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Local Acausality

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Abstract

A fair amount of recent scholarship has been concerned with correcting a supposedly wrong, but wide-spread, assessment of the consequences of the empirical falsification of Bell-type inequalities. In particular, it has been claimed that Bell-type inequalities follow from "locality *tout court*" without additional assumptions such as "realism" or "hidden variables". However, this line of reasoning conflates restrictions on the spatiotemporal relation between causes and their effects ("locality") and the assumption of a cause for every event ("causality"). It thus fails to recognize a substantial restriction of the class of theories that is falsified through Bell-type inequalities.

1 Introduction

Bell's Inequality, and similar constraints, must hold for correlations that are describable by a specific class of theories (see, e.g., Bell 1964; Clauser and Horne 1974; Greenberger et al. 1990; Tittel et al. 1998).[0] Experiments on quantum mechanical systems have shown that there are correlations which significantly violate these constraints (e.g. by Aspect, Dalibard, and Roger 1982; Pan et al. 2000).[0] This contradiction provides the basis for a *reductio ad absurdum* of at least one of the assumptions about the theories supposed to describe the correlations. If none of the assumptions is redundant, i.e. if, after discarding one of them, the constraints cannot be derived any more, giving up only one of the assumptions is sufficient to avoid the contradiction. But even then, one does not know, without additional arguments, just which of the assumptions is the wrong one.

The most important assumption of the derivation of Bell's Inequality[1] is "local causality" (see, e.g., Bell 1975, p. 54, 1990, p. 239). From this condition, together with auxiliary assumptions, Bell's Inequality follows. I take this to be the content of "Bell's theorem", although this term is sometimes reserved to the second part of the derivation only (Norsen 2006b; cf. Goldstein et al. 2011). As I mentioned above, Bell's Inequality is violated by the empirical data

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[0]**Erratum:** The reference to Tittel et al. (1998) is erroneously placed with the references to the theoretical constraints instead of the experiments in the subsequent sentence. (Erratum added May 27, 2014.)

[1]Henceforth, I subsume also the similar constraints under the term "Bell's Inequality".

of certain experiments. Therefore local causality (or at least one of the auxiliary assumptions) is wrong about the theories which are able to describe those experiments.

In recent years, several authors have been concerned with correcting a supposedly wrong, but wide-spread, assessment of the consequences of the empirical falsification of Bell's Inequality (see, e.g., Albert 1992; Maudlin 2002; Norsen 2006a; Laudisa 2008; Gisin 2012; Goldstein 2013). They have argued that a purported substantive assumption (often labeled "realism" or "hidden variables", see, e.g., Aspect 2007 and Mermin 1993) in the derivation of Bell's Inequality is, on closer inspection, redundant. Accordingly rejecting that assumption won't avoid the contradiction. The authors urge that it is therefore necessary to give up the assumption that physical objects interact only locally, which is the only substantial assumption left.

The main purpose of the present paper is to spell out the characteristics of the supposedly wrong view in a way as to make clear that the objections against it are misleading. To this end, I will first reconstruct how the empirical violation of Bell's Inequality can be turned into a argument for the existence of non-local interactions (Section 2). I believe that this captures the essentials of the argument the above mentioned authors intend to make. However, the argument needs to suppose that Bell's condition of "local causality" is implied by requirement that all interactions be local only ("locality"). In Section 3, I will argue that this is the case if theories are assumed to be causal in a sense I will specify. It is this latter assumption, I argue, that the supposedly wrong, but wide-spread view, wishes to bring to the fore as the second substantive assumption in the derivation of Bell's Inequality. If this assumption is dropped, the locality of all interactions can be saved, *pace* the critical authors. This establishes the possibility, in principle, of finding empirically adequate theories that are *local* in the sense that every causal relation is between time-like separated events only. However, such theories will need to be *acausal* in the sense that not every correlation has a causal explanation.

Sections 4–6 draw some further conclusions from my analysis. First (Section 4), the mathematical formalism of a theory such as standard quantum mechanics or Bohm's theory (Bohm 1952a,b) does not determine whether the theory describes non-local interactions or only local ones. Second (Section 5), the complete description of the state of affairs, according to a certain theory, need not provide a causal explanation. Third (Section 6), Einstein, Podolsky, and Rosen's (1935) "criterion of reality" is, in important respects, similar to the requirement for causality contained in local causality. I will end with a short summary (Section 7).

