

Measurement Dependence is not Conspiracy: A Common Cause Model of EPR Correlations

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Abstract

In this paper I assess the adequacy of *no-conspiracy* conditions present in the usual derivations of the Bell inequality in the context of EPR correlations. First, I look at the EPR correlations from a purely phenomenological point of view and claim that common cause explanations of these can not be ruled out. I argue that an appropriate common cause explanation requires that *no-conspiracy* conditions are re-interpreted as mere *common cause-measurement independence* conditions. Violations of measurement independence thus need not entail any kind of conspiracy (nor backwards in time causation). This new reading of measurement dependence provides the grounds for an explicitly non-factorizable (in the sense of Bell's *factorizability*) common cause model for EPR.

1 Introduction

It is still debatable whether common cause explanations are appropriate to account for EPR correlations. Addressing this issue is of both interesting and relevant from the philosophical point of view. Philosophers wanting to understand causation, for instance, need to face the adequacy of the diverse methods of causal inference available. Reichenbach's Principle of the Common Cause (RPCC) is one such method, and it is precisely in the quantum mechanical context that RPCC faces one of its most significant threats.

This paper aims to provide an analysis that recalls our most robust intuitions about causation (assumed to be well reflected in RPCC), with the ultimate purpose of testing them in the context of quantum mechanics. I will not discuss the specific problems related to the philosophical status of RPCC —these are diverse and interesting in themselves even if quantum

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mechanics is not brought into the picture. RPCC will simply be assumed to hold.

The received view takes it that (Reichenbachian) common cause accounts of EPR correlations are to be ruled out.¹ The standard argument views causes as hidden variables onto which several constraints are set, intended to reflect standard requirements typical of any physical system, including temporal order of causal relations and considerations about locality. As a result, some version of Bell’s *factorizability* —and therefore of a Bell-type inequality— is derived. The strength of such arguments relies, as it stands, on the plausibility of the conditions imposed on the common causes.

No-conspiracy is one such condition present, even if implicitly, in the usual derivations of the Bell inequalities. The motivation behind it is that the postulated common causes be independent of the measurement settings. Violations of such independence are standardly interpreted as to entail certain strange “conspiratorial behaviour”, unless backwards in time causation is brought into the picture.²

I shall challenge this standard reading of no-conspiracy-type conditions. I will do this in two steps. I will first look at the very formal structure of such conditions, while remaining neutral as to whether their violation entail any kind of conspiracy. I will then look at the EPR correlations from a purely phenomenological point of view and assess the role of measurement in the EPR experiment. This will suggest a re-interpretation of no-conspiracy-type conditions, under which violations of these can be accommodated without any conspiratorial implications, neither backwards in time causation. This new view will also provide grounds for a common cause model. It will not be hidden-variable model for the EPR correlations as such, though. Instead, the model responds to a purely explanatory motivation, i.e. it constitutes what I take to be a plausible causal explanation of the EPR correlations.

The structure of the paper is as follows. Sections 2 and 3 provide the necessary background on the EPR experiment and Reichenbach’s Principle of the Common Cause respectively. In Section 4 the formal structure of the problem is stated and the idea of *no-conspiracy* introduced. Section 5 looks at the EPR experiment again but from a purely phenomenological point of view this time, and examines the role of measurement in it. This analysis will eventually lead to the common cause model of EPR, outlined in Section 6. The paper closes with a brief discussion on the implications of the model as regards locality and states some open questions for further investigation.

¹See for instance (van Fraassen, 1982), (Cartwright, 1987) or (Butterfield, 1989). (Graßhoff, Portman and Wüthrich, 2005) and (Butterfield, 2007) provide updated discussions on the matter.

²Cf. (Price, 1994), (Berkovitz, 2002) and (Szabó, 2000, 2008).

2 The EPR Correlations

Einstein, Podolsky and Rosen first introduced the so-called EPR thought experiment in 1935³ as an argument to suggest that quantum theory did not provide a complete description of reality. In a later refined version presented by David Bohm, two *entangled* electrons are emitted from a source in opposite directions. The spin component of each of the electrons can be later detected (measured) in three different directions θ_i ($i = 1, 2, 3$) after having passed through an inhomogeneous magnetic field.

Let us first denote L_i and R_j ($i, j = 1, 2, 3$) the different measurement settings in each wing of the experiment. Also, I shall denote by a and b the value of the spin variable of each electron in a given measurement direction which, in the singlet state, can be either ‘spin-up’ (+) or ‘spin-down’ (−) with probability $\frac{1}{2}$. We can then express the corresponding measurement outcome events on each particle along each of the three different measurement directions as L_i^a and R_j^b , with $a, b = +, -$ and $i, j = 1, 2, 3$. It is assumed that the state of the entangled electron pair is the spin *singlet* state:

$$\Psi_s = \frac{1}{\sqrt{2}}(\psi_L^+ \otimes \psi_R^- - \psi_L^- \otimes \psi_R^+)$$

Furthermore, it is assumed that measurement events at each wing of the experiment, L_i^a and R_j^b , are space-like separated events. This is represented in Figure 1 by noting that no time-like world-line can reach from R_j^b to L_i^a or *vice versa*. Under a conventional albeit controversial interpretation of special relativity, such events can not be causally connected.⁴

Quantum mechanics allows us to calculate single and joint conditional probabilities for the different possible outcomes in both wings. When those calculations are performed on the entangled pair in the singlet state, correlations between these outcomes are derived:

$$p(L_i^a \wedge R_j^b) \neq p(L_i^a) \cdot p(R_j^b),$$

where $a, b = +, -$ and $i, j = 1, 2, 3$.

