THE NATURE OF CAUSALITY IN QUANTUM PHENOMENA

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ABSTRACT: The correlations between distant systems in typical quantum situations, such as Einstein-Podolosky-Rosen experiments, strongly suggest that the quantum realm involves curious types of non-local influences. In this paper, I study in detail the nature of these non-local influences, as depicted by various quantum theories. I show how different quantum theories realise non-locality in different ways, which reflect different ontological settings.

Keywords: causality, non-locality; quantum realm; action-at-a-distance; holism; superluminal signalling.

CONTENTS

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1. *Introduction*

Quantum mechanics (henceforth, QM) is probably the most empirically successful theory in the history of physics. Yet, almost a century after its birth, quantum phenomena are still puzzling as ever. One of the most remarkable features of these phenomena is the mysterious correlations between distant physical events. Granted some very plausible assumptions, these correlations strongly suggest the existence of curious non-local influences.

Significant progress has been achieved in the investigation of the nature of the quantum correlations. Nevertheless, an ongoing controversy over the nature and even the existence of quantum non-locality still persists.

Clarifying the nature of quantum non-locality (if quantum reality is indeed non-local as the consensus has it) is important for various reasons. First, it contributes to a better understanding of the quantum realm. Second, an analysis of this nature is crucial for evaluating the compatibility of quantum non-locality with relativity theory. Finally, it is potentially beneficial for studies of the metaphysics of causation. Current theories of causation presuppose assumptions that are inspired by (the metaphysics of) 'classical' physics yet challenged by quantum phenomena.

In this paper, I will focus on clarifying the nature of non-locality as depicted by a number of current quantum theories. In my considerations I will discuss the nature of non-locality in Bohm's (1952) version of the famous Einstein-Podolosky-Rosen (1935) experiment (henceforth, the EPR/B experiment). Yet, since this experiment displays strikingly some of the main characteristics of quantum phenomena, these considerations will be pertinent for other quantum situations.

In Sections 2 and 3, I will review John Bell's general framework for analysing the question of non-locality in models of the EPR/B experiment (Bell 1987, Chaps 2, 4, 7 and 8).

In Section 4, I will turn to discuss a common line of argument for non-locality in quantum phenomena, as depicted by the so-called 'non-factorisable' theories (see Sections 2 and 3). In these theories, the joint probability of (distant) outcomes do not factorise into the product of their single-outcome probabilities. The argument relies on Reichenbach's principle of the common cause (PCC). According to this principle, any correlation between two distant events, which are not causally connected to each other, there is a common cause that screens their correlation off. Granted this principle, local models for the EPR/B experiment have to satisfy the factorisability condition. Now, given some very plausible assumptions about the quantum realm, factorisability is incompatible with the QM statistics. Thus, if QM is empirically adequate, as the consensus has it, models for the EPR/B experiments must involve non-locality.

Although this line of argument can well be motivated, it has been challenged on the grounds that PCC is disputable. More importantly to my considerations, this argument only sheds light on some very general characteristics of quantum non-locality. On the other hand, I believe that a better understanding of the quantum realm requires a detailed investigation of the characteristics of quantum non-locality. Thus, in Sections 5-8, I will consider in detail the nature of quantum non-locality, as portrayed by four non-factorisable theories. Here follows the general background for these considerations.

As I said above, correlations between distant events in EPR/B experiments strongly suggest the existence of non-local influences. According to current quantum theories, these influences are not due to any continuous processes in spacetime. Thus, the quantum realm seems to involve some type of action-at-a-distance.

On the other hand, a common view has it that such action could exist only between distinct, distant systems. But, it is claimed, the distant correlated systems are either non-distinct, because their state is non-separable, or not really at a distance due the holistic nature of quantum phenomena (for details, see Sections 5 and 6).

Assuming provisionally that action-at-distance is compatible with holism and non-separability of states, I will consider in Section 5 whether the quantum realm involves such action. My main conclusions will be that, first, different theories provide different answers to this question. According to some theories, quantum phenomena involve action-at-a-distance, whereas according to others they do not. And second, different theories depict the particular nature of this action differently. As we shall see, this variability reflects ontological differences.

In Section 6, I will consider the nature of non-separability and holism in quantum phenomena. I will argue that the quantum realm as depicted by current non-factorisable theories involves non-separability and/or some type of holism. More generally, some type of non-separability and/or holism seems pertinent to the quantum realm, as portrayed by theories that interpret wave-functions as representing real physical entities or properties (rather than just instruments for policing our ignorance about probabilities of measurement outcomes).

In Section 7, I will motivate the assumption that action-at-a-distance is compatible with holism and non-separability. I will argue that the holistic nature of quantum phenomena explains how non-local influences that do not propagate continuously in spacetime could nevertheless exist.

In Section 8, I will turn to consider whether quantum non-locality can be exploited for superluminal signalling of information. A common view has it that the so-called 'no-signalling theorem' demonstrates that such signalling is impossible in principle in quantum phenomena. I will argue that this theorem only demonstrates that if QM is empirically adequate, superluminal signalling is actually impossible in our universe. Thus, if QM is not (strictly) empirically adequate, such signalling might be possible even in our universe. Moreover, even if QM is empirically adequate, this theorem does not demonstrate that the quantum realm excludes in principle superluminal signalling; it only shows that as a matter of fact, such signalling is impossible.

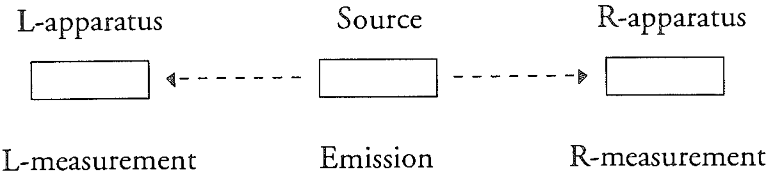
In my considerations, I will focus on quantum theories that satisfy certain plausible physical assumptions. Since all these theories involve non-locality, it is natural to conclude that non-locality is a fundamental characteristic of the quantum realm, rather than just a reflection of peculiar features of certain theories. In Section 9, I will consider some challenges to this view and argue that their physical and/or metaphysical plausibility is questionable.

For lack of space and for simplicity's sake, I will confine my discussion to the non-relativistic realm. But, as I will suggest in the concluding remarks, quantum non-locality does not seem particular to this realm.

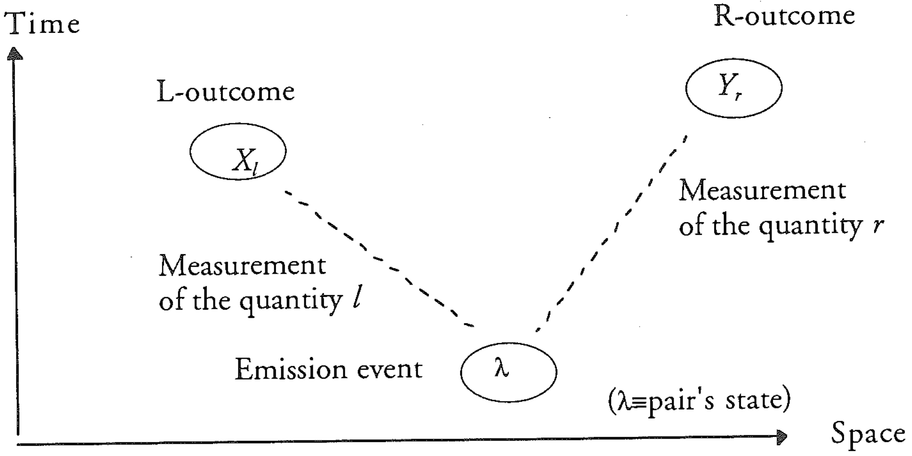
I now turn to review Bell's general framework for studying the question of non-locality in EPR/B experiments.

Fig. 1: The EPR/B Experiment

The Experimental Set-up



A Spacetime Diagram



2. *Factorisable models of EPR/B experiments*

Recall the EPR/B experiment (see Fig. 1 above).[1] Pairs of particles are emitted in opposite directions, *L* (left) and *R* (right). When the particles are far apart (i.e. space-like separated), each of them encounters a measurement apparatus, which can be set to measure one of two different physical quantities: l and l' in the *L*-wing and r and r' in the *R*-wing. In each run of the experiment, measurements of any of these quantities, e.g. l and r, can yield one of two opposite outcomes: x_l and $(\neg x)_l$ in the *L*-wing and y_r and $(\neg y)_r$ in the *R*-wing. In what follows, I will mainly focus on spin measurements, where l and l denote spin components in different directions and x_l and $(\neg x)_l$ denote respectively the outcomes spin 'up' and spin 'down' in the l-direction; and similarly *mutatis mutandis* for the *R*-wing.