2 The Argument against Locality

Locality is the assumption that causes and effects are time-like, not space-like, separated in the sense of the theory of special relativity. That is, if a light-signal which is emitted at the place where a first event is instantiated would reach the place where a second event is instantiated only after the instantiation of that second event, the first event cannot be the cause of the second event.

Definition 1 (Locality) *Locality holds if and only if space-like separated events are causally independent.*

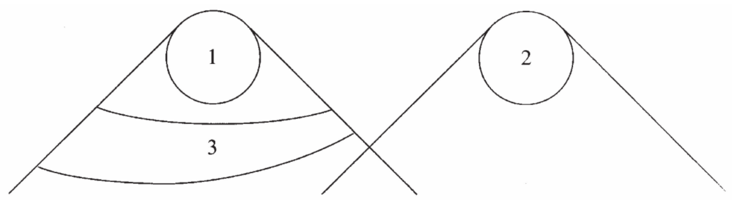

Figure 1: Space-time regions that are relevant for Bell's definition of locally causal theories. Copied from (Norsen 2011, p. 1263), original in (Bell 1990, p. 240).

I mean locality to be the same assumption that Bell expresses as his "intuitive" idea of "local causality":

> The direct causes (and effects) of events are near by, and even the indirect causes (and effects) are no further away than permitted by the velocity of light. (Bell 1990, p. 239)

For Bell, this formulation of locality "is not yet sufficiently sharp and clean for mathematics". In order to improve the formulation, Bell switches to the level of theories and employs the notion of *beables*, which he has introduced before:

> The *be*ables of the theory are those entities in it which are, at least tentatively, to be taken seriously, as corresponding to something real. (Bell 1990, p. 234, emph. in the original)

With this notion in hand, and with reference to Figure 1, he defines *locally causal* theories as follows.

Definition 2 (Locally causal theories, Bell 1990) *A theory will be said to be locally causal if the probabilities attached to values of local beables in a space-time region 1 are unaltered by specification of values of local beables in a space-like region 2, when what happens in the backward light cone of 1 is already sufficiently specified, for example by a full specification of local beables in a space-time region 3. (Bell 1990, pp. 239–240)*

Proceeding from this definition, Bell shows that any locally causal theory is committed to a constraint, the "Clauser–Holt–Horne–Shimony Inequality" (which is just another type of "Bell's Inequality"), on the probabilities or frequencies of outcomes of certain measurements (Bell 1990, p. 244). This is Bell's theorem.

Theorem 1 (Bell) *Locally causal theories satisfy Bell's Inequality.*

However, the outcomes of actually performed measurements in appropriate experimental settings violate the inequality.

Assumption 1 (Empirical data) *Empirically adequate theories must not satisfy Bell's Inequality.*

Therefore, no locally causal theory can be empirically adequate.

It is perhaps useful to state this consequence of Bell's theorem and the empirical data as a failure of "local causality", which suggests to understand local causality as follows.

Locality → Local Causality	If space-like separated events are causally independent, locally causal theories can be empirically adequate.
Bell's theorem & empirical data	No locally causal theory can be empirically adequate.
Not Locality	Some space-like separated events are causally dependent.

Table 1: The argument against locality

Definition 3 (Local Causality) *Local causality holds if and only if locally causal theories can be empirically adequate.*

Defined in this way, "local causality" denotes an empirical condition, which is either satisfied, or not, by processes in nature, irrespective of the theory we use to describe the processes. By contrast, the property of being "locally causal" is one that I use to characterize *theories*. Bell's theorem, then, together with empirical data, teaches us that local causality is not satisfied by our world , i.e. that locally causal theories cannot be empirically adequate.

However, in order to conclude that locality, and not only local causality, is violated one needs to assume that locality implies local causality:

Assumption 2 (Locality → Local Causality) *If space-like separated events are causally independent, locally causal theories can be empirically adequate.*

The argument against locality is then the following sequence of statements. Bell's theorem, together with empirical data, shows us that locally causal theories cannot be empirically adequate. However, they should be empirically adequate if the world were local. Therefore, the world is non-local. Table 1 shows the argument in the form of a table with premises above the middle line and the conclusion below the middle line.

