outcomes', we shall mean 'specific' outcomes, e.g. spin 'up' in the direction *m* (rather than the 'non-specific' outcome spin 'up', which appears in various discussions of quantum non-locality). In RCIQM of the second kind, models of the EPR/B experiments postulate that specific measurement outcomes influence the complete pair-state at the emission, and so the backward influences of the measurement outcomes also embody information about the apparatus settings.

In the contingent EPR/B experiment, the measurement at the right wing of the experiment (henceforth, the *R*-measurement) occurs before the measurement at the left wing of the experiment (henceforth, the *L*-measurement). The *R*-apparatus is set up to measure spin along the direction *r*. The outcome of the *R*-measurement determines, by a subluminal signal, the setting of the *L*-apparatus: if the *R*-outcome is spin 'down' along the direction *r,* the L-apparatus is set up to measure spin along the direction *l*, which is the same as the direction *r*; and if the *R*-outcome is spin 'up' along the direction *r*, the *L*-apparatus is set up to measure spin along a different direction, *l**. Fig. 6 provides a space-time diagram of the causal connections in this experiment. RCIQM of the first kind predict the existence of Loop 1 of Fig. 7 and RCIQM of the second kind predict the existence of Loop 2 of Fig. 7. In Loop 1, the complete pair-state at the emission and the (fixed) setting of the R-apparatus jointly determine the probability of the R-outcome. The R-outcome determines the setting of the L-apparatus and this setting, the setting of the R-apparatus and the QM preparation of the particle pair jointly determine the probability of the complete pair-state at the emission[18]; where the 'QM preparation of the particle pair' is the physical preparation of the particle pair as prescribed by standard QM. In Loop 2, the complete pair-state at the emission and the (fixed) setting of the R-apparatus jointly determine the probability of the R-outcome. The R-outcome determines the setting of the L-apparatus, this setting and the complete pair-state at the emission jointly determine the probability of the L-outcome, and the L-outcome, the R-outcome and the QM preparation of the particle pair jointly determine the probability of the complete pair-state at the emission.

It is noteworthy that for a RCIQM to be local, QM wavefunctions should be interpreted as epistemic states, i.e. states of knowledge about physical systems or the conditions or fields that govern their behavior. Under such an interpretation, the singlet state reflects an epistemic state that is warranted by the QM preparation of the particle pair rather than the ontological state of the pair (for more details, see Section 8).

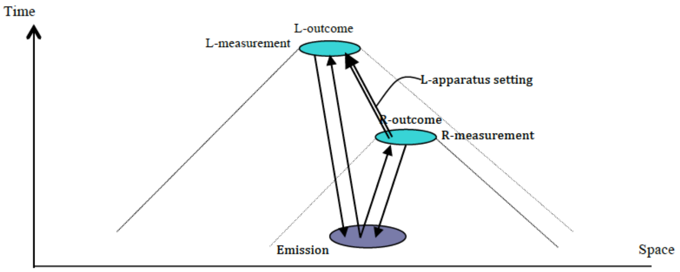

Figure 6: A space-time diagram of the causal connections in the contingent EPR/B experiment according to

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[18] To simplify things, we ignore the question of backward influences on the QM preparation of the particle pair.

RCIQM. Coloured ovals denote events. Dotted lines denote the boundaries of the backward light cones of the measurement outcomes. Arrows denote causal connections. Backward causation from the R- and the L-measurement events convey information about the settings of the L- and the R-apparatus or the outcomes of the L- and R-measurement, depending on the kind of the RCIQM in question.

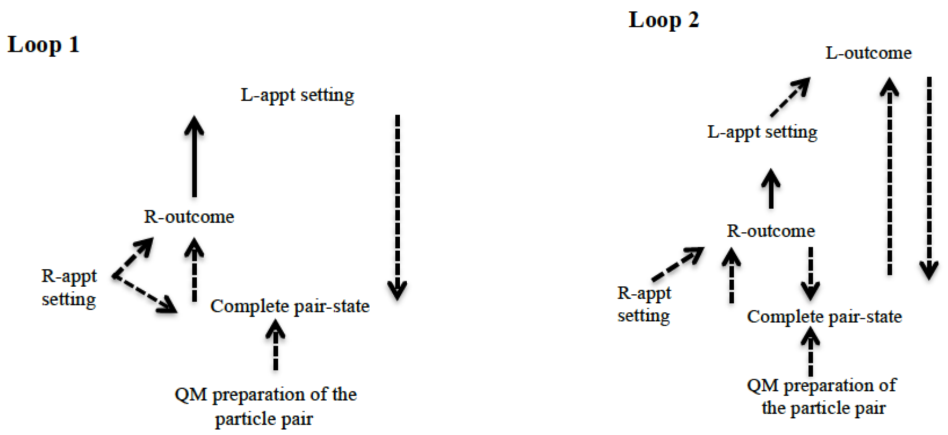

Figure 7: The causal loops that indeterministic RCIQM predict in the contingent EPR/B experiment. Loop 1 depicts the causal loop that occurs in indeterministic RCIQM in which the settings of the measurement apparatuses influence the complete pair-state, and Loop 2 depicts the causal loop that occurs in indeterministic RCIQM in which the measurement outcomes influence the complete pair-state. Solid arrows denote deterministic causal connections and dashed arrows denote indeterministic causal connections.