These are the EPR correlations, which have been often positively tested in experiment, and for which we would like to know whether they are the result of underlying causal processes. At this point already, it seems rather intuitively appealing to attempt at an answer to this question by recalling the idea of common cause. For the space-like separation of the outcomes at each wing of the experiment seems to rule out, at least in principle, direct causal interactions between these. And this is in fact the typical situation common cause explanations are usually suitable for.

³(Einstein, Podolsky and Rosen, 1935).

⁴See (Maudlin, 1994) for a critical discussion.

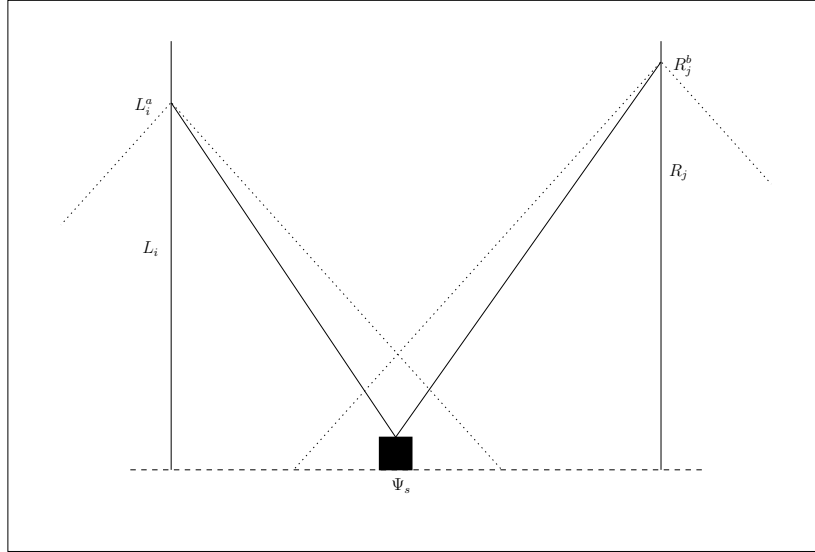


Figure 1: Space-time representation of a typical EPR experiment.

3 Reichenbach's Principle of the Common Cause

The principle of the common cause was first introduced by Reichenbach (1956). It states, in short, that there are *no correlations without causal explanation* (either in terms of direct causal interactions or by means of a common cause).

The idea of correlation is defined within the framework of classical Kolmogorovian probability spaces:⁵

Definition 1. Let (\mathcal{S}, p) be a classical probability measure space with Boolean algebra \mathcal{S} representing the set of random events and with the probability measure p defined on \mathcal{S} . If $A, B \in \mathcal{S}$ are such that

$$\text{Corr}_p(A, B) = p(A \wedge B) - p(A) \cdot p(B) > 0, \quad (1)$$

then the event types A and B are said to be (positively) correlated.

The principle can then be formalised, following Reichenbach's own ideas, as follows:

Definition 2 (RPCC). For any two (positively) correlated event types A and B ($\text{Corr}_p(A, B) > 0$), if A is not a cause of B and neither B is a cause

⁵The definition here is of positive correlation. A completely symmetrical definition may be given for negative correlations. Distinguishing between positive and negative correlations will not be important for the argument here. Thus, if not stated otherwise, positive correlations will be assumed throughout the paper.

of A , there exists a common cause C of A and B such that the following independent conditions hold:

$$p(A \wedge B|C) = p(A|C) \cdot p(B|C) \quad (2)$$

$$p(A \wedge B|\neg C) = p(A|\neg C) \cdot p(B|\neg C) \quad (3)$$

$$p(A|C) > p(A|\neg C) \quad (4)$$

$$p(B|C) > p(B|\neg C) \quad (5)$$

where $p(A|B) = p(A \wedge B)/p(B)$ denotes the probability of A conditional on B and it is assumed that none of the probabilities $p(X)$ ($X = A, B, C, \neg C$) is equal to zero.

The definition above incorporates two quite distinct claims. On the one hand, one may identify a metaphysical existential claim suggesting that ‘common causes’ exist (or are to be provided) for correlations with no direct causal explanation. As such I shall refer to it as the *Postulate of the Common Cause* (PosCC).⁶ This claim *per se* says nothing about how common causes are to be characterised.

This is precisely the role of the second claim in the definition, which provides probabilistic relations (2)-(5) for the characterisation of the common causes. Following Suárez (2007), I shall refer to expressions (2)-(5) as *Reichenbach’s Criterion for Common Causes* (CritCC).

The two last expressions of CritCC are just statistical relevance relations aimed to represent the causal dependence between A and C on the one hand, and B and C on the other. Whether statistical relevance does indeed reflect causal dependence is of course a debatable issue but I will assume so here, as it is standard in most theories of probabilistic causation. As for the first two probabilistic conditions, they express a new restriction on the postulated common cause C . They require, specifically, that if the presence (or the absence) of the common cause is taken into account the correlated events A and B are rendered probabilistically independent. The common cause C is then said to *screen-off* the correlation $Corr(A, B)$.

In contrast to the metaphysical character of PosCC, Reichenbach’s criterion (CritCC) is a purely methodological claim. However, properly distinguishing the two claims is crucial for the assessment of the status of RPCC as a whole. We do not need to address here the various problems associated to the status of either PosCC or CritCC—they each have indeed their own problematic issues. I shall just assume that the PosCC holds, i.e. that common causes may be provided for any given correlation, and that CritCC is the right characterisation of such common cause events. I shall call such common causes irrespectively *Reichenbachian common causes*, *screening-off common causes* or simply *common causes*.

⁶This terminology is borrowed from (San Pedro and Suárez, forthcoming).

Despite the controversies, endorsing RPCC may be motivated by at least two reasons. First, note that for Reichenbach the role of the principle as a whole, and of the screening-off condition in particular, is mainly explanatory.⁷ The explanatory power of screening-off common causes may thus be taken as a good methodological reason to support the adequacy of CritCC for the inference of causal relations from probabilistic facts, even if it can be patently shown not to hold as a necessary nor as a sufficient condition for common causes.

