Lewis' Causation and Quantum Correlations[1]

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Abstract

If we apply Lewis' theory of causation to the quantum correlations which become manifest in the Bell experiments, this theory tells us that these correlations are a case of causation. However, there are strong physical reasons (and concrete suggestions) not to treat these correlations in terms of a physical interaction. The aim of this paper is to assess this conflict. My conclusion is: one can either divorce Lewis' causation from physical interaction, or one can take the quantum case as an argument for an amendment of Lewis' theory of causation.

1. Introduction

The quantum correlations which are confirmed by the Bell experiments are a puzzle not only for the interpretation of quantum physics, but for any theory of causation. The Bell experiments show a counterfactual dependence between space-like separated measurement outcomes. On the one hand, they thus satisfy Lewis' criterion for causation. On the other hand, there is nothing in the formalism of quantum theory which suggests that the two wings of a Bell experiment are connected by some sort of a physical interaction. Furthermore, admitting any such interaction would arguably bring us into conflict with the ontology of special and general relativity.

This paper is about the tension between a theory of causation that is based on *a priori*, philosophical considerations such as Lewis' theory and the results of empirical science, notably quantum physics. I first recall the Bell experiments (section 2) and apply Lewis' criterion for causation to them (section 3). I then sketch an interpretation of quantum physics according to which there is no physical interaction between the two wings of a Bell experiment (section 4) [176]. Finally, I suggest two different lessons that one might draw from this case study (section 5).

2. Bell's theorem and the Bell experiments

Einstein, Podolsky and Rosen (1935) were the first to highlight the fact that quantum theory predicts correlations between space-like separated measurement outcomes. Paying tribute to this paper, these correlations are known as *Einstein–Podolsky–Rosen correlations*. Quantum theory predicts such correlations for any case of measurements on two or more systems whose states are in superposition with each other, no matter what the spatio-temporal interval between these measurements is. Consider the simplest case of such correlations (Bohm (1951), pp. 611–622): Spin is a physical property which is treated only in quantum theory.

1 My reflection on this subject was triggered by a paper of Niko Strobach at a research colloquium of the Swiss Federal Institute of Technology in July 1995. For discussion of these matters, I am furthermore grateful to Jeremy Butterfield and the participants of the Konstanz workshop on causation, in particular Hugh Mellor.

There are systems of spin 1/2 such as electrons and neutrons. In this case, the spin in any of the three orthogonal spatial directions can take only two definite numerical values. Call these values “spin up” and “spin down”. Imagine that two systems of spin 1/2 are emitted together from a source. After the emission, their interaction dies down, because they fly apart in opposite directions. Nonetheless, however far apart in space these two systems are removed, the spin state of the whole, i.e., the joint spin state of these two systems taken together, is a superposition of the first system having spin up and the second system having spin down with the first system having spin down and the second system having spin up in any direction. This state is known as the *singlet state*:

(1) $$\Psi = 1/\sqrt{2}\left(\Psi_1^+ \otimes \Psi_2^- - \Psi_1^- \otimes \Psi_2^+\right)$$

In this formula, Ψ stands for the joint spin state of the whole, i.e., the two systems taken together; Ψ_1 and Ψ_2 stand for the spin states of the two parts; + signifies spin up, – spin down.

Following Schrödinger (1935), p. 555, cases such as the singlet state are known as *entanglement*. If there is entanglement, the states of two or more systems are entangled in such a way that only the whole, i.e., these systems taken together, is in a *pure state*. In the example of the singlet state, only the whole has a definite numerical value of a spin observable, namely the total spin; but neither of the two systems is in a state in which it has a definite numerical value of a local spin observable. A *local observable* is an observable that relates only to one of the two systems. Spin in *z*-direction of the one [177] system and spin in *z*-direction of the other system are examples of local observables.

Assume that we measure the spin of one of two such systems in an arbitrary direction. Before a measurement occurs, the outcome “spin up” and the outcome “spin down” are equally probable. According to the orthodox interpretation of quantum theory which goes back to von Neumann (1932), chapter VI.1, a measurement of one of the two systems dissolves the entanglement: it induces a state reduction of the singlet state (1) to one of the product states

(2) $$\Psi = \Psi_1^+ \otimes \Psi_2^-$$

or (3) $$\Psi = \Psi_1^- \otimes \Psi_2^+.$$

These are product states, because the joint state of the two systems is simply described by the tensor product of the states of the two systems. These formulas show: given the result of the measurement of the spin of the one system, we can predict with certainty (probability one) the result of a measurement of the spin of the other system in the same direction. The probabilities are no longer 0.5 for spin up and 0.5 for spin down, but either spin up or spin down has probability one.