Although Loop 1 and Loop 2 are consistent, they pose a challenge for the predictive power of indeterministic RCIQM. In each of these loops, the theory assigns the probabilities that the loop's causes give their effects. Yet, these probabilities fail to yield predictions for the frequencies of the effects in the reference class of their causes, independently whether they are interpreted as single-case or long-run objective probabilities, or subjective probabilities. Accordingly, RCIQM fail to yield predictions for frequencies of outcomes in Loop 1 and Loop 2. These failures are due to the fact that in causal loops events are much more constrained than in linear causation and that Loop 1 and Loop 2 have more than one indeterministic causal connection (Berkovitz 2008, 2011).[19] Further, the failure of the probabilities that causes give their effects in Loop 1 and Loop 2 to determine the frequencies that effects have in the reference classes of their causes implies that in indeterministic RCIQM, complete pair-states in EPR/B experiments fail to explain the correlation between the measurement outcomes (Berkovitz 2011). That is, the common cause in this experiment – the complete pair-state – fails to explain the correlation between its effects – the measurement outcomes – even if the explanation of this correlation does not require screening off as in Reichenbach's PCC; where a common cause screens off the correlation between its effects if the probability of one effect given

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[19] In causal loops with only one indeterministic causal connection, the probabilities that causes give their effects determine the long-run frequencies of effects in the reference classes of their causes, but not the long-run frequencies of the causes or of the effects (Berkovitz 2008, 2011).

the common cause is independent of the other effect (for more details, see Section 9). So, curiously, although some of these theories provide local, common-cause models of EPR/B experiments in which common causes screen off the correlations between their effects, they fail to live up to the standards of explanation dictated by Reichenbach's principle of the common cause.

The question arises then: Do deterministic RCIQM fare better? In Sections 8-10, we shall consider the prospects of a deterministic local RCIQM, the causally symmetric Bohmian model. In Sections 7 and 8 we introduce Bohmian mechanics and the causally symmetric Bohmian model, respectively.

7 Bohmian Mechanics

Unlike in standard QM, in Bohmian mechanics (BM)[20] wavefunctions of systems do not represent their states. Wavefunctions are states of a 'guiding field' that guides the trajectories of systems. Wavefunctions always evolve according to Schrödinger's equation and thus never 'collapse'. Particles always have definite positions, the so-called 'hidden variables'. The theory is deterministic. The positions of particles and their QM wavefunction at any given time jointly determine the particles' trajectories at all future times. Thus, the positions of systems and their QM wavefunction determine the outcomes of any measurements so long as these outcomes are recorded in the positions of some physical systems, as in any practical measurement. Wavefunctions govern the trajectories of systems according to the 'guidance equation', which expresses the velocity of a system at a time t, $\mathbf{v}(\mathbf{x},t)$, in terms of its wavefunction at that time:

$$\text{(Guidance)} \qquad \mathbf{v}(\mathbf{x},t) = \frac{\bar{h}}{2im}\frac{\psi^{*}\overleftrightarrow{\nabla}\psi}{\psi^{*}\psi};$$

where m is the system's mass, $\mathbf{x}$ is the system's position configuration, $\bar{h}$ is Planck's constant, ψ is the system's QM wavefunction and ψ^{*} is its complex conjugate, $\overleftrightarrow{\nabla}$ stands for $\overrightarrow{\nabla} - \overleftarrow{\nabla}$, and the grad operators $\overrightarrow{\nabla}$ and $\overleftarrow{\nabla}$ act to the right and to the left, respectively.

Since BM is a deterministic theory, its predictions in individual cases are different from those of standard QM. Yet, the theory reproduces the statistical predictions of standard QM by postulating that the distribution of any possible position configuration $\mathbf{x}$ at time t, $\rho(\mathbf{x},t)$, is given by the wavefunction at that time:

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[20] See, for example, Bohm (1952), Bell (1987, Chaps. 4, 14, 15 and 17), Bohm and Hiley (1993) and Goldstein (2001/2013).

(Distribution) $\rho(\mathbf{x},t)=\psi^{*}\psi$.

That is, the QM statistical predictions for measurement outcomes are obtained as weighted averages over all the possible position configurations (according to the weights prescribed by *Distribution*).

BM portrays the quantum realm as involving non-locality (Bell 1987, Chaps. 4, 14, 15 and 17, Goldstein 2001/2013, Berkovitz 2007/2016, Sections 4, 5.3.1 and 7). For *Guidance* entails that in many-particle system in a non-separable wavefunction the velocity of a particle will typically depend upon the positions of the other, possibly distant, particles. Thus, in the EPR/B experiment the outcome of the first, say nearby, measurement influences the outcome of the distant measurement. This non-local influence accounts for the curious correlation between the distant measurement outcomes.