Second, recent results show that, at least formally, it is always possible to provide a Reichenbachian common cause for any given correlation.⁸ These results build on the intuition that any probability space \mathcal{S} containing a set of correlations and which does not include (Reichenbachian) common causes of these, may be extended in such a way that the new probability space \mathcal{S}' does include (Reichenbachian) common causes for each of the original correlations. This is formalised in so-called *extendibility* and *common cause completability* theorems.

Thus (Reichenbachian) *common cause completability* constitutes a very powerful tool if we are to provide common cause explanations of generic correlations. Common cause completability however faces its own problems, especially when it comes to the physical interpretation of either the enlarged probability space \mathcal{S}' or the new common causes contained in it. In particular, it seems a fair criticism to the program to claim that common cause completability is a merely a formal device, which is likely to lack physical meaning in many (perhaps too many) cases. I shall not discuss such matters here but just point out that such criticisms may successfully be dealt with.⁹ I shall assume here that common cause completability is in fact a reliable and powerful tool when aiming at common cause explanations.

There is an important further remark as regards *common cause completability*. It has to do with the distinction between what I'll be referring as *individual*-common causes on the one hand, and *common*-common causes on the other. The fundamental difference between these is that *individual*-common causes are defined to screen-off a single (individual) correlation *only*, while *common*-common causes screen-off a set of two or more correlations (Figure 2). This is indeed an important distinction precisely due to the fact that, while *individual*-common cause completability holds in general for every classical probability space \mathcal{S} , this is not the case for *common*-common causes. In other words, while *common cause completability* guarantees that *individual*-common causes may be provided (at least formally) for any given

⁷Cf. (Reichenbach, 1956, p. 159).

⁸Cf. (Hofer-Szabó, Rédei and Szabó, 1999, 2000).

⁹I point the reader to (San Pedro and Suárez, forthcoming) for a recent assessment the significance of common cause completability, possible criticisms to it and possible strategies to avoid these.

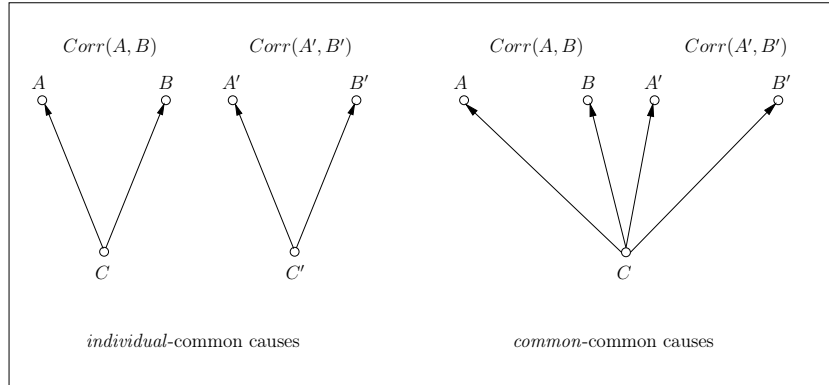


Figure 2: *Individual*-common causes versus *common*-common causes.

correlation, this is not true in general for *common*-common causes.¹⁰ In what follows and if not stated otherwise, when common cause is written it will mean *individual*-common cause.

4 Structure of the Problem

We now seem to be in a position then to attempt at an answer to the question as to whether an explanation of the EPR correlations can be given in terms of common causes. However we should note first that the description of the EPR experiment in Section 2 involves statements about ‘quantum probabilities’, while probabilities in Section 3 are classical. This very fact renders the whole issue about common cause explanations of EPR correlations hardly sensible. For ‘quantum probabilities’ do not express probabilities of real events –they cannot be interpreted as relative frequencies, for instance– and do not therefore fit in the formulation of classical Kolmogorovian probabilities, as it should be the case for Reichenbach’s Criterion for Common Causes (CritCC) to make sense.¹¹

We then seem to have to options. We may want to redefine CritCC in terms of ‘quantum probabilities’, or we may alternatively interpret ‘quantum probabilities’ so that they fit the formulation of classical Kolmogorovian probabilities.

I will take the later option here and interpret quantum mechanical probabilities, i.e trace-like quantities $Tr(\hat{W}\hat{A})$, as *classical conditional* proba-

¹⁰Cf. (Hofer-Szabó, Rédei and Szabó, 2002).

¹¹Cf. (Szabó, 2000, p.4). The fact that I refer here specifically to relative frequencies is motivated by Szabó (2000)’s remarks, and is not crucial for the soundness of the foregoing argument. Indeed, I believe that the arguments provided here do not hinge on a particular interpretation of probability.

bilities —conditional on the measurement operations, that is.¹² In other words, the ‘quantum probability’ that the particle in the left wing of the experiment, for instance, is measured with spin-up will be given by $p(L_i^+|L_i)$, i.e. $p(L_i^+) = p(L_i^+|L_i) \cdot p(L_i)$.

Within this framework “Can a common cause explanation be provided for EPR correlations?” is indeed a sensible question. And considering *common cause completability*, the answer to it would in principle seem quite straightforwardly a positive one. The issue is not so simple, though. For we cannot overlook the fact that if our postulated common causes are to be physically sensible at all, they will need to fulfil certain requirements — besides those in their definition, i.e. equations (2)-(5). The problem becomes thus more complex since we first need to identify and characterise these extra requirements to which (physically sensible) Reichenbachian common causes must conform.