According to QM and (statistical analyses of) actual experimental results, the distant outcomes are correlated with each other. The nature of this correlation strongly suggests the existence of mysterious non-local connections between distant events. The question is then: Are these non-local connections peculiar to QM or are they fundamental characteristics of the quantum realm phenomena -namely characteristics which would be reflected in any other quantum theory?

John Bell introduced a general framework for considering this question (1987, Chaps. 2, 4, 7 and 8). Assuming that QM is empirically adequate, any alternative theory for quantum phenomena will have to reproduce the QM statistics for EPR/B experiments. Accordingly, in any such theory, models of EPR/B experiments will be subjected to certain empirical constraints. Since these experiments reflect well the typical characteristics of quantum phenomena, Bell's framework has become an important tool for analysing the nature of quantum non-locality.

A Bell model of the EPR/B experiment postulates that for each particle pair, there is some physical state λ that together with the setting of the apparatuses to measure l and r jointly prescribe probabilities for both: single-wing outcomes, $P_{\lambda,l}(x_l)$ and $P_{\lambda,r}(y_r)$; and joint outcomes, $P_{\lambda,l,r}(x_l \& y_r)$.

Two remarks: First, for simplicity's sake, it is usually assumed that λ is the pair's state at the emission time and that it does not change in any relevant way until the first measurement occurs. Second, the exact nature of these probabilities is a matter of interpretation. Yet, in the context of the theories discussed below, these probabilities are naturally interpreted as chances, i.e. single-case objective probabilities.

The state λ is generally different from the QM wave function of the particle pair, ψ. ψ is an incomplete pair's state, whereas λ is a (more) complete one. Accordingly, pairs with the same ψ could have different states λ, which give rise to different probabilities of outcomes for the same type of measurements.

The model also postulates for each ψ a distribution $\rho_\psi(\lambda)$ over the different possible λ-states. It is assumed that this distribution is independent of the choice l vs. l' and r vs. r', or the choice not to measure in the L-and/or in the R-wing (henceforth, *λ-independence*).

Although the probabilities of outcomes in states λ generally deviate from the probabilities prescribed by ψ, the model recovers the QM probabilities by postulating that these deviations are washed out. That is, it is assumed that the QM probabilities are reproduced by averaging over the model probabilities according to the distribution of the states λs (henceforth, *QM-predictability*). For instance, assuming *λ-independence*, the QM probability of the joint outcomes x_l and y_r, $P_{\psi,l,r}(x_l \& y_r)$, is recovered as follows: $P_{\psi,l,r}(x_l \& y_r)= \int_\lambda P_{\lambda,l,r}(x_l \& y_r)\, \rho_\psi(\lambda)d\lambda$.

Finally, it is commonly assumed that in local models of these experiments, there would be no influences between the distant wings and accordingly the probability of joint distant outcomes would factorise into the product of the probabilities of single-outcome. More formally, it is assumed that such models would satisfy the following condition: for all λ, l and r,

$$\textit{factorisability} \qquad P_{\lambda,l,r}(x_l \,\&\, y_r) = P_{\lambda,l}(x_l) \cdot P_{\lambda,r}(y_r).$$

Intuitively, the idea is that in local models, the probability of each outcome is determined by events in its past light cone, so that the distant outcome and setting (say in the *R*-wing) are irrelevant for the probability of the nearby outcome (in the *L*-wing) (for more details, see Section 3).

3. Bell's theorem and non-locality

Bell's theorem asserts that any model of the EPR/B experiment that obeys *λ-independence*, QM*-predictability* and *factorisability* is committed to so-called 'Bell inequalities', which are violated by QM (Bell 1987, Chapters 2, 4 and 7; Clauser and Horne 1974; Fine 1982a; Redhead 1987, Section 4.3; Shimony 1993, Chapter 8). Since actual experiments provide an overwhelming support for the QM predictions (Redhead 1987, Section 4.3, and references therein), a consensus has it that *QM-predictability* must hold and that (due to the violation of Bell inequalities) this condition cannot jointly obtain with both *λ-independence* and *factorisability*. It is also widely accepted that denying *λ-independence* is *ad hoc* or even tantamount to assuming a grand conspiracy of nature (for details, see Section 9). Thus, it is usually concluded that *factorisability* fails in EPR/B experiments (for ways out of this conclusion, see Section 9).

A common view has it that a local model of EPR/B experiments must be *factorisable* (for more about this issue, see Section 4). Accordingly, it is maintained that the failure of Bell inequalities indicates some type of non-locality (Bell 1987; Clauser and Horne 1974; Jarrett 1984; Shimony 1993; Redhead 1987; Butterfield 1989, 1992a, 1992b, 1994; Howard 1989; Teller 1989; Maudlin 1994; Berkovitz 1995, 1998a,b). (For the contrary view, see Fine, 1981, 1982a; Cartwright 1989 and Chang and Cartwright 1993.) Yet, an ongoing controversy persists over the nature of this non-locality.

In the last two decades, there has been an intensive effort to analyse the implications of *non-factorisability* for non-locality. *Factorisability* is equivalent to the conjunction of two conditions (Jarrett 1984, 1989; Shimony 1984):[2]

Parameter i ndependence. The probability of a nearby outcome is independent of the distant apparatus-setting.[3]
Outcome independence. The probability of a nearby outcome is independent of the distant outcome.[4]

So *factorisability* can be violated in different ways: by either *parameter dependence* or *outcome dependence.* Following Jarrett (1984) and Shimony (1984), a common view has it that theories which violate *parameter independence* involve different types of non-locality than theories which violate *outcome independence* (for details, see Berkovitz 1998a,b).

In the simple Bell models discussed above, the setting of the measurement apparatus to measure a certain quantity specifies its relevant state. However, some other physical factors in the measurement context might also influence the probability of outcomes. After all, the fact that the apparatus is set to measure a certain quantity is just one feature of the enormously complicated physical structure of measurement processes. As Bell (1987, Chap. 7) and Jarrett (1984) have shown, the simple *factorisable* models can be generalised to reflect these additional influences.

In these generalised models, the probabilities of joint outcomes factorise on the pair's state, the settings and the values of these additional physical factors (rather than only on the pair's state and settings).[5] Similarly to the simple models, this generalised version of *factorisability* can be analysed into two conditions, each of which allegedly manifests a different type of locality.

Distant factor independence: The probability of a nearby outcome (say the *L*-outcome) is independent of the setting and the value of any other physical factors in the distant (*R*-) wing.[6]
G-outcome independence: The pair's state, the settings and all the other relevant factors in the distant wings jointly render the probability of the distant outcomes independent of each other.[7]

The significance of these analyses for the study of quantum non-locality is again a matter of controversy (Jarrett 1984; Shimony 1993, Chaps. 10 and 11; Redhead 1987, Chap. 4; Cartwright 1989; Howard 1989; Teller 1989; Butterfield 1989, 1992a; Jones and Clifton 1993; Chang and Cartwright 1993; Maudlin 1994, p. 98). (Here and henceforth, I will use '*factorisability*' to refer to both the simple and the generalised versions of this condition.)

My own view is that these analyses have some limited contribution to clarifying the nature of quantum non-locality. In particular, as we shall see in Section 8, the analysis of *factorisability* is significant for the question of superluminal signalling. But these analyses are also potentially misleading in that they tend to disguise some fundamental similarities between *non-factorisable* theories (for details, see Berkovitz 1998a,b).

So much for the introduction of Bell's *factorisable* models for the EPR/B experiment. I now turn to consider the main line of argument for the view that *non-factorisability* implies non-locality.

4. *Non-factorisability and superluminal causation*

Following Bell (1987, Chaps. 2, 4, 7), it is common to motivate *factorisability* as a locality condition by the so-called principle of the common cause (henceforth, PCC). The general idea of PCC is that non-accidental correlation between events, which are not causally connected to each other, is 'explained' by a common cause: the common cause screens this correlation off. Another way to express this idea is the following:

PCC. The joint probability of any two events, which are not causally connected to each other, factorises on the union of their partial (separate) causes and the common cause. That is, denoting the events by x and y, their partial causes by $PC(x)$ and $PC(y)$ respectively, and their common cause by CC, we have the following condition (*Factorisability upon the Union of the Causal Pasts*):

$$\textit{FactorUCP} \qquad P_{PC(x)\cup PC(y)\cup CC}(x\&y)= P_{PC\cup CC(x)}(x)\, P_{PC(y)\cup CC}(y).$$

PCC is not really a principle, it is rather a schema of principles: different interpretations of the terms 'cause', 'causal past', 'probability', 'non-accidental correlation' and 'event', will yield different principles (Berkovitz 1999). The tenability of each of these different principles depends on the interpretation that yields it. On some interpretations, the resulting principle is tenable. Here follows an example (for other examples, see Berkovitz 1995).