8 The causally symmetric Bohmian model

The causally symmetric Bohmian model (CSBM) was developed by Rod Sutherland (2008). In this model, the velocity of a system depends on two wavefunctions, ψ_i and ψ_f, which are supposed to record or reflect the system's initial and final boundaries conditions, respectively. Sutherland does not specify the nature of these conditions and accordingly the exact ontological nature of the initial and final wavefunctions is not completely clear. The initial wavefunction ψ_i of a system is its QM wavefuction. ψ_i may be nonseparable, as the wavefunction of the particles in the EPR/B experiment. Yet, as we shall see below, in CSBM such systems also have separable initial wavefunctions. The final wavefunction ψ_f of a system is independent of its initial wavefunction ψ_i and should not be confused with the time-evolved initial wavefunction to a later time. Both of these wavefunctions evolve according to Schrödinger's equation (i.e. they are solutions of the time-dependent Schrödinger equation). ψ_i evolves from past to future, reflecting a forward causal process; whereas ψ_f evolves from future to past, reflecting a backward causal process. The fact that both processes are governed by the same dynamical law implies, for example, that the interaction of a final wavefunction with a measurement apparatus and its evolution from the time after the measurement to the time before it is similar to the interaction of the same initial wavefunction with the measurement apparatus and its evolution from the time before the measurement to the time after it. This means that before interacting with a measurement apparatus, a final wavefunction need not correspond to an outcome of the measurement carried out by this apparatus.

Sutherland proposes that *Guidance* and *Distribution* could be reformulated along the following lines, so as to yield CSBM:

(Guidance$^{\mathrm{S}}$) $$\mathbf{v}(\mathbf{x},t)=\mathrm{Re}\left(\frac{\hbar}{2ima}\frac{\psi_f^{*}\overset{\leftrightarrow}{\nabla}\psi_i}{\psi_f^{*}\psi_i}\right)$$

(Distribution$^{\mathrm{S}}$) $$\rho(\mathbf{x},t)=\mathrm{Re}\left(\frac{1}{a}\psi_f^{*}\,\psi_i\right);$$

where Re(z) gives the real part of z, and a is a normalization factor:

(Normalization) $$a\equiv\int_{-\infty}^{\infty}\psi_f^{*}(\mathbf{x},t)\,\psi_i(\mathbf{x},t)\,d^3\mathbf{x}.$$

That is, Sutherland proposes to substitute ψ_f^{*} for ψ^{*} in *Guidance* and *Distribution* and introduce the normalization factor a, which is required to ensure that the total probability remains equal to one. Given this substitution, the equations in *Guidance* and *Distribution* are no longer real and Sutherland addresses this complication by taking the real part of them.

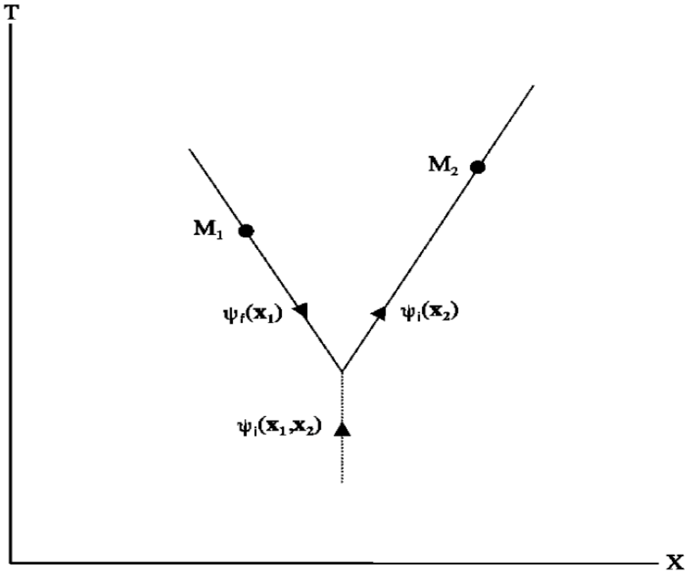

Figure 8: Space-time causal diagram of the formation of the separable initial wavefunction of the R-particle in the EPR/B experiment. The overlap of the initial non-separable wavefunction of the particle pair, $\psi_i(x_1,x_2)$, and the final wavefunction of the L-particle, $\psi_f(x_1)$, yields the separable initial wavefunction of the R-particle, $\psi_i(x_2)$. The initial separable wavefunction of the L-particle is formed in a similar way. M$_1$ and M$_2$ are the L- and the R-measurement, respectively, and x_1 and x_2 are the positions of the L- and the R-particle, respectfully.

While Bohmian mechanics (BM) reproduces the correlations between the distant measurement outcomes in the EPR/B experiment by postulating non-local influences between them, CSBM accounts for these correlations locally by a common-cause: the complete pair-state at the emission from the source – an event that occurs at the intersection of the backward light cones of the measurement outcomes. The complete pair-state is constituted by the positions of the particles and their initial and final wavefunctions, which, as we shall see below, are separable. The final wavefunctions of the particles between the spin measurements and the pair's emission from the source (i.e. after the interaction with the measurement apparatuses) are eigenvectors of spin quantities that correspond to the measurements (see *Predictions* below). The overlap of the initial wavefunction of the particle pair – the singlet state for spin – and the final wavefunction of L-particle between the L-measurement and the emission from the source yields the separable initial wavefunction of the R-particle at the emission (see Fig. 8); and similarly, *mutatis mutandis* for the production of the initial wavefunction of the L-particle. Formally, the separable initial wavefunctions of the particles between the pair's emission from the source and the measurements are obtained as follows:

(SIW)

$$\psi_i(x_1) = \frac{1}{N_1} \int_{-\infty}^{\infty} \psi_f^*(x_2)\, \psi_i(x_1,x_2)\, d^3x_2$$

$$\psi_i(x_2) = \frac{1}{N_2} \int_{-\infty}^{\infty} \psi_f^*(x_1)\, \psi_i(x_1,x_2)\, d^3x_1;$$

where $\psi_i(x_1,x_2)$ is the QM (non-separable) wavefunction of the particle pair, $\psi_i(x_1)$ ($\psi_i(x_2)$) and $\psi_f(x_1)$ ($\psi_f(x_2)$) are the initial and final wavefunctions of the L- (R-) particle, respectively, and N_j are normalization factors ensuring that the total probabilities are equal to 1.[21] Since the initial and final wavefunctions of both particles before the measurements are separable, the measurement outcomes are determined in a perfectly local way. Thus, CSBM provides a local, deterministic common-cause model of EPR/B experiment. The common cause – the complete pair-state at the emission, which is constituted by the particles' separable initial and final wavefunctions and their positions – screens off the correlation between the outcomes: the probability of the L-outcome given the complete pair-state (and the apparatus settings) is independent of the R-outcome; and similarly, *mutatis mutandis*, for the probability of the R-outcome.[22]

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[21] That is, the values of the N_j are such that $\int_{-\infty}^{+\infty} \psi_i^*(x_j)\psi_i(x_j)d^3x_j = 1$.

[22] Accordingly, the joint probability of the outcomes given the complete pair-state (and the apparatus settings) factorizes into the probability of the L-outcome given the complete pair-state (and the L-apparatus setting) and the probability of the R-outcome given this state (and the R-apparatus setting). In fact, the CSBM model for the EPR/B experiment satisfies a stronger condition. The joint probability of the measurement outcomes given the complete pair-state (and the apparatus settings) factorizes into the product of the probability of the L-outcome given the complete state of the L-particle (and the setting of the L-apparatus) and the probability of the R-outcome given the compete state of the R-particle (and the setting of the R-apparatus).

In order for CSBM to be genuinely local, it is necessary to interpret non-separable QM wavefunctions, such as the singlet state, as epistemic states, i.e. states of knowledge about physical systems or the fields that guide them; for any interpretation of the QM wavefunctions of systems as their ontological states or states of fields that guide them would entail non-locality. As we shall see below, in CSBM QM wavefunctions of systems could be interpreted as states of information about the distribution of final wavefunctions. In particular, the singlet state can be interpreted as a state that provides information about the probability distribution of the separable initial and final wavefunctions of the particles in a given QM wavefunction.

Unlike orthodox QM, measurements play no role in the dynamical laws of CSBM. The backward causal influences, which are reflected in final wavefunctions, are not triggered by measurements. Rather, these influences are part of the basic ontology of CSBM. Unlike more ‘conventional’ hidden-variables models of the EPR/B experiment, in the CSBM model of this experiment the QM wavefunction of the particle pair, i.e. the incomplete pair-state, does not determine the probability distribution of complete pair-states.[23] In this model, the distribution of complete pair-states at the emission from the source depends on the distribution of the final wavefunctions of the particles. Thus, in order to reproduce the statistical predictions of standard QM, the model has to be supplemented with a postulate that determines the distribution of the final wavefunctions in any given QM wavefunction and experimental set up. Sutherland proposes the following postulate:

> *Predictions*. Let ψ_i be the QM wavefunction of a (possibly multi-particle) system at some time *t* and ψ_f be the final wavefunction of the system at the same time. If ψ_f corresponds to one of the possible outcomes of a subsequent measurement on the system (like in the case of the particles’ final wavefunctions between the emission from the source and the measurements in the EPR/B experiment), the conditional probability distribution of ψ_f given ψ_i, $\rho(\psi_f, \psi_i)$, is the following
>
> (Predictions) $$\rho(\psi_f, \psi_i) = |a|^2;$$
>
> where the amplitude *a* is as defined in *Normalization*.

In the EPR/B experiment, the system is the particle pair and the pair’s initial QM wavefunction, ψ_i, is the singlet state. Granted *Predictions*, the QM wavefunction determines the distribution of the separable final wavefunctions of the particles between the measurements and the pair’s emission from the source, $\psi_f(x_1)$ and $\psi_f(x_2)$ (see Fig. 8); and granted *SIW*, the distribution of the final wavefunctions determines the distribution of

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[23] The same is true for other local retro-causal interpretations.

the separable initial wavefunctions of the particles at the emission from the source, $\psi_i(x_1)$ and $\psi_i(x_2)$. Although *Predictions* appeals to measurements, it does not entail any dependence of the dynamical laws on measurements. *Predictions* could be thought of as an epistemic postulate: it provides information about the distribution of final wavefunctions of systems, and accordingly information about the distribution of initial wavefunctions, in a given QM wavefunction.

While in BM there is only one probabilistic postulate – *Distribution* – in CSBM there are two independent probabilistic postulates – *Distribution*^{S} and *Predictions*. It is noteworthy that unlike *Distribution* in BM, *Distribution*^{S} does not play any role in reproducing the statistical predictions of standard QM. Further, the information about the position configuration of the particle pair is unnecessary for screening off the correlation between the measurement outcomes in the EPR/B experiment: the initial and final wavefunctions of the particles constitute a local common cause that screens off the correlation between these outcomes. Yet, *Distribution*^{S} is important for the ontology of the causally symmetric Bohmian model and for its solution to the measurement problem.