3 Deriving Local Causality from Locality

In order to leverage Bell's theorem against locality one needs to justify, according to the argument in Section 2, that locally causal theories can be empirically adequate if the world is local, i.e. one needs to justify Assumption 2. In the following I will show that Assumption 2 can be justified if one assumes that complete theoretical descriptions are causal explanations in a sense I will specify. I do not see how Assumption 2 could be justified by a significantly different assumption.

3.1 Causal Theories

Bell avoided, in his definition of locally causal theories (Definition 2), the use of the "rather vague notions" of cause and effect (Bell 1990, p. 240). Indeed, his Inequality is a statement about probabilities or frequencies that one can measure in certain experiments. It is, therefore, necessary to relate the notions of cause and effect to those quantities. In other words, one has to relate the assumption of locality, which is an assumption about causal relations, to statements in terms of probabilities.

This is a notoriously difficult question mainly because, to put it in a slogan, correlation does not imply causation. Since we are concerned here with locality, i.e. with a claim of causal independence, rather than causal dependence, the contrapositive of the slogan is more directly relevant: Absence of causation does not imply absence of correlation. In any case, the simple identification of causal with probabilistic dependence won't do. The problem is how to do otherwise.

The problem has found a partial solution in the theory of probabilistic causality, of which an essential idea is attributed to (Reichenbach 1956, p. 159). The basic idea is that the slogan is not quite correct. Although absence of causation does not, in general, imply absence of correlation, it does so if the relevant probabilities are conditional on the instantiation of common causes of the correlated effects.

To be a bit more precise, using the Reichenbachian notion of probabilistic causality, we can state a necessary condition for a theory to feature a common cause for every correlation that it asserts between causally independent events: The theory must contain, for every causally independent pair of events, a description of another, distinct, event or state such that, conditional on this description, the two events are statistically independent, i.e. not correlated. In other words, a theory can provide explanations of correlations by common causes if it features a "screener-off" for every correlation between causally independent events. The "screener-off" is the state or event conditioned on which the causally independent events are also statistically independent. The "screener-off" screens the two causally independent events off from each other, as far as their probabilities or statistics are concerned.

A theory is causal if and only if it provides causal explanations for every event or correlation that it describes. Theories without screener-offs for causally independent events cannot do this. They fail to satisfy a necessary condition for doing it. On the other hand, theories that feature the appropriate screener-offs can be causal. Appropriate screener-offs are distinct from the correlated events, and also suitably located in space and time (see, e.g., Butterfield 1989).

Definition 4 (Causal theory) *A theory is causal only if it features an appropriate screener-off for each pair of events that it asserts to be causally independent.*

With this definition, locally causal theories (see Definition 2) may not satisfy the mentioned necessary condition for being a causal theory. Although a locally causal theory features a screener-off for any pair of *space-like separated* events, it may not do so for some other (time-like separated) events. If such a locally causal theory moreover asserts the causal independence of these other events, it is not causal. Thus, paradoxically as it may sound, locally causal theories need not be causal theories. "Locally causal" does not imply "causal":

$$\text{locally causal} \not\models \text{ causal} \tag{1}$$

Also, locally causal theories need not be local theories. A theory can feature a screener-off for any pair of space-like separated events but it needs not assert them to be causally independent.

$$\text{locally causal} \not\models \text{ local} \tag{2}$$

To be sure, in locally causal theories, if the probability of the event in region 1 (see Figure 1) is conditioned on the "full specification of local beables in a space-time region 3", or some other appropriate specification of the backward light-cones of the two correlated events, the probability is "unaltered" if one conditions, in addition, on the event in region 2. In other words, the appropriate specification is a *screener-off* for space-like separated events. But Bell's definition of locally causal theories is silent about whether it asserts space-like separated events to be causally independent or not.

As mentioned before, Bell avoided the notion of cause and effect in his definition. But he felt "one is likely to throw out the baby with the bathwater" (Bell 1990, p. 239) in doing this. Bell probably intended to *define* causal independence, as asserted by a theory, of space-like separated events by the theory's assertion that they are uncorrelated given an appropriate conditional probability (cf. Norsen 2006a, pp. 641–642). Like this, he was able to distinguish (absence of) causation from mere (absence of) correlation. But with such a definition, he tacitly adopted a specific analysis of causation, namely a probabilistic one in the spirit of Reichenbach, as well as the requirement that there must be causes for correlations.