Let probability be chance, i.e. single-case objective probability (Popper 1990; Mellor 1995, Chaps 3 and 4) and events be intrinsic properties of spacetime regions or objects that are located in such regions. Intuitively, a property of an object is *intrinsic* if the object could possess this type of property in and of itself, independently of the existence or the state of other objects or things (cf. Lewis 1983; 1986a, pp. 262-6; 1986b, pp. 61-9).[8] Let two events (x and y) be 'non-accidentally correlated' if they are probabilistically dependent on each other, i.e. $P(x\&y) \neq P(x)\ P(y)$. Suppose that chances of events are properties of the relevant circumstances in which these events occur or do not occur, as the case may be (Mellor 1995, Chaps. 3 and 4; Berkovitz 1998b, Section 2.6). Suppose also that chances of an event at different times are (generally) properties of circumstances that occur at different times. For example, the chance of 'heads' at the tossing time is a property of the nature of the coin and the tossing set-up, whereas the chance of 'heads' shortly before landing is a property of the coin's nature, its elevation and other relevant circumstances at that time.

Suppose a theory of causation where chances of events are properties of their causal pasts, so that chances of effects are determined by their causal pasts. Let the circumstances $C(x)$ constitute a 'causal past' of event x just in case x has a definite chance that is a property of $C(x)$ and there is no other chance of x which is a property of circumstances that include $C(x)$. Intuitively, in non-relativistic universes (which include no backwards causation) a 'causal past' of event x can be any part of x's history that is sufficient to determine the chance that x has just before its occurrence.

Granted this interpretation of the schema of the PCC, the resulting principle could well be motivated in all the four quantum theories discussed below.

In any case, assuming PCC, it is easily shown that *non-factorisable* models of EPR/B experiments involve superluminal causation. The reasoning is straightforward. Let λ be the pair's state at the emission time, l and r be the settings of the L- and the R-apparatus respectively, and x_l and y_r be the L- and the R-outcome on measurements with these settings. Suppose, for simplicity's sake, that the pair's state does not change (in any relevant sense) between the emission-time and the first measurement, and that the settings and the pair's state just before this measurement jointly prescribe the chance of single and joint outcomes at that time. In such local models of EPR/B experiments, λ would constitute the common (partial) cause of x_l and y_r and l and r would constitute the partial, separate causes of x_l and y_r respectively. Accordingly, PCC implies *factorisability.* And so (granted PCC), *non-factorisability* implies the existence of superluminal causation.

As the reasoning above demonstrates, the quantum world as depicted by *non-factorisable* models would involves superluminal influences according to theories of causation that satisfy PCC. Yet, this reasoning and other general analyses of *non-factorisability* only illuminates some very general characteristics of quantum non-locality (e.g. the dependence of the chance of nearby outcome on distant events). My main aim in this paper is, however, to investigate in detail the nature of this non-locality. Thus, in what follows, I will study the particular characteristics of non-local influences in four current *non-factorisable* theories.

5. Action-at-a-distance

EPR/B experiments, as depicted by current *non-factorisable* theories, seem to involve some type of action-at-a-distance: the correlation between distant events result from non-local influences that do not propagate by any continuous process in spacetime.

Yet, a common view has it that EPR/B correlations are not due to action-at-a-distance, they are rather manifestations of some type of holism and/or non-separability. According to this view, action-at-a-distance occurs only between *distant, distinct* things, whereas the relevant systems in EPR/B experiments are non-distinct from each other since their joint state is non-separable or not really distant because they are connected to each other by holistic entities (see below and Section 6).

The ongoing controversy about this issue is largely due the fact that the terms 'action-at-a-distance', 'non-separability' and 'holism' are typically kept imprecise. In the next section, I will propose some specifications of the term 'action-at-a-distance' and in Sections 5.2-5.5 I will consider whether quantum reality (as depicted by four *non-factorisable* theories) involves action-at-a-distance according to these specifications. My working assumption in these considerations will be that action-at-a-distance is not incompatible with non-separability or holism. I will motivate this assumption in Section 7.

5.1. What exactly is action-at-a-distance

The term 'action-at-a-distance' has various connotations (for an interesting history of this notion, see Hesse 1969). In particular, action-at-a-distance is not transmitted by a continuous process in spacetime, it is between distinct entities and it is at a distance, namely between entities that are 'widely' separated in space. Some other connotations are more controversial. Typically, action-at-a-distance is taken to be instantaneous, asymmetric and controllable (at least in theory). But there is no principle reason for excluding the possibility of superluminal or subluminal action, and the paradigm of action-at-a-distance -namely, Newtonian gravitation- is symmetric (in that massive bodies act on each other).

Based on these connotations, I will now propose a few characterisations of action-at-a-distance. The first one has already been anticipated by Einstein (1948, p. 322) (for similar characterisations, see Howard (1989, p. 234) and Healey (1994, p. 352)).

(A1) Action-at-a-distance between *A* and *B* exists just in case *A* and *B* are distinct, distant physical things, and external influences on *A* have *instantaneous* effects on *B*, which do not propagate continuously in spacetime.

The terms 'external influence', 'effect' and 'distant, distinct things' are vague and hard to specify in general. Fortunately, the discussion below will only require the following natural assumptions: (i) A measurement on a system *A* is an external influence on it. (ii) The particles in EPR/B experiments are distinct, distant things.[5] And (iii) *A* has an effect on *B just in* case *B*'s intrinsic properties change (do not change), and this change (lack of change) is not accountable by either the influence of other things or *B's* 'free evolution'. (Here, *A* and *B* can be thought of as objects or local fields, and an object's free evolution is the evolution of its intrinsic state when it is not subjected to any external interaction.)

(A1) characterises an *instantaneous* action-at-a-distance, or more precisely it provides necessary and sufficient conditions for its existence. However, substituting 'superluminal' for 'instantaneous', (A1) is generalised to include superluminal action-at-a-distance (henceforth, (A1s)).

(A1) and (A1s) reflect the main connotations of 'action-at-a-distance', but they differ in an important respect from the paradigm of Newtonian gravitation. In Newton's theory, the gravitational action that one massive object *A* extracts on another massive object *B* exists independently of influences that *B* endures by other objects, such as the influence of a third massive object *C*. On the other hand, (A1) and (A1s) require no such constrain. Indeed, as we shall see in Subsection 5.2, action-at-a-distance in the sense of (A1s) and (A1) can exist even if the influence that a measurement on a system *A* has on a distant system *B* is realised only when *B* undergoes some local interactions, such as a measurement. Thus, the following characterisation expresses better Newtonian action-at-a-distance:

(A2) Action-at-a-distance between *A* and *B* exists just in case *A* and *B* are distinct distant physical things, and external influences on *A* have *instantaneous* effects on *B* (which do not propagate continuously in spacetime) independently of any other influences that *B* endures.

(A2) characterises an *instantaneous* action-at-a-distance. However, similarly to (A1), substituting 'superluminal' for 'instantaneous', (A2) is generalised to include superluminal action-at-a-distance (henceforth, (A2s)). (Note that (A2) is 'logically' stronger than (A1), (A1s) and (A2s); (A2) implies, but is not implied by, these actions. (A2s) is 'logically' stronger than (A1s); it implies, but is not implied by, (A1s).) As we shall see below, the distinctions between these types of actions are not immaterial. In current quantum theories, these distinctions reflect interesting ontological differences.

So much for the characterisation of actions-at-a-distance, I now turn to consider whether four *non-factorisable* theories involve such action-at-a-distance. I start with the so-called 'minimal' Bohm theory.

5.2. The minimal Bohm theory

Recall Bell's (1987, Chap. 17) 'minimal' version of Bohm's (1952) theory (cf. Albert 1992, Chapter 7; Dürr, Goldstein and Zanghi 1992a,b; Cushing 1994). The quantum-mechanical wave function always evolves according to Schrödinger's equation, and so it never 'collapses'. The wave function is interpreted as a 'holistic' field: its intrinsic properties do not supervene on any intrinsic properties of spacetime points and the spacetime relations between them (see Sections 6 and 7).[10] This holistic field (which has no sources or any other dependence on the particles) governs the particles in their trajectories according to the so-called *guidance equation.*

The theory is deterministic. The positions of particles and their wave function at a certain time jointly determine their trajectories for all future times. Thus, they determine the outcome of any measurements (so long as these outcomes get recorded in the positions of particles).

Since the theory is deterministic, probabilities of individual outcomes in EPR/B experiments generally differ from those of QM. Yet the theory reproduces the QM statistics by postulating a certain distribution, the so-called 'quantum-equilibrium distribution', over all the possible positions of pairs with the same wave function. In this distribution, the density of possible positions q with a wave function ψ at time t is given by $|\psi(q,t)|^2$. Integrating over this density, the QM statistics are reproduced.

In the minimal theory, spins are not intrinsic properties of particles. A particle's spin depends on the guiding field and the measuring apparatus; particles with the same (intrinsic) state can have different spins or spin dispositions depending on the guiding field and the measurement device.