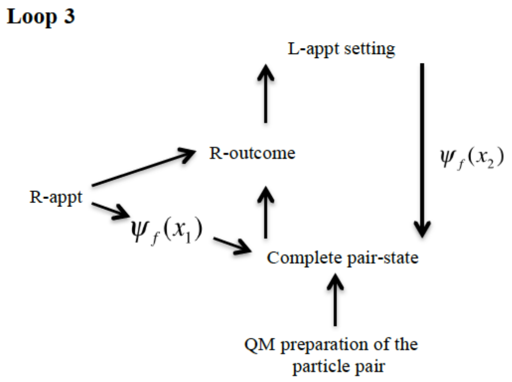

Figure 9: The causal loop that the causally symmetric Bohmian model predicts in the contingent EPR/B experiment (see Figs. 5 and 6).

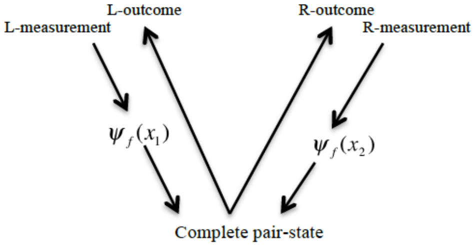

Figure 10: The common-cause scenario in the EPR/B experiment according to the causally symmetric Bohmian model. The common cause – the complete pair-state at the emission – is influenced by the final wavefunctions of the particles, which result from interaction between the particles and the measurement apparatuses. Notably, the measurement outcomes do not influence the complete pair-state.

Like other RCIQM, CSBM predicts the existence of a causal loop in the contingent EPR/B experiment (see Figs. 5 and 6). This loop, henceforth Loop 3 (see Fig. 9), is different from Loop 1 and Loop 2 in two important respects. First, in Loop 3 all the causal connections are deterministic. Second, unlike Loop 2, in Loop 3 the measurement outcomes do not influence the complete pair-state at the source (see Fig. 10), though (due to *Predictions*) the measurement apparatuses send signals, carried by the final wavefunctions, that *correspond* to the measurement outcomes. That is, the final wavefunctions of the particles that emerge from the interactions with the measurement apparatuses and evolve back to the source are 'eigenvectors' of spins that correspond to the measurement outcomes. Thus, unlike RCIQM in which the measurement outcomes influence the complete pair-state, CSBM does not predict causal loops in 'conventional' EPR/B experiments. In Loop 3, the complete pair-state at the source and the setting of the (fixed) R-measurement apparatus jointly determine the R-outcome, the R-outcome determines the setting of the L-measurement apparatus, and the final wavefunctions from the L- and the R-apparatus and the QM preparation of the particle pair (and the position configuration of the particles) jointly determine the complete pair-state at the source.

Unlike Loop 1 and Loop 2, in Loop 3 it is easy to figure out the frequencies of outcomes in the reference class of a given complete pair-state. And, given *Predictions*, it is also possible to predict the frequencies of the measurement outcomes in a given QM wavefunction. Thus, CSBM overcomes the predictive challenges that the indeterministic RCIQM we discussed in Section 6 encounter.[24] In Section 10, we shall discuss the question whether CSBM also overcomes the explanatory challenges that indeterministic RCIQM encounter. To prepare the ground for this discussion we need first to consider Reichenbach's principle of the common cause in the context of CSBM.

9 On Reichenbach's principle of the common cause

Recall that Reichenbach proposed that the direction of time could be reduced to the fork asymmetry in macroscopic phenomena – namely, the fact that in such phenomena all the open v-shaped causal forks have the same direction (see Fig. 1a). The kind of open causal forks that Reichenbach had in mind is a macroscopic situation in which: (i) there is a non-accidental correlation between two macroscopic events, *A* and *B*, neither of which causes the other; (ii) *A* and *B* are effects of a common cause, a macroscopic event *C*; (iii) *C* is probabilistic cause of *A* and *B*; and (iv) *C* screens off the correlation between *A* and *B*.

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[24] The question whether indeterministic RCIQM in which the complete pair-state is determined by events/states that correspond to the measurement outcomes (but are not the outcomes themselves) could overcome these challenges, is beyond the scope this chapter.

(i)-(iv) characterize Reichenbach's principle of the common cause (*PCC*).[25] The underlying idea of this principle is that any non-accidental correlation between events has a causal explanation, that non-accidental correlation between events, neither of which causes the other, is due to a common cause, and that the common cause explains the correlation between its effects when it screens off the correlation between them.[26]

Reichenbach introduced *PCC* by characterizing correlation as 'improbable coincidence': "If an improbable coincidence has occurred, there must exist a common cause" (Recihenbach 1956, p. 157). He gave examples of 'improbable coincidence' but did not explicate the exact meaning of this term. He generalized the above preliminary statement of *PCC* to cases of 'frequent improbable coincidences' of the same kind by defining correlation between events as (positive) probabilistic dependence:

(Correlation) $$P(A \,\&\, B) > P(A) \cdot P(B),$$

where $P(X)$ denotes the probability of X. Reichenbach interpreted probability as long-run frequency, though in the current understanding of the principle the interpretation of probability is an open question. Reichenbach did not explicate the exact nature of the probabilistic causation he had in mind. He just required that the causal fork of Fig. 1a satisfy the following conditions:

(ProbDep) $$P(A/C) > P(A/\sim C)$$
$$P(B/C) > P(B/\sim C)$$

(Screening Off) $$P(A \,\&\, B/C) = P(A/C) \cdot P(B/C)$$
$$P(A \,\&\, B/\sim C) = P(A/\sim C) \cdot P(B/\sim C),$$

where $P(X/Y)$ denotes the probability of X given Y (ibid.). Here, probabilistic causation does not mean indeterministic causation: it is neutral between determinism and indeterminism. *Correlation*, *ProbDep* and *Screening Off* define a 'conjunctive fork', "that is, a fork which makes the conjunction of two events *A* and *B* more frequent than it would be for independent events" (ibid.).