Conditions of this sort typically include those intended to capture in some sense or another the idea of physical locality —so as to avoid conflict with special relativity. Bell’s *factorizability*¹³ is perhaps the most famous and influential of these conditions:

$$p(L_i^a \wedge R_j^b | L_i \wedge R_j \wedge C_{ij}^{ab}) = p(L_i^a | L_i \wedge C_{ij}^{ab}) \cdot p(R_j^b | R_j \wedge C_{ij}^{ab}). \quad (6)$$

Consistently with the notation in Section 2, C_{ij}^{ab} designs here a (Reichenbachian) common cause of the correlation $Corr(L_i^a, R_j^b)$ between two generic outcomes of an EPR-Bohm experiment.

Requiring *factorizability* leads, of course, to the Bell inequalities, which are well known to be violated by experiment. Whether Bell’s *factorizability* indeed reflects physical locality is not completely settled. I shall not look at such issues in detail here and just point the reader to (Fine, 1981, 1986), (Wessels, 1985), (Maudlin, 1994) or (Butterfield, 2007) for discussions of such issues. In any case, if we are to provide a Reichenbachian common cause explanation of the correlations while avoiding the charge of Bell’s theorem, sensible constraints other than *factorizability* are to be required for the postulated common causes.

The strategy is then to define a set of conditions that altogether does not amount to *factorizability* which, along with the idea of Reichenbachian common cause, provides a satisfactory explanation of the correlations. Ideally we would like to make sure that such restrictions do not entail the idea of *common*-common cause either. For, as I have pointed out it is not likely that *common*-common cause explanations may be provided for any set of correlations in general.

¹²The difference between ‘measurement operations’ and ‘measurement setting operations’ (or ‘measurement settings’ for short) will not play any major role for the purposes of the discussion here. I shall thus use those two expressions equivalently.

¹³Cf. (Bell, 1964).

One of the most remarkable attempts to provide common cause model for EPR following this strategy is Szabó (2000). Szabó’s model is explicitly construed by recursively applying the ideas of *extensibility* and *common cause completability* but it turns out that it features unwanted dependencies between certain combinations of the postulated common causes and the measurement setting events. These dependencies are usually interpreted as conspiratorial.

Avoiding such conspiratorial features is indeed the role of so-called *no-conspiracy* conditions which are, in one way or another, standard in the derivations of the Bell inequalities, along with other restrictions—intended to reflect locality, etc.—on the common causes. Roughly, *no-conspiracy* conditions require statistical independence between the common causes and the measurement settings:

$$p(L_i \wedge C) = p(L_i) \cdot p(C), \quad (7)$$

$$p(R_j \wedge C) = p(R_j) \cdot p(C). \quad (8)$$

The usual interpretation being that the postulated common causes must not have an influence, or be otherwise influenced, by the choices of measurement settings. Existence of such influences—i.e. violations of the equations (7) and (8)—would be conspiratorial in the sense that the taking place of the common cause would somehow ‘force’ or determine to some extent the presumably free independent decisions of the experimenter about measurement.

Equations (7) and (8) may be regarded as ‘simple’ *no-conspiracy* conditions, in that they involve only one common cause event at a time. More complex conditions may involve combinations (both conjunctions and disjunctions) of the different postulated *individual*-common causes, e.g. $p(L_i \wedge C_{ij}^{ab} \wedge C_{i'j'}^{a'b'})$.¹⁴ We need not discuss the later case here. For I will be arguing that violations of the ‘simple’ case, i.e. of equations (7) and (8), are consistent with a plausible common cause explanation of EPR correlations. But, of course, violations of the ‘simple’ *no-conspiracy* conditions already entail violations of the more complex relations.

The significance of *no-conspiracy* assumptions relies heavily on another underlying implicit assumption. This is the assumption that the postulated common causes take place (or happen) *before* the apparatus are set for measurement, and therefore also *before* (always in the rest-frame of the laboratory) measurement is performed. And it is only by assuming this specific time-order framework that one can make sense of the standard interpretation involving claims about world conspiracies and free will (or the lack of it).¹⁵

¹⁴These later complex *no-conspiracy* conditions are what Szabó (2000)’s model fails to satisfy

¹⁵In fact, I think this is why discussions about free will and backwards in time causation

This is a crucial assumption but I think it is not completely warranted. Indeed, I shall challenge it and suggest therefore that violations of (7) and (8) do not necessarily entail that there being world conspiracies. In order to keep neutral as regards the possible conspiratorial implications of the violation of (7) and (8), I shall refer to them as *measurement independence* conditions.

5 EPR from a Phenomenological Point of View

5.1 Pure Phenomenological Data Correlations

I pointed out in Section 3 that Reichenbach’s Principle of the Common Cause (RPCC) was originally proposed to account for classical correlations (and common causes). In dealing with quantum correlations I suggested, following Szabó, that we should take quantum probabilities, i.e. trace-like quantities, as classical conditional probabilities (conditional on the corresponding measurement operations, that is) so that the quantum formalism is adapted to the classical talk of RPCC. This led to a reformulation of the problem in which measurement operations were explicitly present in the corresponding probability relations.

I would now like to tackle the issue from a somehow different point of view, however. More specifically, I shall not look at the EPR correlations as ‘quantum correlations’ —i.e. as correlations defined between conditional probabilities, as Szabó suggested—, and then postulate the corresponding *individual*-common causes. Instead, I shall look at the EPR correlations from a completely classical perspective first, postulate common causes for them, and then provide these with an appropriate quantum mechanical interpretation. To illustrate this let us consider a simple example:

Suppose that a good friend of us, who is well familiar with quantum theory, has designed a device which collects the information of an EPR experiment and ‘translates’ it into light flashes. The device (Figure 3) has two identical panels (PANEL A and PANEL B) with green and red lights in three rows. Each row, in particular, has a pair of lights, one green and the other red. The device is somehow connected to the EPR detectors. Spin measurement outcomes in the left wing of the EPR experiment then make the lights in PANEL A flash. Say, for instance, that if the outcome L_3^+ has been measured, then the green light in the third row of PANEL A flashes; or that if L_1^- is obtained in the EPR experiment, the first row’s red light in ‘PANEL A’ flashes. Similarly for the right wing outcomes. Say,

are so much entangled. For those defending backwards causation still assume the (timely) priority of common causes in relation to measurement operations. (Only, in those cases, time order and causal order are not assumed to coincide.) See, for instance, (Price, 1994) or (Berkovitz, 2002). More generally, whether *no-conspiracy*-type assumptions capture any intuition related to free will is a subtle issue which would deserve a whole paper on its own.