Spins are defined in terms of the trajectories that particles have in spin measurements; for example, a particle spins 'up' (down') in the *z*-direction if it emerges from a Stern-Gerlach (S-G) device above (below) a plane aligned in the z-direction. Before the measurements occur, particles have various spin dispositions relative to a given measurement apparatus; e.g. the disposition to spin 'up' in *z*-spin measurement, spin 'down' in *x*-spin measurement etc. A particle's spin-dispositions are not definite unless we specify the measurement context. Indeed the particle's (intrinsic) state and the guiding field do not determine the particle's spin dispositions; the particle can have different *z*-spin dispositions for different types of *z*-spin measurements!

Since the holistic guiding field constitutes part of the categorical basis of particles' spin dispositions, changes in the guiding field can alter a particle's spin dispositions without thus changing any of its intrinsic properties! Thus, the minimal theory does not involve action-at-a-distance of type (A2) or (A2s). Here is why.

Consider an EPR/B experiment in which the particle pair is prepared in the singlet state for spin, the distant *L*- and the *R*-apparatus, say S-G devices, are set to measure *z*-spin and the *L*-measurement occurs first. Suppose that the spin dispositions of the *R*-particle are such that if the *R*-measurement occurred first, the *R*-particle would emerge from the S-G device *above* a plane aligned in the *z*-direction, i.e. spin 'up' in that direction. Suppose also that the *L*-measurement actually turns 'up', i.e. the *L*-particle emerges above a plane aligned in the *z*-direction. Then, due to the perfect anti-correlation of the singlet, the *L*-outcome immediately changes the *R*-particle's spin dispositions; the *R*-particle is now disposed to spin 'down', instead of 'up', in a *z*-spin measurement (see figure 2). Yet, this instantaneous change of dispositions is not due to any change in the *R*-particle's intrinsic properties; the only immediate change is in the holistic guiding field, which (partly) grounds these dispositions. That is, ignoring the little arrows, the behaviour of the *L*- and the *R*-particle during the *L*-measurement is just as depicted in Fig. 2 below. Accordingly, the minimal theory does *not* involve action-at-a-distance of type (A2) or (A2s).

However, since this instantaneous change of dispositions causes the *R*-particle to spin 'down' instead of 'up' in the *R*-measurement, i.e. to emerge below instead of above a plane aligned in the *z*-direction, there is action-at-a-distance of type (A1s) or (A1). (If the *R*-measurement occurs simultaneously with the *L*-measurement, there is action of type (A1); otherwise there is action of type (A1s).) For the *L*-measurement, i.e. an external influence on the *L*-particle, has instantaneous or superluminal influence on the position of the *R*-particle, an intrinsic property of it.

Finally, it is noteworthy that although the influences between the two wings do not propagate in spacetime, they are not unmediated: the influence of the *L*-measurement on the trajectory of the *R*-particle during the *L*-measurement is mediated by the holistic guiding-field (for more about this issue, see Section 7).

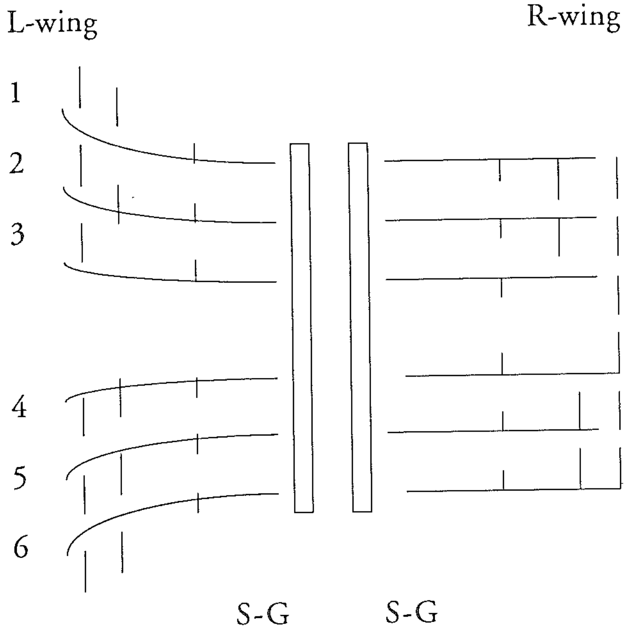


Fig. 2: Trajectories of particles in the singlet state after a (impulsive) z-spin measurement on the L-particle. The little arrows denote z-spin components in the so-called "non-minimal" Bohm theories (reproduced from Holland 1993).

5.3. The non-minimal Bohm theory

In contrast to the minimal Bohm theory, in some other versions of this theory spins are intrinsic properties (see Dewdney, Holland and Kyprianidis 1987; Bohm and Hiley 1993; Holland 1993). Similarly to the minimal theory, these 'non-minimal' theories are deterministic. The wave function always evolves according to Schrödinger's equation. The wave function is interpreted as 'quantum field' (which again has no sources or any other dependence on the particles). The quantum field guides the particles via the 'quantum potential', a holistic entity (its properties do not supervene on intrinsic properties of spacetime points and the spacetime relations between them), which is determined from the quantum field.[11] And similarly to the minimal theory, the quantum field and the positions of particles at a certain time jointly determine the trajectories of the particles at all times.

Non-minimal Bohm theories involve action-at-a-distance of type (A2). Here is why. Consider an EPR/B experiment for spin in which the *L*- and the *R*-apparatus are both set to measure *z*-spin and the *L*-measurement occurs earlier. Suppose that the *R*-outcome would have turned 'up' if the *R*-measurement had occurred first. Similarly to the minimal theory, during the *L*-measurement the quantum field and accordingly the quantum potential change immediately and continuously. However, in contrast to the minimal theory, these changes induce an immediate influence in the *z*-spin of the *R*-particle. If *L*-particle starts to spin 'up' in the z-direction, the *R*-particle will instantaneously start to spin 'down' in the same direction (see Fig. 2 above) (Dewdney et. al. 1987; Bohm and Hiley 1993, Section 10.6; Holland 1993, Section 11.3). So the *L*-measurement, an external influence on the *L*-particle, has an immediate effect on the spin of the distant *R*-particle, an intrinsic property of that particle, independently of any other local influences it endures.

As in the minimal Bohm theory, this action, though at a distance, is mediated by a holistic entity -the quantum potential.

5.4. Dynamical models for state-vector reduction

So far, I focused on deterministic, no-collapse theories. In this section and in the next one, I will consider the question of action-at-a-distance in collapse and no-collapse indeterministic theories: the so-called 'dynamical models of state-vector reduction' and the so-called 'modal interpretations'. I start with the dynamical models (Ghirardi, Rimini and Weber 1986; Bell 1987, Chap. 22), focusing on the non-linear Continuous Stochastic Localisation model (Pearle 1989; Ghirardi, Pearle and Rimini 1990; Butterfield, Fleming, Ghirardi and Grassi 1993).

In the non-linear CSL model, the wave function represents the most exhaustive, complete specification of the state of an individual system.

Accordingly, systems in entangled states do not possess (the relevant) definite properties. (For example, particles in the singlet state for spin do not possess any definite spin quantities. The state of the pair is in a superposition, i.e. a linear combination, of two states: the state spin 'up' for the *L*-particle and spin 'down' for the *R*-particle and the state spin 'down' for the *L*-particle and spin 'up' for the *R*-particle.) The wave function does not always evolve according to the linear, deterministic and reversible dynamical laws of QM; its evolution equation includes non-linear stochastic terms that yield a fundamentally irreversible behaviour. The unfolding of any individual physical processes is governed by an evolution equation depending on the system's initial state, its interactions with other systems and a stochastic process that is due to a 'classical' fluctuating field.

These stochastic processes play a crucial role in recovering quantum phenomena in general and outcomes of experiments in particular. These processes give rise to 'tiny spontaneous localisations' of particles, which continuously 'strive' to reduce linear superpositions into one of their components, namely states in which the systems involved come to possess definite properties. In a superposition of states describing micro-systems, the tiny spontaneous localisations have a negligible influence on the state-vector, and so the chance of a state-reduction is negligible. By contrast, in a superposition of states describing a macroscopic collection of particles in different places, these tiny spontaneous localisations become very effective in reducing the superposed state into one of its components (i.e. eigenstates). The chance that these localisations will start a reduction within a short time is very high. Since the dynamical models are indeterministic, the outcome of reductions is a matter of sheer chance.

In EPR/B experiments for spin, the first (say) *L*-measurement entangles the state of the particle pair with the state of the *L*-apparatus to create a macroscopic superposition of these three systems. This superposition is a linear combination of two states: the state in which the *L*-particle possesses *z*-spin 'up', the *R*-particle possesses *z*-spin 'down' and the *L*-apparatus displays 'up' and the state in which the *L*-particle possesses *z*-spin 'down', the *R*-particle possesses *z*-spin 'up' and the *L*-apparatus displays 'down'. Then, the tiny spontaneous localisations induce (with a very high probability) a reduction of this superposition toward one of these states.