While Reichenbach intended *PCC* to apply to macroscopic phenomena, the principle has also been applied to microscopic phenomena. Indeed, John Bell's (1987) arguments for quantum non-locality are based on the application of *PCC* or a close cousin of it to v-

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[25] Berkovitz (2002a,b) argues that *PCC* is not really a principle but rater a principle schema: for different specifications of the terms that appear in this schema – 'events', 'correlation', 'causation' and 'common cause' – we obtain different principles.

[26] In fact, Reichenbach (1956, p. 158) talked about simultaneous events, but on the common understanding of *PCC* the principle is not limited to such events. For discussions of *PCC*, see for example Hitchcock (1997/2012, Section 2.3), Artzenius (1999/2010), Sober (2001) and Berkovitz (2000, 2002b).

shaped forks open to the future that include both macroscopic and microscopic events or states – namely, forks with a microscopic common cause and macroscopic effects.[27] Further, there is nothing in *PCC per se* to exclude its application to causal structures that involve backward causation.

Indeed, there have been various objections to *PCC*. Here are some notable examples. Fine (1981, 1986, 1989) denies that non-accidental correlations must have causal explanation. Sober (1988, 2001) argues that some non-accidental correlations between events, neither of which causes the other, have no common cause. Van Fraassen (1980)**,** Cartwright (1989) and Chang and Cartwright (1993) argue that in indeterministic v-shaped common-cause forks, the common cause might fail to screen off the non-accidental correlation between its effects. And Sober and Eells (1986) argue that 'indirect' probabilistic common causes might fail to screen off the correlations between their effects.[28]

The objections above aim to challenge the idea that all non-accidental correlations between events, neither of which causes the other, share a common cause, or the idea that the common cause of such events screens off the correlation between them. Thus, these objections are irrelevant for the question of whether *PCC* obtains in CSBM; for in this interpretation of QM, the measurement outcomes in the EPR/B experiment share a common cause – the complete pair-state at the emission from the source – and this cause does screen off the correlation between the outcomes.

Assuming that *PCC* applies to both macroscopic and microscopic phenomena, the question arises then: does this principle obtain in CSBM?

10 On causal explanation of correlations in the causally symmetric Bohmian model

The causally symmetric Bohmian model (CSBM) conforms to the letter of *PCC* but runs counter to its spirit. While the common cause of the measurement outcomes in the EPR/B experiment – the complete pair-state at the emission – screens off the correlation between them, it fails to explain this correlation! The correlation between the measurement outcomes is due to the correlation between the final wavefunctions of the particles. But this correlation, which is postulated by *Predictions*, has no causal explanation: the separable

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[27] Bell generalized the principle to circumstances in which *Screening Off* is applied to a set of mutually exclusive common causes rather than a common cause and its absence. That is, in the local 'hidden-variables' models of the EPR/B experiment that Bell considered there are generally many different possible complete pair-states (which are compatible with the QM wavefunction of the particle pair), and Bell applied *Screening Off* to all these states.

[28] Sober and Eells give as an example a case where an event *C* is a probabilistic cause of an event *D* which is a common cause of events *A* and *B*.

final wavefunctions of the particles are neither linked by (a chain of) ‘direct’ causal connections nor share a common cause. Indeed, in CSBM this correlation is a curious brute fact. Thus, while the model salvages locality and accordingly has better prospects for reconciling QM with relativity theory, it sacrifices an important motivation for RCIQM and more generally for local hidden-variables interpretations of QM: namely, to provide a local *causal* explanation of the curious quantum correlations between the properties of distant systems.

It may be argued that the common-cause scenario depicted by CSBM is different from the v-shaped common-cause fork open to the future that Reichenbach considered (see Fig. 1a). That is, it may be argued that, unlike the fork Reichenbach considered, in CSBM the joint effects influence each other through the common cause: the final wavefunction of the L-particle (between the L-measurement and the pair’s emission from the source), which corresponds to the L-measurement outcome, influences the R-measurement outcome; and the final wavefunction of the R-particle (between the R-measurement and the pair’s emission from the source), which corresponds to the R-measurement outcome, influences the L-measurement outcome (see Figs. 8 and 10). It is noteworthy, however, that while these final wavefunctions correspond to the measurement outcomes, they are neither the measurement outcomes, nor caused by them. Thus, in the CSBM model of the EPR/B experiment the effects of the common cause do not influence each other. It is also noteworthy that the influence of the final wavefunction of each of the particles on the distant measurement outcome is irrelevant for the question of why the common cause fails to explain the correlation between its effects. First, these influences do not change the fact that the complete pair-state at the emission and the measurement outcomes constitute a v-shaped causal fork open toward the future (see Fig. 10); for the influence of the final wavefunction of each of the particles on the distant measurement outcome is mediated by the complete pair-state at the emission from the source (see Fig. 11). Second, as Reichenbach (1956, Section 22) maintains, an intermediate cause between a cause and its effect should screen off the correlation between the cause and the effect. Accordingly, any influence that the final wavefunction of the L-particle (R-particle) has on the R-measurement outcome (L-measurement outcome) is screened off by the complete pair-state at the emission from the source. Thus, if *Screening Off* were a sufficient condition for a common cause explaining the correlation between its effects in a v-shaped causal fork, the complete pair-state at the emission would explain the correlation between the distant measurement outcomes in the CSBM model of the EPR/B experiment. Indeed, in this model the failure of the complete pair-state to explain the correlation between the measurement outcomes is not due to the causal influences of the final wavefunctions on the measurement outcomes, but rather due to the fact that the complete pair-state is not the source of the correlation between its effects.