I will discuss more of this in the next subsection because the question whether locally causal theories are, in fact, local or causal is, for the present purposes, not the primary issue. Rather, it is the question whether local theories are indeed locally causal theories. They are if they are causal theories, as I will argue in the next subsection.

3.2 The Restriction to Causal Theories

I now show how local causality can be derived from locality (Assumption 2) if one assumes that every theory is a causal theory. I cannot see how Assumption 2 can be justified without a similar premise.

In order to have a relationship between certain classes of theories and how the world is, as in the case of locally causal theories and local causality, I assume that locality means nothing else than that local theories can be empirically adequate. This is expressed in the following two definitions and in the following assumption.

Definition 5 (Local theory) *A local theory asserts that space-like separated events are causally independent.*

Definition 6 (Locality′) *Locality′ holds if and only if local theories can be empirically adequate.*

Assumption 3 (Locality → Locality′) *If space-like separated events are causally independent, local theories can be empirically adequate.*

Assumption 3 is almost the wanted Assumption 2 except for the fact that we have not established that *local* theories are *locally causal* theories. As we have seen in the previous subsection, locally causal theories feature a screener-off for each pair of space-like separated events. Local theories assert the causal

Locality $\to$ Locality$'$	If space-like separated events are causally independent, theories that assert the causal independence of space-like separated events (i.e. local theories) can be empirically adequate.
Theories are causal	A theory features a screener-off for any pair of causally independent events.
Locality $\to$ Local Causality	If space-like separated events are causally independent, theories that feature a screener-off for each pair of space-like separated events can be empirically adequate.

Table 2: Justification of Assumption 2

independence of any pair of space-like separated events. Therefore, in order for local theories to be locally causal theories, the local theories need to feature a screener-off for each pair of, according to them, causally independent events.

This is a specific case of the more general assumption that if a theory asserts the causal independence of a set of pairs of events, it features a screener-off for each of the pairs. By Definition 4, it is the assumption that every theory is a causal theory, or at least a theory that satisfies a specific necessary condition (screening-off) for being one. According to this assumption, every theory satisfies a necessary condition for being causal.

Assumption 4 (Theories are causal) *A theory features a screener-off for any causal independence it asserts of pairs of events.*

Thus, local theories are locally causal, if they are causal theories:

$$\text{local \& causal} \models \text{locally causal} \tag{3}$$

The justification for Assumption 2 is then the following. A local theory asserts, by Definition 5, that space-like separated events are causally independent. Because, by Assumption 4, every theory is a causal theory, a local theory features a screener-off for any space-like separated pair of events. But such theories are, according to Definition 2, locally causal theories. Therefore, if local theories can be empirically adequate, then so can locally causal ones. If we assume that locality implies that local theories can be empirically adequate (Assumption 3), then locality implies that locally causal theories can be empirically adequate, which is what we wanted to justify.

3.3 Saving Locality by Giving up Causality

The justification of Assumption 2 is summarized in Table 2. With this analysis in hand, the argument against locality (Section 2) can be given in more details. Just substitute the premises shown in Table 2 for the first premise in Table 1. Accordingly, the conclusion that there are non-local interactions in the world rests on Assumptions 1, 3, 4, and on Bell's theorem. I cannot see how an argument against locality can be made with premises that are weaker in a significant sense. As long as no such argument is available, the conclusion of non-locality can be avoided by giving up Assumption 1, 3, 4, or one of the auxiliary assumptions of Bell's theorem. For the present discussion Assumption 4 is the important one. I believe the conclusion of non-locality seems inevitable to some of the authors mentioned in the Introduction because they tacitly make this assumption.

If we do not require theories to be causal, empirically adequate theories for the quantum correlations may be local. Every causal relation that an empirically adequate theory asserts may be between two events that are time-like, not space-like, separated. Every event may have all its causes in its backward light-cone, and no effect may lie outside the forward light-cone of its causes. However, in a local but "acausal" (or "non-causal", see Definition 4) theory, there will be some events or correlations for which the theory does not provide a causal explanation (not a screener-off at any rate). Some events may just have no causes, and therefore also no non-local ones.