If the reduction took a very short time (as it is natural to expect from a collapse theory in which wave functions represent the complete specification of systems' states), the non-linear CSL model would involve action-at-a-distance of type (A2s). For example, if the *L*-measurement turned 'up', the *R*-particle would superluminally come to possess a (definite) *z*-spin 'down'. So the *L*-measurement, an external influence on the *L*-particle, would superluminally induce a new intrinsic property in the distant *R*-particle (even when the *R*-apparatus is switched off).

Things are a bit more complicated, however. Strictly speaking, the reduction of the superposition of the particle pair and the *L*-apparatus into one of the superimposed states does not end in any finite time. Accordingly, if the completion of the reduction were a necessary condition for the *R*-particle possessing a definite spin property, there would be no superluminal influences between the wings. Yet, if measurements are to have definite outcomes within a finite time (as the supporters of the non-linear CSL model presuppose), the *L*-outcome would have to be definite even before the reduction ends.

A natural solution to this problem would be to postulate that the *L*-measurement outcome and the spins of the *L*- and the *R*-particle become definite before the reduction concludes, say when the superposition *approaches* one of its component states.[12] If so, the non-linear CSL model would involve action-at-a-distance of type (A2s).

5.5. Modal interpretations

I now turn to the modal interpretations of QM (van Fraassen 1979, 1991; Kochen 1985; Dieks 1988; Healey 1989; Bub 1997; Vermaas and Dieks 1995), focusing on Healey's version. In contrast to the reduction models, in modal interpretations the wave function never collapses. The wave function always evolves according to Schrödinger's linear evolution, and it does not provide a complete state of physical systems. Systems could have definite spin properties even when they are in a superposition of spins. And similarly to the reduction models, modal interpretations are indeterministic: wave functions, particles' definite properties and settings jointly determine the chance of measurement outcomes rather than the outcome themselves.

Healey's modal interpretation accounts for correlations between distant systems in EPR/B experiments in the following way (1992, Section V; 1994, Section VII). Suppose that the particle pair is prepared in the singlet state for spin and the distant *L*- and *R*- apparatus are both set to measure *z*-spin. Before both measurements occur, the pair possesses a certain holistic correlational property that determines all possible correlations between *L*- and *R*- outcomes. Granted this property, any outcomes of joint measurements of the same spin-quantity are anti-correlated and each of the particles has a chance 1/2 to display 'up' in an earlier *z*-spin measurement.

The earlier (say) *L*-measurement does not induce any change in the intrinsic properties of the *R*-particle or the *R*-apparatus, it only causes an instantaneous change in the pair's holistic properties. The pair comes to possess a 'weaker' (more specific) correlational property, corresponding to the fact that anti-correlation in spins will now be only in the *z*-direction. This new holistic property grounds a new chance for *R*-outcomes. If, for example, the *L*-outcome turned 'up' in the *z*-direction, the chance of *R*-outcome 'down' in *z*-spin measurement will now be 1 instead of 1/2.

Since the *L*-measurement itself does not modify any intrinsic properties in the *R*-particle -all the changes in the dispositions of the *R*-particle are due to changes in holistic properties -there is no action of type (A2) or (A2s).

The question of whether Healey's theory involves action of type (A1s) or (A1) is more delicate. Similarly to the minimal Bohm theory, the *L*-measurement induces only a change in the dispositions of the *R*-particle. But in contrast to the minimal Bohm theory, in Healey's theory the *R*-particle had a chance 1/2 to spin 'down' in a *z*-spin measurement even before the *L*-measurement occurred. So while in Bohm's theory it is clear that the *z*-spin measurement in the *L*-wing is a (partial) cause of the *R*-outcome *z*-spin 'down', whereas in Healey's theory it is less obvious that the *L*-measurement is a (partial) cause of the *R*-outcome.

Probabilistic theorists of causation maintain that *A* causes *B* if *A* and *B* are actual, distinct events and *A* influences the chance of *B*. If so, *A* may influence *B* even when it does *not* bring about any intrinsic changes in *B*. Accordingly, Healey's theory would involve action-at-a-distance of type (A1s) or (A1).

On the other hand, there are those, including Healey's (1992, 1994) himself, who prefer to preserve the term action-at-a-distance for a 'stronger' notion of causation, where causes *do* bring about their effects and not only influence their chance. According to this alternative view, Healey's theory involves none of the actions mentioned above; and the EPR/B correlations are rather dubbed as 'passion-at-a-distance' (to use Shimony's (1984) terminology).

5.6. Concluding remarks

I have argued above that the question of the existence and the nature of action-at-a-distance in the quantum realm cannot be discussed in full generality, say by analysing some general probabilistic conditions such as *parameter dependence* or *outcome dependence* (see Section 3). On the other hand, a number of authors deny this view: they maintain that the quantum realm involves action-at-a-distance only according to non-factorisable theories that manifest *parameter dependence* or *distant factor dependence.* I cannot consider this opposite view here, but (as I argued elsewhere) I believe that it is misguided (Berkovitz 1998a, Sections 5 and 6.3; 1998b, Section 2.1).

6. Holism and non-separability

In all the theories discussed above, wave functions represent either the state of holistic entities (e.g. the guiding field in the minimal Bohm theory), or some holistic properties (e.g. the correlational properties in Healey's modal interpretation) or non-separable state of systems (e.g. entangled states in the reduction models). So the quantum realm, as depicted by these theories, involves some type of non-separability and/or holism. Yet, to make this view more precise we have to specify more accurately the terms 'holism' and 'non-separability'.

'Holism' and non-separability' can be characterised in various ways (see, for example, Howard 1989, Teller 1989 and Healey 1991, 1992 and 1994). I cannot consider all of them, I will rather focus on the following ones:

> *Spatio-temporal holism.* There are physical objects, not all of whose qualitative, intrinsic physical properties and relations supervene upon qualitative, intrinsic properties of spacetime points (regions) and the spacetime relations between them.
>
> *State non-separability.* The violation of the assumption that each physical system possesses a separate state, which determines its qualitative intrinsic properties, and the state of any composite system is wholly determined by the separate states of its components.

Intuitively, a property of an object is *intrinsic* just in case the object has this property in and of itself, independently of the existence or the state of other objects or things individual.[13] And a property is *qualitative* (as opposed to *individual*) if it does not depend on the existence of any particular object.

Bohmian theories involve holism. The guiding field in the minimal Bohm theory and the quantum potential in the non-minimal Bohm theory are spatio-temporal holistic: their properties do not supervene on qualitative, intrinsic properties of spacetime points. On a natural interpretation, Bohmian theories do not involve *state non-separability* since wave functions do not represent particles' intrinsic states (i.e. their intrinsic properties and relations), but rather entities that influence these states.

The non-linear CSL model (as well as other dynamical models for state-vector reduction) involves both holism and non-separability. The model involves *state non-separability* since the separate intrinsic states of entangled systems (if they exist) do not determine their joint state. And the model involves *spatio-temporal holism* because some intrinsic relations of pairs in entangled states (say spin correlations) do not supervene on any qualitative, intrinsic properties of spacetime points (regions) and their spacetime relations.

Healey's modal interpretation also involves holism and non-separability. This theory involves *spatio-temporal holism* since the qualitative intrinsic properties of entangled composite systems, such as correlational properties in the singlet state, do not supervene on any qualitative intrinsic properties of spacetime points (regions) and the spacetime relations between them. And similarly to the non-linear CSL model, Healey's theory involves *state non-separability*: separate states of systems in entangled states do not determine their joint state (Healey 1994).

So the quantum realm as depicted by all the four *non-factorisable* theories above involves non-separability and/or holism. The question arises then: Are non-separability or holism fundamental characteristics of the quantum realm, or are they just artefacts of these theories?

Some authors argued that *outcome dependence* implies some type of holism or non-separability, at least if certain plausible assumptions are granted (Howard 1989; Teller 1989). If these arguments were cogent, the peculiar characteristics of the theories above would be immanent to quantum phenomena as pictured by any *outcome-dependent* theory.

I believe, however, that neither *outcome dependence* nor *non-factorisability* implies holism or non-separability in the intended sense. These conditions basically state the violation of the assumptions that a pair's state and the settings of apparatuses jointly (a) screen off measurement outcomes (*outcome independence*) or (b) factorise their probabilities (*factorisability*). And in theory, each of these conditions could fail in a separable, non-holistic universe (for more details, see Berkovitz 1998a, Section 6).

Nevertheless, I believe that the prospects of separable, non-holistic models for quantum phenomena, as represented by *non-factorisable* theories, are dim. Here is why. An allegedly separable, non-holistic model of EPR/B experiments would require that each of the particles have some separable, non-holistic means of superluminal communication. Moreover, in order to reproduce the QM statistics, each of the particles would have to carry the following instructions. If it arrives at the nearby measurement apparatus without having received a message from its partner (in the pair), it should spin 'up' ('down') with certain chance, which depends on its state and the measured spin quantity. It then has to communicate to its partner its specific outcome, say spin 'up' in the *x*-direction. On the other hand, if it receives a message from its partner, its state is modified so as to reproduce the QM statistics. Finally, we could picture such a communication by superluminal particles (e.g. tachyons) that carry the instructions from one particle to another.