Consequently, the outcomes of a measurement of the spin in the same direction on both systems are maximally correlated: if the one outcome is spin up, the other outcome is spin down. Measuring the spin in the same direction on both systems means that the same local observable is measured on both systems: there is no difference in the two parameters that are measured. If the parameters differ by an angle, there is no longer a maximal correlation between the outcomes of both measurements, but still a probabilistic one. If we know the outcome of a measurement of the one system, we can no longer predict the outcome of a measurement of the other system with certainty. But given the outcome of a measurement of the one system, the probability for the outcome spin up and the outcome spin down of the other system is no longer 0.5 each either. One outcome is more probable than the other one. Such a probability can be calculated for each difference of the angles of the parameters that are measured on both systems. Only if that difference is orthogonal so that, for example, spin z on the one and spin x on the other system are measured, there are no correlations between the outcomes any more.

The famous theorem of Bell (1964) imposes an upper limit on such correlations between the measurement outcomes. Quantum theory, by contrast, predicts higher correlations than Bell's theorem permits. In the case of the [178] singlet state, the maximal correlations between the two measurement outcomes do not violate Bell's theorem. This is due to mathematical peculiarities of a two-dimensional Hilbert space, in which the singlet state is represented. However, for certain differences between the parameters that are measured on two systems in the singlet state, quantum theory predicts probability correlations between the outcomes of both measurements which are higher than Bell's theorem permits. Furthermore, if we consider three systems of spin 1/2 whose spin states are entangled, there are maximal correlations between the spin measurement outcomes which violate Bell's theorem (Greenberger et al. (1990)).

This result can be generalized: Every case of entanglement of the states of two or more systems leads to higher correlations between the outcomes of measurements of some local observables on these systems than Bell's theorem allows (Gisin (1991), Popescu and Rohrlich (1992)). Moreover, cases of entanglement are ubiquitous among quantum systems according to quantum theory: whenever we consider a whole which is composed of two or more quantum systems of whatever kinds, quantum theory tells us that, apart from very exceptional cases, the states of these systems are entangled. Nonetheless, in order to confirm correlations that are due to entanglement by experiment, great skill is required.

Bell's theorem is based on *factorizability*. I adopt the formula of Shimony (1993), p. 147, with slight modifications:

$$p_{\lambda}^{12}\,(x_a, x_b \mid a, b) = p_{\lambda}^{1}\,(x_a \mid a) \cdot p_{\lambda}^{2}\,(x_b \mid b) \tag{4}$$

In this formula, p is probability, and λ denotes the state of the whole system, i.e., the singlet state in the case under consideration; 1 and 2 refer to the two parts, i.e., the two systems of spin 1/2; x_a and x_b stand for the outcomes of a measurement of part 1 and part 2 respectively ($x_a = \pm 1$, $x_b = \pm 1$); a denotes the parameter which is measured on part 1, and b denotes the parameter which is measured on part 2. Factorizability means: given the state of the whole system, the probability for the outcome of a measurement of part 1 depends only on the parameter which is measured on part 1; and the probability for the outcome of a measurement of part 2 depends only on the parameter which is measured on part 2. The probability for both outcomes, given both parameters, is the product of these probabilities.

Jarrett (1984) showed that factorizability, to which he refers as strong locality, can be analyzed into two conditions: it is the conjunction of what he calls "locality" and "completeness". Shimony (1993), pp. 146–147, introduced the terms "parameter independence" and "outcome independence" for Jarrett's [179] locality and Jarrett's completeness respectively. Shimony's terminology is much more appropriate: it has no misleading connotations for the interpretation of quantum theory. I adopt Shimony's formulae for *parameter independence* with a slight simplification:

(5) $$p_\lambda^1 (x_a \mid a, b) = p_\lambda^1 (x_a \mid a)$$

(6) $$p_\lambda^2 (x_b \mid a, b) = p_\lambda^2 (x_b \mid b)$$

These formulae say: in the state λ of the whole system, the probability for the outcome of a measurement of part 1 is independent of the parameter that is measured on part 2 (and *vice versa*). *Outcome independence* states the following (again, I adopt Shimony's formulae):

(7) $$p_\lambda^1 (x_a \mid a, b) = p_\lambda^1 (x_a \mid a, b, x_b)$$

(8) $$p_\lambda^2 (x_b \mid a, b) = p_\lambda^2 (x_b \mid a, b, x_a)$$

These formulae say: in the state λ of the whole system and given the parameters that are measured on both parts, the outcome of a measurement of part 1 is independent of the outcome of a measurement of part 2. If the outcome of a measurement of part 2 is given, the probability for the outcome of a measurement of part 1 is not changed (and *vice versa*).