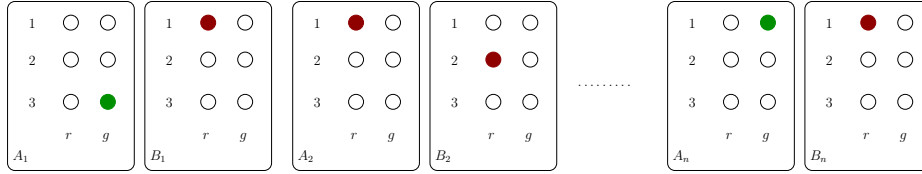


Figure 3: A sequence of red (r) and green (g) flashing lights.

for instance, that the outcome R_1^- has occurred, then the red light of the first row in PANEL B flashes. Moreover, the device is such that the causal connections between the EPR events and their corresponding flashing light events are known to be deterministic and work completely independently for each panel.¹⁶ It is clear then that the correlations between the two panels' flashing light events exactly mirror those of the EPR experiment.

Suppose, on the other hand, that we do not know anything about quantum EPR, nor do we know what is the origin of the correlations observed between the lights. We just observe the correlation. Say however that we do know about Reichenbach's Principle of the Common Cause (RPCC) and are then ready to postulate a common cause for each of the observed correlations (especially if we make use of *common cause completability*). I shall stress that to us the whole issue is entirely classical, i.e. classical correlations (between lights) are observed and classical Reichenbachian common causes are to be postulated.

Our good friend intends to use the information that we may provide about our postulated common causes and attempt at an explanation of the EPR correlations. Yet, she is aware of an extra issue that might be problematic, namely that unlike the correlations between the flashing lights observed by us, those in the EPR experiment are space-like separated. On reflection, however, she realizes that it should not make a difference. For she knows that each EPR outcome is the one and only cause of its corresponding flashing light event. (Say for instance that she knows the detailed causal structure that relates each of the outcome events in the EPR experiment and the corresponding flashing light event). She has then come to the conclusion that the postulated common causes for the flashing light correlations may very well be the same that the common causes for the corresponding EPR correlations.

Our friend thus sets for a common cause explanation of her EPR correlations in terms of our postulated common causes. Only, she will later need to give an appropriate interpretation of such common causes in order to accommodate the specific features of the EPR experiment, such as the

¹⁶Say for instance that the mechanisms connecting each wing with its corresponding panel are completely reliable and operate independently.

space-like separation of the two wings, etc.

5.2 Common Causes of EPR

She may then ask what is the structure of the C_{ij}^{ab} , or in what sense these common causes are associated to the quantum mechanical system, i.e. to the singlet state.

The first thing to note is that our (classically) postulated common causes are Reichenbachian *individual*-common causes. (This is so by construction). This is to say, they are common causes which screen-off one, and only one, of the correlations. Consequently, the postulated common causes have a label which identifies the specific correlation (between flashing lights in our case, or the corresponding EPR outcomes in her case).

Let us denote such a common cause, for instance, C_{ij}^{ab} .¹⁷ We will then have:

$$p(L_i^a \wedge R_j^b | C_{ij}^{ab}) = p(L_i^a | C_{ij}^{ab}) \cdot p(R_j^b | C_{ij}^{ab}), \quad (9)$$

$$p(L_i^a \wedge R_j^b | \neg C_{ij}^{ab}) = p(L_i^a | \neg C_{ij}^{ab}) \cdot p(R_j^b | \neg C_{ij}^{ab}), \quad (10)$$

$$p(L_i^a | C_{ij}^{ab}) > p(L_i^a | \neg C_{ij}^{ab}), \quad (11)$$

$$p(R_j^b | C_{ij}^{ab}) > p(R_j^b | \neg C_{ij}^{ab}). \quad (12)$$

Note as well that the postulated common causes are not necessarily deterministic, i.e. their occurrence does not necessarily entail that the corresponding outcomes will occur with certainty.

On the other hand, our friend may recall that the common causes were originally postulated for classical correlations (between the different light flashes) and that she were led to think that the same common cause would explain both the classical correlations and the corresponding quantum ones. These observations —perhaps the latter in particular— seem to suggest that the C_{ij}^{ab} are events that somehow *contain* or *include* the measurement operations. In other words, *measurement operations are causally relevant to the common causes*. This is indeed a remarkable feature of the postulated common causes, although far from controversial. Causal relevance of measurement may be motivated through the following example.

Imagine the following fictitious situation. Suppose we have some identically looking spherical objects the nature of whose we would like to understand better. In order to do so we chose to measure something we call ‘elasticity’. Suppose for the sake of the argument that ‘elasticity’ is a property that all objects have and which can only take on one of two possible values when measured, either ‘0’ or ‘1’. Thus, when it comes to ‘elasticity’ we can only find ‘0-elasticity’ objects and ‘1-elasticity’ objects.

¹⁷I am following here basically the same notation to that in the rest of the paper. I am just denoting the common cause of the classical correlations with a serif font C_{ij}^{ab} instead of the usual *italic* C_{ij}^{ab} in order to stress the fact that they are indeed different events.