A model of this type was proposed by Maudlin (1994, p. 98) in his criticism of Howard's view that *outcome dependence* implies non-separability (a similar and more detailed model is Cartwright and Suárez, forthcoming). As is easily seen, such a model would be *outcome dependent*. Yet, argues Maudlin, it seems perfectly separable and non-holistic in that "the [particles] and the tachyon all have perfectly determinate intrinsic states at all times, and the joint state of two distinct regions or systems is just the sum [product] of their individual systems" (ibid.).

While I agree with Maudlin's general criticism -namely, that *outcome dependence* (logically) implies neither non-separability nor holism -I believe that the prospects of his alleged separable, non-holistic model are dim. Such a model would be separable and non-holistic in the intended sense only if the required communication instructions could be realised by the qualitative, intrinsic properties of the separate particles. Now, such realisation would require that: (i) each of the particles would keep an open line of communication *only* with its partner in the midst of (possibly) many similar particles (i.e. particles in the same type of state); and (ii) particles' qualitative, intrinsic properties could encode all the different instructions needed in different (entangled) pair's states. But, I believe, a reflection on such a model -especially on the nature of the physical quantities that would be required to encode the communication instructions in the particles' separate (intrinsic) states and the grave difficulties involved in such non-local communication -would undermine its physical plausibility.

7. Action-at-a-distance with holism: a peaceful coexistence

In Section 5, I assumed that action-at-a-distance could exist in holistic and non-separable universes. Some authors, notably Redhead (1987, pp. 107, 150-1 and 168-9) and Teller (1989, p. 215), argue that the notion of 'action-at-a-distance' makes sense or has its intended meaning only in separable, non-holistic situations. Moreover, many believe that action-at-a-distance does not make a good sense in any context. In fact, according to current prevalent interpretations, Newton himself expressed such a view:

> It is inconceivable that inanimate brute matter should...operate upon and affect other matter without mutual contact ... that one body may act upon another at a distance and through a vacuum without the mediation of anything else by and through which their action or force may be conveyed from one to another is for me so great an absurdity that I believe no man who has in philosophical matters any competent faculty of thinking can ever fall into. (Turnbull 1959, vol. 3, p. 253)

According to this interpretation, Newton maintained that gravity must be mediated but left to his readers the question of whether such mediation should be due to a material or immaterial 'agent'.[14]

Seen in this light, actions-at-a-distance are not real mechanical actions, they are rather phenomena that call for causal explanation (for a similar view, see McMullin 1989, Sections 5-8); and so (A1), (A1s), (A2) and (A2s) may be seen as characterising various types of such phenomena. If so, there is no principle reason to exclude action-at-a-distance from holistic or non-separable universes. On the contrary, in such universes actions-at-a-distance would make better sense: they would be either mediated by holistic entities or reflect the non-separability of distant systems. For example, in non-minimal Bohmian universes, the (earlier) measurement interaction between the nearby particle and the nearby apparatus in EPR/B experiments induces an instantaneous change in the holistic quantum potential, which in turn causes an instantaneous influence in the spin of the *R*-particle (see Section 5.3). So although this influence is not due to any continuous process in space-time, it is not unmediated.

Agreed, this type of mediation is mysterious, and many will probably hesitate to count it as providing a causal explanation. But, Clarke, Newton's disciple, had already anticipated the possibility that action-at-a-distance might not be accounted for in a traditional mechanistic way, e.g. by a continuous propagation of influence in spacetime. Thus, he said that "the means by which two bodies attract each other may be invisible and intangible, and of a different nature from mechanism" (Alexander 1956, p. 43).

It is also noteworthy that the differences between current *non-factorisable* theories that involve action-at-a-distance and those that do not, as well as the variability of the nature of these actions, disguise a fundamental similarity. In all these theories, wave functions in entangled states represent holistic entities or properties that account for the correlation between distant particles in EPR/B experiments.

8. Superluminal Signalling

Quantum phenomena, as depicted by *non-factorisable* theories, involve superluminal influences between distant systems (Sections 4-7). The question is then: Could these influences be 'exploited' to give superluminal signalling of information?

Superluminal signalling requires that a nearby controllable physical factor (say, a keyboard in my computer) superluminally influence distant observable physical phenomena (e.g. a pattern on a computer screen many light years away). The influence may be deterministic or indeterministic, but in any case it should make some statistical difference in physical phenomena.

It is commonly agreed that practically superluminal signalling is impossible in quantum phenomena. Moreover, many believe that such signalling is excluded in principle by the so-called 'no-signalling theorem' (Ghirardi et. al 1980; Redhead 1987, pp. 113-116). It is thus frequently claimed with respect to EPR/B experiments that there is no such thing as a Bell telephone, namely a telephone that could exploit the violation of Bell inequalities for superluminal signalling of information.

But, first, the no-signalling theorem demonstrates that QM (i.e. the orthodox theory) excludes any possibility of superluminal signalling. According to this theory, no controllable physical factor (e.g. setting) in nearby systems can influence the statistics of distant observable phenomena (e.g. the statistics of measurement outcomes). Now, the consensus has it that QM is empirically adequate. If so, the QM statistical predictions prevail in our universe and accordingly superluminal signalling is excluded as a matter of fact; for if QM is empirically adequate, any quantum theory will have to reproduce its statistics.

The no-signalling theorem does not demonstrate, however, that superluminal signalling would be impossible in our universe if QM were not empirically adequate. And it is noteworthy that some current quantum theories do not strictly reproduce the QM statistics yet seem to account for all current accessible observations. Anyway, even if the QM is indeed empirically adequate, the no-signalling theorem does not show that superluminal signalling is in principle impossible in the quantum realm as depicted by theories that *actually* reproduce the QM statistics but do not prohibit in theory the violation of this statistics.

The question arises then: Does the quantum realm, as portrayed by *non-factorisable* theories, prohibit in principle superluminal signalling?

8.1. Necessary and sufficient conditions for superluminal signalling

Superluminal signalling in EPR/B experiments would be possible in theory just in case the value of some controllable physical quantity in the nearby wing could influence the statistics of measurement outcomes in the distant wing. And such influence would be possible *just in case* the following conditions obtained:

Controllable probabilistic dependence: Probabilities of distant outcomes depend on nearby, controllable physical quantities; and

λ-control: The distribution of pair's states is controllable: in theory, there could be ensembles of particle pairs with *either* (i) all the pairs in the same state λ, *or* (ii) with a distribution of states λs that violates *QM*-predictability (see Section 2).[15]

In Sections 8.2-8.4, I will consider the prospects of *controllable probabilistic dependence* and *λ-control* in *non-factorisable* theories. Here follows the background of my considerations. *Distant factor dependence* -namely, the dependence of the probability of a nearby outcome on a distant factor- is necessary but not sufficient for *controllable probabilistic dependence. Controllable probabilistic dependence* also requires that the distant factor be controllable. Some theories, like Bohm's, involve a controllable *distant factor dependence.* Indeed, as we shall see in Section 8.2, in Bohmian theories the *distant factor dependence* is due to *parameter dependence* -namely, the dependence of the probability of a nearby outcome on a distant setting. Accordingly, superluminal signalling would be possible in principle if *λ-control* obtained.

In some other theories that manifest *distant factor dependence,* e.g. the dynamical models for state-vector reduction (see Subsection 5.4), λ-

control obtains trivially because wave functions represent complete state of systems. Thus, as we shall see in Section 8.3, in these theories the question of superluminal signalling turns on whether the *distant factor dependence* is due to a controllable factor.

Yet in a number of other *non-factorisable* theories, for instance modal interpretations, the question of superluminal signalling seems not to arise at all; for in these theories *distant factor independence* apparently obtains. Appearance may be deceptive, however. In discussions of EPR/B experiments, it is common to make unrealistic assumptions about measurement interactions, such as the assumption that settings characterise the total relevant state of measurement apparatuses: no other aspects of the measurement context influence the chance of outcomes. And as we shall see in Section 8.4, if these assumptions are relaxed, *distant factor independence* seems likely to fail.

8.2. Bohm's Theory

I now turn to consider the question of superluminal signalling in Bohm's theory. (The differences between the different versions of this theory are immaterial for this question.) Recall (Subsection 5.2) the minimal Bohm's theory. The wave function and the position of particles at a certain time jointly determine the trajectories of the particles for all times. The wave function always evolves according to Schrödinger's equation, and it is interpreted as a 'holistic' guiding field that governs the particles in their trajectories according to the so-called 'guidance equation'. Since the theory is deterministic, the outcomes of individual EPR/B experiments generally differ from those of QM. Yet the theory reproduces the QM statistics by assuming the quantum-equilibrium distribution over the positions of particles.