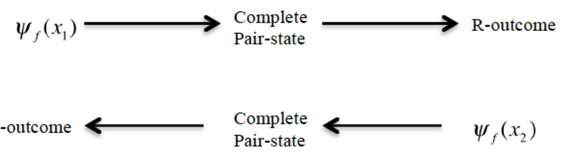

Figure 11: The causal connections between the final wavefunctions and the measurement outcomes in the causally symmetric Bohmian model for the EPR/B experiment (see Figs. 8 and 10).

Reichenbach did not take *Screening Off per se* to be a sufficient condition for a causal explanation of correlation. He analyzed two kinds of v-shaped causal forks. The first kind, which we discussed above, is open to the future and constituted by a common cause and its joint effects (see Fig. 1a). The second kind is open to the past and constituted by two causes and their joint effect (see Fig. 1b). As Reichenbach notes, a common effect E in the second kind of v-shaped fork may satisfy the probabilistic relations *ProbDep* and *Screening Off* with 'E' substituted for 'C'. But, obviously, even if E screened off a correlation between its causes A and B, it would not explain them. Reichenbach thought that the second law of thermodynamics excludes any non-accidental correlation that is not due to a common cause. Any non-accidental correlation between the causes A and B of a common effect E will be due to a common cause C. That is, C, A, B and E will form a double v-shaped causal fork, constituted by a common cause and a common effect (see Fig. 12). It is noteworthy, however, that at the microscopic realm the second law excludes neither the second kind of v-shaped fork, nor a third kind of v-shaped fork that is open to the future but is constituted by two causally independent causes and their past common effect (see Fig. 13). Further, the exclusion of v-shaped forks of the second and the third kinds does not imply that *Screening Off* shouldn't be a sufficient condition for a common cause explaining the correlation between its effects in forks of the first kind (see Fig. 1a). In fact, a common view has it that *Screening Off* in such forks is a sufficient condition for a common cause explaining the correlation between its joint effects. Accordingly, CSBM poses a new challenge for the idea that *Screening Off* is the key for common-cause explanations of correlations: *Screening Off* cannot even be a sufficient condition for a common cause explaining the correlation between its joint effects.

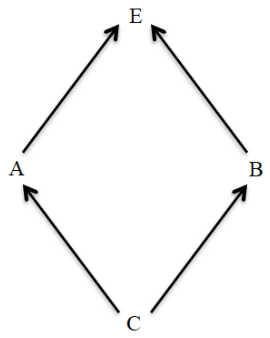

Figure 12: Double fork constituted by a common cause and a common effect.

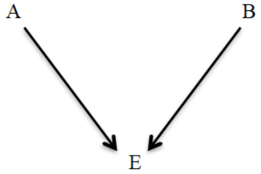

Figure 13: A v-shaped fork open toward the future, constituted by two causally independent causes and their common past effect.

Finally, it is noteworthy that the causally unexplained correlations that CSBM postulate are not like the apparent inexplicable correlations that prevent the so-called causal paradoxes (see Section 4); for the latter correlations do have causal explanations (Dowe 2003). Consider, for example, the following version of the 'grandfather paradox', where Tim embarks on a time travel in order to kill his grandfather at a time before his mother was conceived. Tim waits in front of his grandfather's house. When grandpa leaves the house Tim shoots, but slipping on a banana skins he misses and grandpa survives. Let *A* be Tim's attempt to kill his grandfather by shooting him, *B* be the fortuitous existence of banana skins at the crime scene, *F* be Tim's shooting misses gradfather, *S* be grandfather's survival, and *T* be Tim's embarking on a time travel with the intent to kill his grandfather. *A* and *B* jointly cause *F*, *F* causes *S*, *S* causes *T* and *T* causes *A* (see Fig 14); where by a 'cause' here we mean an event or state that in the actual circumstances causes its effect. For a detailed analysis of this causal loop, see Dowe (2003).

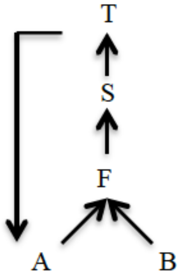

Figure 14: The causal loop in the above version of the grandfather paradox (see above). Arrows denote causal connections. The causal connection from *T* to *A* is backward in time.

Multiple time travels to the past with the intent to kill grandfather seem bound to fail due to 'mundane' reasons like the existence of banana skins at the crime scene. Horwich (1987) argues that the coincidences between events like Tim's attempt to kill his grandfather and the existence of conditions that undermine his attempt, such as the existence of a banana skin at the crime scene, are inexplicable. But, as it is not difficult to see from Fig. 14, Tim's attempt to kill his grandfather is an indirect effect of the existence of banana skin at the crime scene, and accordingly the correlation between these 'events' has a causal explanation.