Note, that the "acausality" needs by no means to be ubiquitous. Locally acausal theories may very well explain almost all events and correlations in its domain of application by causes which act only locally. Just very few, or even a single, correlation may have to be left causally unexplained in an acausal theory. Of course, in the present context, we would be mainly interested in those theories that are sufficiently acausal to be able to violate the various types of Bell inequalities.

4 The Need for Interpretation

The analysis I propose here has the consequence that whether a theory is local or not is not determined by the set of events it postulates and the probabilities it assigns to them. Quantum mechanics, for instance, does not provide an appropriate screener-off for all space-like separated measurement outcomes it describes. It is, therefore, not a locally causal theory. But to conclude from this that it is non-local, we need to assume that it is a causal theory (Assumption 4). Only then must it assert the causal dependence of some space-like separated events. If, however, we give up Assumption 4, the quantum mechanical formalism can be interpreted locally. Nothing forces us, in that case, to assert that some space-like separated events are causally dependent. We can add to the quantum mechanical formalism the causal claim that every space-like separated pair of events is causally independent. We then just cannot require that a theory provide a screener-off for every pair of causally independent events.

The lack of screener-offs, in turn, can have various reasons. Maybe common causes do not screen-off. The quantum mechanical singlet state could then be taken for the common cause of the correlated measurement outcomes (see, e.g., Cartwright 1994). Or maybe the lack of a screener-off is due to an outright lack of common causes, see Section 5.

Like standard quantum mechanics, Bohm's theory (Bohm 1952a,b) is not locally causal. Again, whether Bohm's theory is local or not cannot be judged on the sole basis of its assignments of probabilities to the events it postulates. It can be local if it is denied that theories must be causal theories. This may come as a surprise since Bohm's theory is usually taken as a prime example of an explicitly non-local theory. In fact, it is only an explicitly "non-locally-causal" theory. It violates what is usually called parameter independence. This is a condition which requires a screener-off for the distant measurement settings and the nearby measurement outcome. But to interpret such an unscreened-off correlation as a causal dependence is exactly endorsing Assumption 4, namely to say, that if the events were causally independent it would be possible to display a screener-off for them.

The same remarks apply to the version of quantum mechanics by Ghirardi, Rimini and Weber (Ghirardi, Rimini, and Weber 1986), and to any other empirically adequate theory of quantum correlations. They must not be locally causal in order to be able to violate Bell's Inequality. But whether or not to interpret the violation of local causality as a violation of locality depends on whether we endorse Assumption 4 or not.

I do not wish to suggest, however, that Assumption 4 is the only criterion for whether an empirically adequate quantum theory is local or not. Other considerations will have a bearing as well. For example, it may well make a difference whether the unscreened-off correlation involves a *manipulable* factor such as the measurement settings, or instead factors that are, for all we know, not manipulable in principle such as the measurement outcomes.

Also, particular theories, such as Bohm's, may be most naturally interpreted in a way which satisfies Assumption 4, or they may be intended to be interpreted in this way by those who proposed the theory or work with it. But not for all empirically adequate theories need this be the case. At any rate, the violation of local causality alone is not sufficient to conclude the violation of locality.

5 Causal Incompleteness

The possibility I delineate here of saving locality means giving up a certain notion of causality. Just as we may have to accept that not for every event (e.g. the outcome of a spin measurement) there is a deterministic cause, we might have to accept that there is not always a directed causal link between two correlated events nor a common cause — not even in the probabilistic sense (cf. Fine 1989; van Fraassen 1982). A further possibility would be that the probabilistic definition of causality through screening-off relations is inadequate, but I do not explore this option here (Cartwright 1994).

Imagine for a moment that you have a deterministic notion of causality, and that you assume that causes lie in the backward light-cones of their effects (locality). You would then expect that whether or not a certain event is instantiated in region 1 (see Figure 1) is determined by the complete description of matter of facts in region 3. Now suppose you find that this is not so. What must you conclude from that? I urge that you have at least two options: (1) It could be that things outside the backward light-cone of region 1 causally influence what happens in region 1. This would be a case of non-locality. (2) The other possibility is that there are just no deterministic causes. Accordingly, the theory's complete description of region 3 does not determine what happens in region 1. If you do not insist that causes must be deterministic you lose an incentive to look for causes outside the light-cone, and you are not forced to conclude that you are dealing with a case of non-locality.