Bohm's theory involves *parameter dependence* and thus *distant factor dependence*: the probability of a nearby outcome depends on the setting of the distant apparatus. For example, in some pair's states λ, the earlier *L*-setting influences the probability of the later *R*-outcome: the probability of *R*-outcome 'up' is 1 if the *L*-apparatus is set to measure *z*-spin and 0 if the *L*-apparatus is switched off (see Section 5.2). Thus, the question of superluminal signalling turns on whether the distribution of the particles' positions is controllable, that is whether the quantum-equilibrium distribution can be violated (cf. Valentini 1991a).

So far, no argument has established the impossibility of quantum non-equilibrium. The usual arguments try to establish the 'a-typicality', or the very low likelihood, of quantum non-equilibrium rather than its impossibility (Dürr, Goldstein and Zanghi 1992a,b; 1996, fn. 15). Moreover, some believe that there are good reasons to think that our universe may well have started off in a state of quantum non-equilibrium and is now approaching gradually a state of equilibrium, so that even today some residual non-equilibrium must be present (Valentini 1996, p. 63).[16]

8.3. Dynamical models for state-vector reduction

I now turn to the dynamical models for state-vector reduction, focusing as before on the non-linear CSL model (see Subsection 5.4). Recall that in this model, wave functions represent the most exhaustive, complete specification of states of individual systems. Thus *λ-control* obtains trivially -pairs prepared with the same wave function have the same state. So the question of superluminal signalling turns on the whether the model involves *controllable probabilistic dependence.*

The non-linear CSL model involves *distant factor dependence.* Yet, it is not clear that this dependence is controllable. Here is why. Consider an EPR/B experiment in which the particle pair is prepared in the singlet state, the measurement apparatuses in both wings are set to measure *z*-spin and the *R*-measurement occurs first. Recall that the unfolding of any individual physical processes is governed by an evolution equation depending on the system's initial state, its interactions with other systems and a 'classical' fluctuating field, which gives rise to the collapse of in macroscopic superpositions. In the experiment above, the individual physical process leading to the *R*-outcome is governed by: (i) the macroscopic superposition that result from the interaction of the particle pair and the *R*-apparatus; and (ii) the specific realisation of the stochastic process that (with very high probability) collapses this superposition. It follows from the familiar perfect anti-correlation of the singlet state that if the specific realisation of the stochastic process in the *R*-wing yields spin 'up', the probability of spin 'up' in the *L*-wing is 0. However, if the *R*-measurement had not occurred, the probability of 'up' in the *L*-wing would have been 1/2. Accordingly, the probability of the *L*-outcome depends on a distant physical factor, namely the specific realisation of the stochastic process in the *R*-wing.

If this dependence were controllable, i.e. if the distribution of the possible realisations of stochastic processes in the *R*-wing were controllable in theory, so that the distribution of the specific realisations of the processes that the *R*-outcome could be controllable, superluminal signalling would be possible in principle. Such control would enable experimenters to manipulate the statistics of nearby *R*-outcomes, and thus (due to the perfect anti-correlation of the singlet state) influence superluminally the statistics of the distant *L*-outcomes..

The question of the controllability of the realisation of these stochastic processes is still open, however. The non-linear CSL model is indeterministic. Accordingly, the collapse of the superposition of the pair and the *L*-apparatus to (one of its component states and thus to) one definite *L*-outcome (say 'up') rather than another ('down') is a matter of sheer chance. A control over the 'classical' fluctuating field that causes the collapse would influence the chance of the collapse. But it is not clear that such control could influence the chance that the collapse will go one way rather than another (e.g. spin 'up' instead of 'down'). Yet, if this chance is not controllable, the *distant factor dependence* will be uncontrollable, and so superluminal signalling will be impossible in principle.

8.4. *The prospects of distant factor dependence*

The question of the controllability of measurement processes and its implications for the in-principle possibility of superluminal signalling is not specific to the dynamical models for state-vector reduction. It seems likely to arise in other quantum theories that model measurements realistically; for such theories might well involve *distant factor dependence.*

Here is why. Real measurements take time. And during that time, there might be physical factors, other than the system's state and the setting of the apparatus to measure a certain quantity, which influence the (single-case objective) probability of its measurement outcome. Thus, focusing on EPR/B experiments, let us make the very mild assumption that during the *L*-measurement, the value of some physical quantity in the *L*-wing will (generally) be relevant for the probability of the *local* *L*-outcome. That is, suppose that in the same pair's state and *L*-setting, different values of this quantity will give rise to different probabilities of *L*-outcomes. Then, it follows from the familiar perfect anti-correlation of the singlet state that *distant factor independence* fails: the probability of the *R*-outcome will depend on the value of a physical quantity in the *L*-wing (for details, see Berkovitz 1998a, Section 4.3).

8.5 Superluminal signalling and action-at-a-distance

Finally, note that if superluminal signalling were possible in EPR/B experiments, it would not require any superluminal, continuous process in spacetime to mediate between the two wings, e.g. a process involving tachyons or any other superluminal particles. Indeed, according to current theories the *distant factor dependence* is never due to such a continuous process; it is rather due to some type of action or 'passion' at a distance.

9. Ways out of non-locality?

In Sections 4-8, I focused on exploring the nature of quantum non-locality in *non-factorisable* theories. This focus was motivated by the fact that granted plausible assumptions, *factorisability* must fail in quantum phenomena. But if any of these assumptions failed, *factorisability*, and thus locality, could be maintained. Here are some examples.

First, in arguments for non-locality it is presupposed that distant measurement outcomes are real physical events. In their 'many-minds' interpretation of QM, Albert and Lower (1988) suggest that a local quantum theory could exist if this presupposition is abandoned (cf. Albert 1992, pp. 130-2). According to this radical interpretation, the wave function always evolves linearly according to the Schrödinger's equation (and so it never collapses), and it provides a complete picture of the physical reality. The state of particle pairs and measurement apparatuses remains entangled after the measurement interactions end and even after human observation. So (in general) definite measurement outcomes do not exist in the physical world (the measurement apparatuses are generally in a state of superposition), they exist only in individual minds of observers. Thus, sacrificing some of our most fundamental presuppositions about physical reality and assuming a controversial mind-body dualism, locality is obtained.

Another way to maintain locality is to deny *λ-independence* -i.e. the assumption that the distribution of possible pairs' states is independent of the measured quantities -rather than *factorisability*. There are two possible causal explanations for such a denial. First, to hypothesise that pairs' states and apparatus settings share a common cause which correlate certain types of states with certain types of settings (e.g. states λ_1 are correlated with settings *l* and *r*, states λ_2 are correlated with settings *l' and r'*, etc.).

The problem is then to motivate such hypothesis. On the face of it, settings are (generally) controllable; they can be determined at experimenters' whim. More importantly, thinking of all the many different ways in which measurement settings can be chosen, a common-cause explanation for settings and outcomes would seem *ad hoc* or even conspiratorial.

Alternatively, one could hypothesise backwards causation from measurement events to pairs' states, so that the distribution of states at the source at an earlier time will depend on the actual measured quantities at a later time (Cramer 1980 and 1986).

At the moment, the prospects of a satisfactory backwards-causation model for EPR/B experiments seem dim (Maudlin 1994, pp. 197-199). (For a different view, see Price 1996 and Dowe 1997.)

A third way out of non-locality is to "exploit" the inefficiency of measurement devices or (more generally) measurement set-ups. Recall that in any *actual* experiment, many of the particles fail to be detected, so that only a sample of the particle pairs is observed. Assuming that the observed sample is not biased, it is now generally agreed that the QM statistics for outcomes in EPR/B experiments is vindicated (Redhead 1987, Section 4.5). But if this assumption is abandoned, there are perfectly local ways to account for actual experimental results (Clauser and Horne 1974; Fine 1982b and 1989a).

Many believe that this way out of non-locality is *ad hoc*, at least according to our background knowledge. Moreover, this strategy would fail if the efficiency of measurement devices exceeded a certain threshold (Fine 1989a; Maudlin 1994, Chapter 6).

Finally, there are those who question the assumption that *factorisability* is a locality condition (Fine 1981, 1986, pp. 59-60 and 1989b; Cartwright 1989, Chaps. 3 and 6; Chang and Cartwright 1993). Accordingly, they deny the implication from *non-factorisability* to non-locality. The main thrust of this line of reasoning is that the principle of the common cause (PCC or R-PCC) is not generally valid. Some, notably Cartwright (1989) and Chang and Cartwright (1993), challenge the assumption that common causes always screen off the correlation between their effects whereas others, notably Fine, deny that correlations must have causal explanation.[17]

While these arguments challenge the view that the quantum realm as depicted by *non-factorisable* theories *must* be non-local, they do not show that such theories could be local. Indeed, so far none of the attempts to construct local, *non-factorisable* models for EPR/B experiments has been successful.