11 On time, causal symmetry and explanation in the causally symmetric Bohmian model

In the causally symmetric Bohmian model (CSBM), the causal asymmetry at the macroscopic realm is compatible with the causal symmetry at the microscopic realm. Thus, this retro-causal interpretation of QM does not exclude theories of time in which the direction of time is determined by the direction of macroscopic causal processes. In particular, it does not exclude Reichenbach's (1956) theory of the direction of time. Recall that in this theory, the direction of time is determined by the direction of the open v-shaped macroscopic causal forks. Reichenbach argued that all such forks have the same direction and constituton – they are open to the future and are constituted by a common cause and its joint effects (see Fig. 1a) – and that this asymmetry supervenes on the asymmetry of thermodynamic processes.

Those who subscribe to the idea that correlations have causal explanations will naturally expect that if all the v-shaped macroscopic causal forks open to the future were as Reichenbach proposed, any correlation between macroscopic events, neither of which causes the other, would originate from a macroscopic event in their past. This expectation would be natural even if common causes failed to screen off the correlations between their effects, i.e. even Reichenbach's view about how correlations are explained by common causes were rejected. Thus, in particular, those who subscribe to Reichenbach's ideas about causal explanations at the macroscopic realm would naturally expect that the correlation between the measurement outcomes in the EPR/B experiment would originate from a macroscopic event in their common past. In fact, this expectation seems to be shared by many of those who reject Reichenbach's view that explanation of correlations between events, neither of which cause the other, require *Screening Off*. Yet, as we have seen in Sections 8 and 10, this is not true for CSBM. Indeed, the measurement outcomes have a common cause – the complete state of the particle pair at the emission from the source – and this cause screens off the correlation between the outcomes. But, unlike Reichenbach's view, the common cause of these macroscopic events is not a macroscopic event. And while the common cause screens off the correlation between its effects, it does not explain them. The correlation between the measurement outcomes originates from the causally unexplained correlation between the particles' final wavefunctions, which propagate backward in time.

It may be argued that the CSBM model the EPR/B experiment does not really violate *PCC* since this principle was intended to apply to macroscopic events. However, reflecting on local hidden-variables models of the EPR/B experiments, it seems more reasonable to expect *Screening Off* in the case of v-shaped forks open to the future with a microscopic common cause. It may also be argued that backward causation does not exist at the macroscopic realm, and accordingly if *PCC* were limited to the macroscopic realm, *Screening Off* could be a sufficient condition for a common cause explaining the correlation between its joint effects in this realm. Indeed, backward causation does not seem to exist in the macroscopic phenomena we are familiar with, but it is premature to conclude that it does not exist all at the macroscopic realm. In any case, while the above violation of *PCC* is involved with backward causation, a similar violation could also occur in v-shaped causal forks open to the future that do not involve backward causation. The v-shaped causal fork that the CSBM model of the EPR/B experiment predicts is constituted by two macroscopic effects (the measurement outcomes) and a microscopic common-cause (the complete pair-state at the emission from the source). The microscopic common cause is determined by three partial causes (see Fig. 15a): a macroscopic event (the QM preparation of the singlet state), which is a forward cause, and two microscopic events/states (the particles' final wavefunctions between the measurements and the emission), which are backward causes. The violation of *PCC* is due to the fact that the correlation between these miscroscopic partial causes has no causal explanation, and a similar violation could occur if these causes were forward rather than backward and macroscopic rather than microscopic (see Fig. 15b). Yet, the question is whether the causal scenario of Fig. 15b could be theoretically motivated.

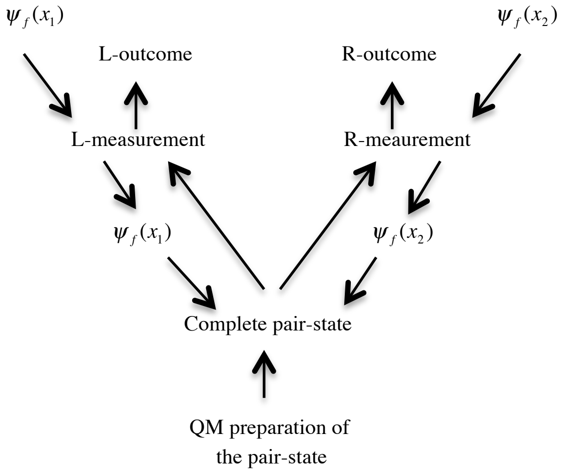

Figure 15a: The common-cause scenario in the CSBM model of the EPR/B experiment.

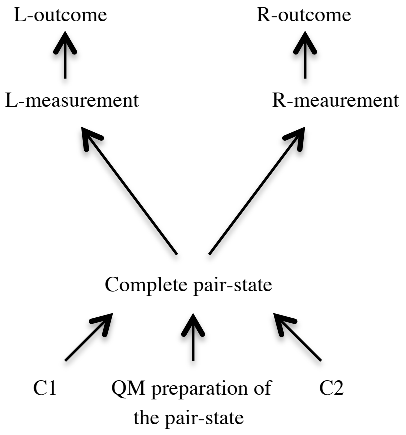

Figure 15b: A common-cause scenario in which the macroscopic events C1 and C2 are correlated but share no common cause.

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List of Acronyms

BM: Bohmian mechanics
CSBM: causally symmetric Bohmian model
EPR/B experiment: Einstein-Podolsky-Rosen/Bohm experiment
PCC: Reichenbach's principle of the common cause
RCIQM: retro-causal interpretations of quantum mechanics
QM: quantum mechanics

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