We want then to find out whether our spheres have ‘0-elasticity’ or ‘1-elasticity’ so we set up a simple experiment to this end. As it happens, though, ‘elasticity’ is a property which is not directly observable and needs to be inferred from other experimental facts. Thus, our experiment consists in hitting the spheres, one at a time, with a hammer —with the same hammer and with the same strength each time. The recorded events are of two kinds: we measure the hammer’s recoil after hitting the sphere as well as the sound produced. (We can suppose for simplicity that typically we will find the hammer recoiling in two modes, so to speak, a ‘large recoil’ and a ‘short recoil’. Similarly, the sounds emitted when hitting the spheres with the hammer turn out to be of two kinds only, one ‘higher pitched’ and the other ‘lower pitched’). Finally, suppose that the information compiled about recoil and sound modes is enough to tell whether our spheres have ‘0-elasticity’ or ‘1-elasticity’. That is, if a ‘short’ hammer recoil and a ‘high pitch’ emitted sound are measured we can safely infer that the sphere has ‘0-elasticity’. Otherwise, the sphere has ‘1-elasticity’.

This example I think illustrates sufficiently how measurement may have a causal role in a causal explanation. In particular, our measurement operations —the hammer hits— are responsible, causally responsible that is, for the observed outcomes that allow us in turn to infer a property of the system at hand. This is not to say, of course, that the hammering is the cause of the sphere having a particular value of the property ‘elasticity’, i.e. having ‘0-elasticity’ or ‘1-elasticity’. But once more, what the hammering is causally relevant for is the particular sound and degree of recoil which allow us to make an inference regarding the ‘elasticity’ of the spheres. We could perhaps say that our measurement operations *reveal* what the value of the ‘elasticity’ of the spheres is by *causing* further events (related to that property).

Spin measurement experiments may be taken to some extent to be similar to ‘elasticity’ measurements in the example above, at least empirically, i.e. as far as empirical observations are concerned. Recall, for instance that in an EPR experiment spin components (values) of the electrons are *detected* by letting the particles through an inhomogeneous magnetic field (a Stern-Gerlach magnet) and observing them flashing on the screen, either on its upper or lower side. The electron spin component is thus *inferred* from the effect that the Stern-Gerlach magnet has on the particle. Thus, the magnetic field may be taken not to cause the electron to have a particular spin value but to *reveal* such a spin value by causing a change of the electron trajectory (in either way).

Of course, this may be soon rejected by proponents of the orthodox interpretation of quantum mechanics on the grounds that no such property exists, really, before measurement. The orthodox’s critique would surely undermine the identification I made above between the case of ‘elasticity’ and spin to the extent that both are taken in each case to be real physical

properties of the system. But it seems to me that it would leave untouched the claim that measurement settings may be taken to be causally relevant to the outcomes (whatever the underlying reality of the system is). Thus, we may still follow with such an idea in mind, regardless of the degree of realism we are committed to.

Note finally that measurement operations as considered above are not to be taken as the only relevant causal factors of the observed outcomes. In the classical case, for instance, outcomes do strongly depend on the property in question. In particular, whether the spheres have ‘0-elasticity’ or ‘1-elasticity’ seems clearly crucial for the fact that a particular sound and degree of recoil is observed. And such an influence, I would say, seems to be causal as well.

The case of spin measurements is different just for reasons similar to those concerning the orthodox critique above. For in such a view it seems difficult to maintain that a property, which is not taken to exist, is in any sense responsible for an outcome. However, there seem to be good intuitive grounds to say that if one takes it that there is some causal connection between the unmeasured quantum system and the measured outcomes, this will include some feature exclusive to the system itself. In the EPR context, in fact, it is very often assumed that the spin-singlet state itself—or perhaps some factor closely related to it—is causally relevant to the EPR outcomes.¹⁸

6 A non-Factorizable Common Cause Model for EPR Correlations

The conclusions of the discussion in the previous section about measurement and the structure of the postulated common causes can be expressed formally, in terms of algebra events and probabilistic relations.

6.1 *Individual-Common Causes and outcome independence*

Recall first that the common causes were each postulated to screen-off a single correlation—these are what I called *individual*-common causes. I expressed that by means of the screening-off conditions (9)-(10).

Now the role of measurement in the model can be explicitly accounted for if we think of the postulated *individual*-common causes C_{ij}^{ab} as the result of a conjunction of the specific measurement operations L_i and R_j and some other causally relevant factor Λ . That is:

$$C_{ij}^{ab} \subset L_i \wedge R_j \wedge \Lambda. \quad (13)$$

¹⁸This is indeed commonplace. See, for instance (Cartwright, 1987), (Cartwright and Jones, 1991), (Chang and Cartwright, 1993), (Healey, 1992), (van Fraassen, 1982), or more recently (Price, 1994) or (Suárez, 2007).

Typically, Λ will most probably be associated to the singlet state Ψ_s itself, and perhaps to some other relevant causal factors prior to the preparation of the entangled system.¹⁹ In some sense Λ seems much more deeply related to the ‘inner’ quantum mechanical structure of the system than the postulated common causes C_{ij}^{ab} . This observation is also supported by the fact that the C_{ij}^{ab} have been postulated in a purely classical context, such as that of the flashing light panels. Indeed, the model’s common causes C_{ij}^{ab} are not to be thought of as hidden variables as such. For they are not aimed to complete the quantum description of the system in any way. Their role is much more explanatory than anything else.

We may assume furthermore that the causal factor Λ is common to several (or even to all) correlations in the EPR experiment. It is important to note however that Λ , in contrast to the C_{ij}^{ab} , will not in general screen-off the correlations. I shall explicitly require this in order to avoid problems concerning *common*-common causes. That such problems may arise is clear, since if Λ is a screening-off causal factor common to all the possible outcomes of the experiment, it surely is a *common*-common cause of all the outcome correlations. And a *common*-common cause model cannot in general be guaranteed to exist. Moreover, in the EPR context, assuming *common*-common causes leads quite straightforwardly to the Bell inequalities.