In a similar manner, the failure of local causality in some quantum experiments can be attributed to either the failure of locality or the lack of probabilistic causes. If you do not insist that there be (probabilistic) causes for the measurement outcomes you lose an incentive to look for or even postulate (probabilistic) causes outside the backward light-cone of the measurement outcomes in question. The reason why a complete description of region 3 fails to screen-off region 1 from region 2 may be that there are just no probabilistic causes, or only partial ones, for the events in region 1. The complete description need not be the description of a complete, i.e. screening-off (probabilistic) cause.

Complete state descriptions that are not descriptions of causes (neither probabilistic nor deterministic) may seem "incomplete" because the absence of a deterministic or screening-off cause is often due to not taking into account all relevant factors. But maybe quantum mechanical phenomena show us that the world itself is causally "incomplete" in the sense that there is not a complete probabilistic cause for every event or correlation.

Gyenis and Rédei (2004) investigated whether causal completeness, in this sense, can be ruled out on the basis of probabilistic constraints alone. They found that it cannot. They showed that probability spaces can be extended such that they are "common cause closed" with respect to any causal independence relation that is stronger than logical independence. But still, as an empirical hypothesis, causal completeness, or "closedeness", may fail. Also, their analysis is an example of how to treat, in a consistent way, causal independence and screening-off conditions as two distinct, logically independent, assumptions in line with the analysis proposed here.

I think that also Jarrett (1984, p. 585) meant "incomplete" state description (which he put in scare quotes!) in the sense described above. Jarrett's completeness is a special case of the assumption that a specification of all relevant factors behaves as we expect from causal reasoning, namely that it provides an appropriate screener-off or even a sufficient condition ("deterministic cause"). Jarrett's completeness is more a characterization of the assumed *consequences* of complete specification than the assumption of a complete specification *per se*. Jarrett's "completeness" is not Bell's "full specification" or, for that matter, a specification of all relevant factors. Therefore, *pace* Norsen (2009), one can perfectly take care of Bell's requirement of full specification of all causally relevant factors and, at the same time, deny Jarrett's assumption of causal "completeness" of that specification.

However, let me emphasize that my analysis is distinct from the familiar result that local causality is implied by "outcome independence" and "parameter independence" (Shimony 1986).[2] All these conditions express probabilistic independencies and the decomposition is not unique (Maudlin 2002, p. 95). My analysis, by contrast, decomposes Bell's local causality into an assumption about causal independencies and an assumption about the existence of a screener-off for causally independent events. If a theory is local (see Definition 5) and causal (see Definition 4), the theory is locally causal (see Equation 3). The locality or the causality of the theory alone, however, does not imply its local causality.

As such, my analysis also applies to the sub-conditions that the familiar decomposition identifies. The assumption of *causal* independence of the measurement outcomes alone does not imply "outcome independence", but it does so together with the assumption that the theory under consideration is a causal one. Similarly, the assumption of *causal* independence of the measurement out-

[2] Other current names are "factorizability" (Fine 1980) for "local causality", "completeness" and "locality" (Jarrett 1984), or "causality" and "hidden locality" (van Fraassen 1982) for "outcome independence" and "parameter independence".

comes from the distant measurement settings alone does not imply "parameter independence", but it does so together with the assumption that the theory under consideration is a causal one. Thus, in particular, both Jarrett's "completeness" and Jarrett's "locality" condition may fail either because the theories are causally incomplete or because the theories are not local.

Butterfield (1992, pp. 73–76) provided a similar analysis long ago (see also Butterfield 1989). His "Past Prescribes Stochastic Independence" corresponds to my condition that theories be causal. His "prohibition of superluminal causation" (not his, and Jarrett's, "locality"!) corresponds to my condition of Locality. My goal here is to bring this kind of analysis to bear on the criticism, mentioned in the Introduction, which does not acknowledge it sufficiently.