In any case, these challenges do not undermine our considerations in Sections 5-8; for as we have seen, the quantum realm as portrayed by current *non-factorisable* theories are non-local in one way or another.

10. Summary and concluding remarks

Granted some very plausible assumptions, the quantum realm involves probabilistic dependence between distant events (systems). In particular, in EPR/B experiments, the chance of the measurement-outcome in the nearby wing depends on the measurement-outcome and possibly some other physical factors in the distant wing. On a natural interpretation, this dependence, which gives rise to the *non-factorisability* in the probability of joint outcomes, implies the existence of curious non-local influences between systems in the distant wings.

I argued above that a better understanding of the nature of non-locality in the realm requires a particular investigation of the ontology of *non-factorisable* theories. Different *non-factorisable* theories realise non-local influences differently. For example, according to some theories *non-factorisability* involves certain types of action-at-a-distance, whereas according to others it does not. For another example, in some realisations of non-locality superluminal signalling of information is excluded in principle, whereas in others the question of such signalling seems still open.

Yet, the quantum realm according to all current *non-factorisable* theories seems to involve some type non-separability of states of composite systems and/or holism, and the influences between the distant wings do not propagate continuously in spacetime. Accordingly, these influences would not count as causal according to 'process' theories of causation, such as Salmon's (1994) and Dowe's (1995).

Finally, it may be tempting to think that non-locality is particular to non-relativistic quantum phenomena and that non-locality would not be pertinent to the relativistic realm. Indeed, this view is natural in light of the popular view that relativity prohibits any superluminal influence.

It is noteworthy, however, that special relativity does not *per se* prohibit holism, non-separability, superluminal counterfactual causation, action-at-a-distance or superluminal signalling. Special relativity only requires that such types of non-locality, if they existed, would conform to the relativistic spacetime, i.e. the Minkowski spacetime. Thus, although it is difficult to frame these types of non-locality within special relativity (Maudlin 1994; Berkovitz 1998b, Section 3), the view that non-locality would not exist in the relativistic realm is far from obvious.

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Notes

[1] The following description is intuitive in nature; it does not attempt at physical rigour.

[2] For earlier analyses of *factorisability*, see Suppes and Zanotti (1976) and Van Fraassen (1982).

[3] More precisely, for any λ, l, l', r and r': $P_{\lambda,l,r}(x_l/y_r)=P_{\lambda,l,r}(x_l/\neg y_r)$ and $P_{\lambda,l,r}(y_r/x_l)=P_{\lambda,l,r}(y_r/\neg x_l)$; where $P_{\lambda,l,r}(x_l/y_r)$ is the conditional probability that λ, l and r jointly prescribe to the outcome x_l given the outcome y_r; and similarly *mutatis mutandis* for the other conditional probabilities.

[4] More precisely, for any λ, l, l', r and r': $P_{\lambda,l,r}(x_l)=P_{\lambda,l,r}(x_l)=P_{\lambda,l}(x_l)$; $P_{\lambda,l,r}(y_r)=P_{\lambda,l',r}(y_r)=P_{\lambda,r}(y_r)$; where $P_{\lambda,l,r}(x_l)$ is the probability that λ, l and r jointly prescribe to the outcome x_l, and similarly *mutatis mutandis* for $P_{\lambda,l,r}(x_l)$, $P_{\lambda,l,r}(y_r)$ and $P_{\lambda,l',r}(y_r)$.

[5] That is, denoting the values of these additional factors in the L- and the R-wing by α and β respectively, *factorisability* can be generalised as follows: for any λ, l, r, α and β,
$P_{\lambda,l,r,\alpha,\beta}(x_l \,\&\, y_r)=P_{\lambda,l,\alpha}(x_l)\,.\,P_{\lambda,l,\beta}(y_r)$.

[6] More precisely, for any λ, l, l', r, r', α, α', β and β':
$P_{\lambda,l,r,\alpha,\beta}(x_l)=P_{\lambda,l,r',\alpha,\beta'}(x_l)$ and $P_{\lambda,l,r,\alpha,\beta}(y_r)=P_{\lambda,l',r,\alpha',\beta}(y_r)$.

[7] More precisely, for any λ, l, r, α and β:
$P_{\lambda,l,r,\alpha,\beta}(x_l/y_r)=P_{\lambda,l,r,\alpha,\beta}(x_l/\neg y_r)$ and $P_{\lambda,l,r,\alpha,\beta}(y_r/x_l)=P_{\lambda,l,r,\alpha,\beta}(y_r/\neg x_l)$.

[8] Although compelling, it is not at all easy to make a good sense of this intuition; for more details, see Section 6, fn. 14.

[9] I will argue below that according to various theories, there is action-at-a-distance between the particles in EPR/B experiments. To simplify things, I will focus on EPR/B experiments with identity particles (e.g. electrons). This raises a difficulty, as according to a number of theories identical particles are not really at a distance before the measurements occur; the particles' positions are in a superposition of the '*L*-particle' being 'here' and the '*R*-particle' being 'there' and the *L*-particle being 'there' and the *R*-particle being 'here'. This difficulty can be avoided by focusing on EPR/B with non-identical particles. Yet, as the discussion of such experiment will complicate things, I will pretend that identical particles are at a distance even before the measurements. Anyway, as is not difficult to show, action-at-a-distance exists also when particles are not at a distance.

[10] In technical terminology, the guiding field 'lives' in 'configurations' space, i.e. a space in which each single point specifies the exact configuration of the field expressed in position space. Since the field is not generally factorisable, it cannot be reduced to any assignment of intrinsic properties of spacetime points and the spacetime relations between them.

[11] As in the minimal theory, the quantum field 'lives' in configuration space.

[12] For some curious consequences of this suggestion, see Albert and Lower (1995).

[13] Although compelling, it is not at all easy to make good sense of this intuition since the meaning of intrinsic properties is generally given in terms of their relation to other things. For example, it is difficult to make sense of the idea of an object having mass or charge, typical paradigms of intrinsic properties, in a universe with no other things. Yet, our consideration only requires a pragmatic distinction between intrinsic and extrinsic properties: namely, a distinction between properties that an object can naturally be said to posses and those that it cannot (for some examples, see the discussion of spin quantities in Bohmian theories in Sections 5.2-5.3).

[14] For a different and interesting interpretation, see Hendry (1994).

[15] The argument for the necessity of these conditions is straightforward. If the probabilistic dependence of the distant outcome on nearby factors were not controllable, there would be no way to manipulate the statistics of the distant outcome. And if *λ-control* did not hold, *controllable probabilistic dependence* would be of no use for superluminal manipulation of this statistics: the probabilistic dependence of the distant outcome on the nearby, controllable factor would be washed out. The argument for the sufficiency of these conditions is also straightforward. If *λ-control* held, it would be possible in theory to arrange ensembles in which *controllable probabilistic dependence* would not be washed out. Thus, if the probabilistic dependence of distant outcomes on nearby factors were controllable, a nearby factor could influence the statistics of distant outcomes.

[16] Note that according to this suggestion, the statistical predictions of Bohm's theory deviate from those of QM.

[17] Fine (1981; 1989b) was the first to introduce the term 'factorisability' and to distinguish it from (Bell's) locality assumptions, whereas Cartwright (1981) and Chang and Cartwright (1993) question the idea that common-cause models for the EPR/B must be factorisable.

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EPILOGUE

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This volume brings together two different, almost disjoint ways of thinking about causation in physics; and that, to my mind, is its special virtue. In describing these two modes of thought it will help to use a conventional philosophical device: a diagrammatic contrast between Kant and Hume. For Kant causality involves order under the universal rule of law. For Hume the concept is intimately connected with our sense that we can make things happen and a projection from that to the presumption that causes in the world outside ourselves similarly make these effects occur. The first point of view has dominated discussions about causality in modern physics throughout the century, both in the general and special theories of relativity and in the various quantum theories. The second has only really entered with the serious discussion of action at a distance in quantum mechanics following the discovery of the Bell inequalities, and that in a piecemeal and not obviously consistent way, for the two traditions sit uneasily together.

Causality in the 'making it happen' sense requires, on the one hand, more than the necessity prescribed by Kant but, on the other, falls far short of it. Yet it is clear that the two brands of causation must be brought together not only in order to understand the real structure of our fundamental theories but also to explain how -or why- they can be put to use to produce the effects that are taken to argue so powerfully for the truth of those theories. That is why the kinds of careful studies we find in this volume showing how the two fit together (or not) are of such importance.

We can see these two separate traditions in more detail in the papers themselves. No one denies that operators for quantities at space-like separated events do not commute, as Pauli showed; nor the related facts about Green's function propagators between the events. That is part of the order under universal law precious in the Kantian tradition. But, Jordi Cat argues these facts merely constrain the possibilities for causal connections between