Similar reasons lead us to require as well that the conjunction of Λ with the measurement operation events, i.e. $L_i \wedge R_j \wedge \Lambda$, be non-screening-off events. In particular, $L_i \wedge R_j \wedge \Lambda$ is assumed to be a causal factor common to all the correlations that involve these particular measurement settings.

This suggests that $L_i \wedge R_j \wedge \Lambda$ *contains* all the postulated common causes C_{ij}^{ab} of the correlations displayed for these specific measurement settings. That is:

$$L_i \wedge R_j \wedge \Lambda \supseteq C_{ij}^{++} \vee C_{ij}^{+-} \vee C_{ij}^{-+} \vee C_{ij}^{--}. \quad (14)$$

One may however think that the above would entail that the C_{ij}^{ab} be *common*-common causes. In order to avoid that and guarantee that C_{ij}^{ab} be *individual*-common causes, we shall require that they be mutually exclusive, i.e.

$$C_{ij}^{ab} \wedge C_{ij}^{a'b'} = \emptyset, \quad (15)$$

where $a, b, a', b' = +, -$ and $ab \neq a'b'$.

The *individual*-common cause event structure resulting from the above considerations can be seen in Figure 4.

¹⁹This characterisation of Λ somehow reminds to the kind of events Cartwright considers the right common cause events for EPR. That the similarity is quite so it will become clear in a moment, since I will be requiring (or at least allowing) that the Λ be non-screening-off events, just like in Cartwright’s common cause account of EPR. See for instance (Cartwright, 1987; Cartwright and Jones, 1991) and (Chang and Cartwright, 1993).

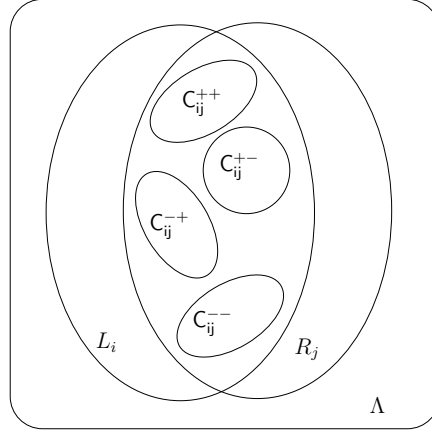


Figure 4: The *individual*-common cause model event structure for EPR correlations with measurement settings L_i and R_j .

A remarkable feature of the resulting event structure is that our postulated common causes C_{ij}^{ab} satisfy a familiar condition very closely related to the derivation of the Bell inequalities, namely *outcome independence* (OI):

$$p(L_i^a \wedge R_j^b | L_i \wedge R_j \wedge C_{ij}^{ab}) = p(L_i^a | L_i \wedge R_j \wedge C_{ij}^{ab}) \cdot p(R_j^b | L_i \wedge R_j \wedge C_{ij}^{ab}), \quad (16)$$

This is indeed what expressions (9) and (10) encapsulate. But note as well that, on the other hand, the event Λ (and also $L_i \wedge R_j \wedge \Lambda$) will not in general satisfy such constraint. In particular, both Λ and $L_i \wedge R_j \wedge \Lambda$ will in general violate *outcome independence* due to the requirement that they shall not screen-off the correlations. (This was explicitly required in order to avoid the usual problems regarding *common*-common causes.)

Thus the model is able to accommodate the usual interpretation of the violations of the Bell inequalities, i.e. the violations of Bell's *factorizability*. The standard view in this respect takes it that quantum mechanics violates *outcome independence*—while being compatible with so-called *parameter independence*.²⁰ Thus, the fact that the *outcome independence* condition is violated when Λ is taken as the hidden variable in our model is in complete agreement with this standard view.

On the other hand, since the postulated common causes C_{ij}^{ab} in the model are viewed as events which in principle are not part of the ‘inner’ quantum description (or structure) of the system—although they are of course clearly related to it via equation (13)—, it seems quite natural to think of them as satisfying *outcome independence*.

²⁰Such claims are normally supported by the fact that the spin-singlet state has a spherical symmetry.

6.2 Common Cause Dependence is not Conspiracy

A second remarkable feature of the model is that, because the dependence of the common causes on measurement, the C_{ij}^{ab} violate what I called *measurement independence*. That is:

$$p(C_{ij}^{ab} \wedge L_i) \neq p(C_{ij}^{ab}) \cdot p(L_i), \quad (17)$$

$$p(C_{ij}^{ab} \wedge R_j) \neq p(C_{ij}^{ab}) \cdot p(R_j). \quad (18)$$

Recall that *measurement independence* was a condition explicitly required—usually under the name of *no-conspiracy*—on the grounds that its violation would amount to some sort of ‘universal conspiracy’. The question then seems quite straightforward: In the light of expressions (17) and (18), is our model a ‘conspiratorial’ model (in the sense above)? Alternatively, is *measurement independence* a reasonable assumption for common causes of EPR correlations? The answer to both these questions, I think, is negative.

The charge of conspiracy may be avoided in different ways. Appealing to backwards in time causation is one of them. I shall briefly comment this option in the next section.

Another possibility opens up if we look closely at the role of measurement in the experiment. In fact, one of the things I pointed out when discussing the significance of *measurement independence* as an assumption underlying EPR was that it seemed appropriate only if one assumed that the common causes take place prior to the measurement apparatus is set up. It is only in those cases that probabilistic dependencies between the common causes and measurement settings, i.e. violations of *measurement independence*, may be sensibly interpreted as some sort of ‘world conspiracy’. However, there is nothing in the notion of common cause, nor in the very structure of the EPR experiment, that forces us to stick to the idea that the common cause must take place prior to measurement (and therefore prior to the setting-up of the measurement devices). This was motivated through the flashing lights example in Section 5.1.