6 The Role of the EPR Argument

I now come back to the main issue of the present paper as outlined in the Introduction (Section 1). I would like to hope that the present analysis helps clear up enduring misunderstandings concerning the principal options one has in the face of the empirical violation of Bell's Inequality. Granting commonly accepted auxiliary assumptions, there remain "two camps" (Norsen 2006a, p. 633) which maintain apparently contradictory positions. According to the "first camp" the empirical violation of Bell's Inequality shows that there are non-local interactions in the world.

> So experiments verifying the violation of Bell's Inequality would doom locality *tout court.* (Maudlin 2002, p. 20)

According to the "second camp" there is a second option. One can hold fast to locality but deny that it is possible to have a "hidden variables" theory of the quantum correlations in question:

> To those for whom nonlocality is anathema, Bell's theorem finally spells the death of the hidden-variables program. (Mermin 1993, p. 814)

A variant of the second camp's option is to invoke "realism" as one of the principal assumptions of Bell's theorem, besides locality. Accordingly, the empirical violation of Bell's Inequality would not force one to give up locality. One should be able to maintain locality by giving up realism:

> The experimental violation of mathematical relations known as Bell's inequalities sounded the death-knell of Einstein's idea of 'local realism' in quantum mechanics. But which concept, locality or realism, is the problem? (Aspect 2007, p. 866)

I will not enter here into a general discussion about what exactly "realism" should mean. I take it that, for the present purposes, the option of giving up "realism" and the option of giving up "the hidden-variables program" are the same. This seems right to me especially because the criticism by the first camp of the tenability of the second camp's option is virtually the same for both variants. The first camp admonishes, first and foremost, that

> [t]hose in the second camp either failed to understand the role of the EPR argument [Einstein, Podolsky, and Rosen 1935] as part-one [*sic*] of Bell's two-part argument for non-locality, or have (following Bohr and his supporters) rejected the EPR argument as invalid. (Norsen 2006a, p. 634; see also Norsen 2007; and Albert and Galchen 2009)

I think neither is the case. It seems to me that the second camp's option is even better in line with the EPR argument than the first camp's exclusive focus on locality.

6.1 The Derivation of Deterministic Hidden Variables

The logic of the original EPR argument is notoriously convoluted if not obscure.[3] I do, therefore, not venture here into a thorough and detailed exegesis of EPR's paper. Rather, I will use one of Bell's summaries of EPR's argument. I aim to show that the EPR argument does not remove the second camp's option of rejecting hidden variables or realism while maintaining locality.[4]

The crucial issue is whether an argument in the spirit of EPR's can derive the existence of hidden variables ("realism") from locality, i.e.

$$(\text{Locality} \models \text{Hidden Variables})? \tag{4}$$

If the answer is yes, then the first camp is right in pointing out that the existence of hidden variables cannot be denied without, at the same time, denying the failure of locality.

Bell's summary[5] begins by stating that the outcomes are predictable because they are perfectly correlated: "The EPRB correlations are such that the result of the experiment on one side immediately foretells that on the other, whenever the analyzers happen to be parallel". The next clause states the requirement of locality: "If we do not accept the intervention on one side as a causal influence on the other, [...]" In the associated main clause, Bell concludes that the outcomes have to be determined by some other factors than the distant settings or outcomes, i.e. "[...] that the results on both sides are determined in advance anyway, independently of the intervention on the other side, by signals from the source and by the local magnet setting."

However, he hedges the conclusion by adding the phrase "we seem obliged to admit".[6] This is indicative of his making an implicit assumption at this point. It is the assumption that if the outcomes are perfectly correlated but do not cause each other, there must be some further factors that would determine the outcomes.

[3] For an illuminating discussion and a proposal of how to untangle the argument, see (Fine 1986, Chapter 3).

[4] Wüthrich (2013) makes a similar point, but relies on the particular derivation of Bell's Inequality by Graßhoff, Portmann, and Wüthrich (2005).

[5] Bell 1981, p. 149; cf. Goldstein 2013, Section 2. Bell also gave another summary of the EPR argument, which, however, is unnecessarily long for the present purposes (Bell 1964, pp. 14–15).