The work of Jarrett shows that a violation of factorizability and hence a violation of Bell's theorem can in principle be accounted for in two different ways: by a violation of parameter independence or by a violation of outcome independence. Quantum theory conforms to parameter independence: if the parameter that is to be measured on the one system is given, the probabilities for the outcome of a measurement of the other system are not changed. However, quantum theory violates outcome independence: if the outcome of a measurement of the one system and the parameter measured are given, the probabilities for the outcome of a measurement of the other system are changed. In the spin case under consideration, the probability is no longer 0.5 for spin up and 0.5 for spin down, but one result is more probable than the other one (unless the spin is measured on both systems in orthogonal directions). In the following, I therefore speak in terms of quantum theory implying *outcome dependence*.

The outcome dependence which quantum theory implies does not make superluminal signalling possible; for we cannot manipulate the outcome: in [180] the mentioned example, the result "spin up" and the result "spin down" are equally probable. Moreover, for a local observer, i.e., an observer who does not know which measurements are carried out at a distance, both these results are always equally probable. It is only *post festum* by comparing the outcomes of a sequence of measurements on the one side with the outcomes of the corresponding sequence of measurements on the other side that the correlations can be discovered.

Subsequent to Bell's theorem, a number of experiments have been carried out which confirm the predictions of quantum theory. All these experiments are referred to as *Bell experiments*. The most significant type of these experiments goes back to the experiment of Aspect, Dalibard and Roger (1982). This experiment, like most other experiments, consists in correlation measurements of the polarization of two photons which are emitted together from a source and then fly apart in opposite directions. Although photons are not systems of spin 1/2, the polarization state of such pairs of photons is the singlet state. Aspect's experiment is very significant, because two automatic switches adjust the parameter which is to be measured on each photon only after the photons have been emitted from the source; the switching event and the detection event on the one side of the source are separated by a space-like interval from the switching event and the detection event on the other side of the source. This experiment yields a violation of Bell's theorem. It conforms to the predictions of quantum theory. In recent years more experiments have been carried out which show Einstein–Podolsky–Rosen correlations between the outcomes of space-like separated measurements (See, in particular, the recent experiment by Tittel et al. (1998) and the experiment planned by Weihs, Weinfurter and Zeilinger (1997)).

The correlations between the measurement outcomes in the Bell experiments cannot be dismissed as coincidence. These correlations have been confirmed in a lot of experiments. In each of these experiments, measurements have been carried out on a great number of pairs of photons. To dismiss these correlations as coincidence would therefore amount to a dismissal of any experimental evidence. However, as in every experiment, loopholes can be found in the Bell experiments too. The following three objections can be raised:

1) Almost all the experiments carried out hitherto are experiments with photons (but consider the experiment recently reported by Hagley et al. (1997)). Photons have zero rest mass. This implies that, for the photons, no proper time passes between their emission from the source and the measurement.
2) In the experiment of Aspect, there is no question of a signal which transmits the parameter that is to be measured on the one side to the other [181] side of the experimental arrangement in one measurement (unless one assumes superluminal signals). However, the switches do not adjust randomly the parameter that is to be measured (compare the critical remark in Aspect, Dalibard and Roger (1982), p. 1807; Aspect and Grangier (1985), p. 69).
3) In all experiments carried out up to now, the detectors are inefficient: a considerable number of photons are not detected.

The third objection is more important than the other ones. Building on the inefficiency of the detectors, it is possible to construct models of hidden variables which account for the results of the Bell experiments that are performed hitherto without assuming a violation of Bell's theorem (see already Fine (1982), and, subsequent to the experiment of Aspect, see Marshall, Santos and Selleri (1985); Pascazio (1988); Uchiyama (1995)). However, one can retort that it would amount to conspiracy if hidden variables of each of the systems influenced the detection of each of the photons just in such a way that the result is a confirmation of the predictions of quantum theory (compare Mermin (1986), p. 422, and Maudlin (1994), pp. 175–186). Despite the mentioned loopholes, by far the most physicists and philosophers of science acknowledge that a violation of Bell's theorem has been shown by experiment.

3. Lewis' counterfactual analysis of causation

The violation of Bell's theorem by experiment manifests some sort of non-locality: two space-like separated measurement outcomes are correlated without the preparation event, i.e., the emission of the two systems from the source, acting as a common cause that screens the one measurement outcome off from the other measurement outcome (as to the philosophical consequences of Bell's theorem, see Redhead (1987) as well as the papers in Cushing and McMullin (1989)). Does this mean that there is superluminal causation between the two wings of a Bell experiment?