In fact, relations (2)-(5) in page 5—taken as a definition (Reichenbachian) common cause—do not include spatio-temporal information of any sort. This is mainly due to the fact that they involve event types, which are not defined in space time. It is only in virtue of them being collections of token events that we can refer to them spatio-temporally. In this interpretation, the intuition is that common cause events in expressions (2)-(5) are to be located in the causal past of the events which are correlated. In the particular case of the EPR experiment, we want to require that the postulated common causes and the corresponding outcome events be time-like (ensuring hence temporal priority of the common causes). But, once more, this needs not entail that such common causes be located prior to measurement operations.

So, we may perfectly allow instead that the common causes take place after the measurement devices have been set-up, and even after measurement operations have been performed. In such a case, requiring *measurement independence* conditions to hold does not seem particularly appealing and, more importantly, there is nothing conspiratorial about them being violated. This is indeed the possibility the model above exploits.

6.3 Parameter Dependence and non-factorizability

As a direct consequence of the violation of *measurement independence*, the model turns out to be non-factorizable, i.e. Bell's *factorizability* is also violated. This soon becomes evident if we note that *measurement independence* is necessary for a more general independence condition, namely *parameter independence*, which is in turn necessary for *factorizability*. In particular, a violation of *measurement independence* entails, as we have seen in the previous section, that the common cause is not independent of *both* the measurement settings. That is:

$$\begin{aligned} p(C_{ij}^{ab} \wedge L_i) &\neq p(C_{ij}^{ab}) \cdot p(L_i), \\ p(C_{ij}^{ab} \wedge R_j) &\neq p(C_{ij}^{ab}) \cdot p(R_j), \end{aligned}$$

which entails that

$$p(C_{ij}^{ab} \wedge L_i \wedge R_j) \neq p(C_{ij}^{ab}) \cdot p(L_i \wedge R_j),$$

as long as we assume $p(L_i)$ and $p(R_j)$ probabilistically independent.²¹

This in turn means that the outcomes will also statistically depend on *both* measurement settings, since they obviously depend on the common cause, i.e.

$$\begin{aligned} p(L_i^a | L_i \wedge R_j \wedge C_{ij}^{ab}) &\neq p(L_i^a | L_i \wedge C_{ij}^{ab}), \\ p(R_j^b | L_i \wedge R_j \wedge C_{ij}^{ab}) &\neq p(R_j^b | R_j \wedge C_{ij}^{ab}). \end{aligned}$$

This expression is nothing more than the violation of *parameter independence*. And since *parameter independence* is necessary for Bell's *factorizability*, the above just means that a failure of *measurement independence* entails a violation of *factorizability* as well.

The rejection of *factorizability* has two obvious consequences, one which may be seen to support the model, the other which might be problematic for it. First, it is obvious that the Bell inequalities can not be derived for the model's event structure. This is certainly good, for it means that the model avoids the implications of Bell's theorem, and more importantly that it is perfectly compatible with the (empirically confirmed) quantum mechanical predictions for the EPR correlations.

²¹This expression is nothing more than *Hidden Locality* in van Fraassen (1982).

On the other hand, the violation of Bell's *factorizability* may be interpreted as a sign of non-local behaviour. I already pointed out that claims along these lines are far from being uncontroversial, especially if locality is merely associated with the requirement that there not be superluminal signalling between the two wings of the EPR experiment.

Other, more radical views retain locality intuitions by appealing, for instance, to backwards in time causation. Such views usually exploit the failure of Bell's *factorizability* via violations of *parameter independence* —as opposed to standard view that quantum mechanics violates *outcome independence*—, and in particular to violations of *measurement independence* (just as in the model I just proposed) which are interpreted as implying backwards in time causation.

The possibility of backwards in time influences is not, by any means, new. This possibility was explored in a common cause model suggested by Price.²² Indeed Price's model needs to assume backwards in time influences in order for the postulated common causes to operate locally. In particular, Price assumes that the common cause events take place in the overlap of the backward light-cones of the correlated EPR outcomes. Violations of *measurement independence* therefore obtain due to the influences of the settings on the common causes operating backwards in time.

Note that the probabilistic event structure of Price's model and my own is exactly the same. Only, the interpretation of the events is different. The model I just proposed has what I think might be an advantage, even if only at the intuitive level, over that of Price, namely that appeal to backwards in time causation is not needed. But recall that it is precisely backwards causation what allows Price's common causes to operate locally. This suggests that, since backwards in time causation is not a feature of our model, we might not be able to retain locality. This observation seems to be supported by the fact that our model has certain parallels with Bohm's quantum mechanics. They both violate, for instance, *parameter independence*, while conform to *outcome independence*. And, again, Bohm's quantum mechanics is explicitly non-local. So, is our model non-local as well?

A somehow qualitative and partial answer to this question might be advanced by stressing that in developing the model I have only paid attention to the significance and adequacy of *measurement independence*. And recall that *measurement independence* (or the equivalent *no-conspiracy*) conditions are just some of the extra restrictions imposed on the idea of Reichenbachian Common Cause (RCC), alongside other further conditions, normally

²²Cf. (Price, 1994). Although the model was initially presented as a common cause model (containing backwards in time causal influences), Price seemed later to retract from interpreting it as causal. In particular, Price (1996) seems to suggest that the backwards in time influences of the model be of no causal origin. An explicit causal interpretation of Price's model is given in (Suárez, 2007). I shall assume, for the sake of the argument, that Price's model may indeed be interpreted causally.

associated to locality requirements. What this means is that, by construction, our model is supposed to have retained some notion of locality within its event structure. So the question rather seems to be to what extent the model can be thought to be local (or equivalently non-local).

Locality issues are subtle. It is not clear, for instance, what notion of locality may best fit the (causal) structure in our model. Or whether the very concept of common cause would still stand if we are to retain local causal interactions. In addressing such matters a thorough assessment of the ontological implications of the model will quite likely be of help.

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