[6] The complete passage reads: "The EPRB correlations are such that the result of the experiment on one side immediately foretells that on the other, whenever the analyzers happen to be parallel. If we do not accept the intervention on one side as a causal influence on the other, we seem obliged to admit that the results on both sides are determined in advance anyway, independently of the intervention on the other side, by signals from the source and by the local magnet setting." (Bell 1981, p. 149)

This is a special case of my Assumption 4: The outcomes are predictable because they are perfectly correlated. By locality, none of the distant outcomes or settings is (part of) the cause of the nearby outcomes, i.e. the distant events are causally independent. We thus have a correlation between causally independent events. Assumption 4 requires the introduction of at least one further factor because there must be, according to this assumption, a screener-off for the correlated events. Yet, a screener-off for a perfect correlation is a deterministic cause — or at least a sufficient condition — for the correlated events.[7]

Also, an assumption of this kind is, in fact, explicit in the original EPR argument in the form of their "criterion of reality":

> If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity. (Einstein, Podolsky, and Rosen 1935, p. 777)

"Without in any way disturbing a system" expresses an assumption of locality. That "we can predict with certainty" is due to the perfect correlations. In such a situation, EPR's criterion of reality requires the existence of "an element of physical reality" that has not yet been taken in to account.

This requirement is almost exactly equivalent to my Assumption 4. They are both dealing with a situation in which we have a correlation between events, the "measurement outcomes" or the system's displaying a certain "value of a physical quantity", which, for good reasons, should be causally independent. Both assumptions state that this cannot be the case. Instead, there must be a further factor, a "screener-off" or an "an element of physical reality", that explains the correlation.

Thus the second camp's position can be characterized by rejecting Assumption 4 in the form of EPR's criterion of reality or in the form of the requirement for screening-off hidden variables. As with Assumption 4, if you do not accept EPR's "realism" or the "hidden variables program", you have no incentive to look for causes for every outcome or correlation. So, even if you cannot find local causes, you are not forced to accept non-local ones. Such a non-realistic position does, therefore, by no means imply that EPR's argument is not valid. The "antirealists" just reject one of the premises, namely EPR's criterion of reality. They are, therefore, not forced to accept the conclusion of the argument (that there are deterministic hidden variables, i.e. a special case of local causality) even if they accept, as I think they do, that the EPR argument is valid.

I think that John Bell himself was aware of such an "antirealistic" option. He rejected it, but not because he thought it were ruled out by EPR's argument. Rather, he rejected it because it may require a problematic distinction between a macroscopic and a microscopic domain, and because it leads to a, for him, "unscientific attitude" (see Bell 1981, p. 152). At any rate, when Bell discusses

[7] See, e.g., Suppes and Zanotti (1976); van Fraassen (1982); Graßhoff, Portmann, and Wüthrich (2005). As Bell rightly emphasizes, determinism is not an assumption of the derivation of Bell's inequality (Bell 1981, p. 143). It follows from the other assumptions in case of perfect correlations.

possible consequences of the empirical violation of the "Clauser–Holt–Horne–Shimony Inequality", one of the options he lists is the following.

> Fourthly and finally, it may be that Bohr's intuition was right — in that there is no reality below some 'classical' 'macroscopic' level. Then fundamental physical theory would remain fundamentally vague, until concepts like 'macroscopic' could be made sharper than they are today. (Bell 1981, p. 155)

The possibility he considers here, I take it, is that of a lack of microscopic causes for the macroscopically observed phenomena. Note that the sketched position is not a wholesale rejection of physical reality. The reality of the macroscopically observed phenomena remains uncontested. But not for all of them, and not even for all correlations among them, there is an unobserved cause which brings them about, according to this option. The conveyed point of view holds that there is no deeper-lying reality the workings of which would explain the macroscopic observations.

7 Summary

I have shown that Bell's local causality follows from locality and from the requirement that theories provide screener-offs for correlated, but causally independent, events (causality). As long as no other justification of local causality is available its failure need not be attributed to the failure of locality — it may equally well be due to a failure of causality. Similarly, if EPR's criterion of reality is rejected there is no need to accept non-locality. This is so because the EPR argument derives a special case of local causality (deterministic hidden variables) not from locality alone but together with the criterion of reality. The failure of local causality, as exhibited by Bell's theorem, may either teach us that the world is non-local *or* that it is causally incomplete.

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