Butterfield (1992) and Maudlin (1994), in particular chapter 5, argue that if we endorse a counterfactual criterion of causal dependence such as the proposal of Lewis (1986), chapter 21, in particular pp. 175–179, we have to conclude that there is causal dependence and hence causation between two space-like separated events. If we focus on the changes in the states of the two measuring instruments which register the outcomes, we clearly have two distinct events, and these events are correlated. Maudlin speaks of a superluminal causal connection between two space-like separated measuring events in a Bell experiment and of a superluminal transmission of information. [182] However, he emphasizes that a violation of Bell's theorem implies neither a superluminal matter or energy transport nor the possibility of superluminal signalling (see in particular the summary in chapter 9).

Given a measurement outcome x_a in one wing of such an experiment, the probability for a specific outcome x_b in the other wing is raised. If there had not been the outcome x_a in the one wing, the outcome x_b in the other wing would have been less probable. Causation in Lewis' sense of counterfactual dependence is a consequence of outcome dependence in quantum theory, although Lewis does not formulate his criterion of counterfactual dependence in terms of conditional probabilities. (As regards this and other differences between Lewis' criterion and outcome dependence and an argument for the irrelevance of these differences, see Butterfield (1992)). Hence, if we take Lewis' theory of causation as it stands, then we have to conclude the following: if this theory is applied to the Bell experiments, it tells us that there is superluminal causation between the changes in the states of the two measuring instruments which register the outcomes.

4. An interpretation of quantum physics

In this section, I present an interpretation of quantum theory which suggests that there is no causation in any physical sense between the two measuring events in a Bell experiment. I regard an interpretation along the lines which I shall sketch as a plausible option in the philosophy of quantum physics. However, for this paper I need only to claim that the option which I shall present is not obviously wrong-headed.

Bell's theorem is motivated by Einstein's objections to quantum theory. The background of Bell's assumption of factorizability are two metaphysical principles which are at the centre of Einstein's world-view, namely *separability* and *local action*. (The clearest statement of these principles is Einstein (1948), pp. 321–322). Starting from Einstein's work, Howard (1989) formulates separability as the claim that (1) spatially separated systems possess their own, distinct physical state each and that (2) the joint state of two or more spatially separated systems is wholly determined by their separate states (pp. 225–227). Taking up Howard's work, I propose the following characterization of separability:

Principle of separability

> Physical systems have a state each in the sense that (1) this state completely determines the state-dependent, local properties [183] of the system and (2) the joint state of two or more systems supervenes on the states which each of these systems has.

In this characterization of separability, I have left out the condition of spatial separation. There are cases of entanglement where there is no question of a spatial separation. For instance, the joint spin state of the two electrons of a helium atom in the groundstate is the singlet state too, and these electrons are not spatially separated. Furthermore, in quantum computation, one considers the entanglement of the states of many systems which are usually not localized in such a way that they are separated in space. It is reasonable to treat such cases as cases of quantum non-separability too. Therefore, it is sensible to explain separability without imposing the condition that this principle applies only to systems which are separated in space.

The second principle which Einstein presupposes is a locality requirement. I suggest speaking of the principle of local action. Local action imposes a restriction on the way in which the states of physical systems can change by interaction. It thereby presupposes separability: the systems in question have states each which completely determine their local properties. The idea is that interactions propagate contiguously from point to neighbouring point with a finite velocity. Having the discussion on whether or not quantum theory is compatible with special relativity in mind, I propose to characterize local action in relativistic terms:

Principle of local action

> Every interaction (force) propagates contiguously with a finite velocity, i.e. – in relativistic terms – a velocity that is not higher than the velocity of light in vacuum.

All the known physical forces satisfy local action. In the discussion on Bell’s theorem, the conjunction of separability and local action is often referred to as locality without further qualification.

There is nothing in quantum theory which violates local action. But quantum theory contradicts separability, as the cases of entanglement of the states of two or more quantum systems show. Consider the example of the singlet state. We can give a description of each of the two systems which contains all the information that is available about the one system considered independently of the other system. We can even regard this description as a sort of state description. We then have to work with the notion of a so-called mixed state in the sense of what is known as an improper mixture (d’Espagnat (1971), chapter 6.3). But the point is: this description does not completely determine the state-dependent properties of the system. It ignores the correlations between the possible values of the local spin observables which can be acquired [184] in measurement. Thus, this description ignores the disposition of each system to acquire a certain value of spin in a given direction relative to the value of spin in a given direction which the other system acquires. Consequently, in the case of entanglement, the description which relates to each of the systems in question does not completely specify the local observables of this system. Furthermore, this description does not specify the state of the whole, i.e., the joint state of these systems taken together. It is possible that two systems can be described in terms of the same mixed states as in the mentioned case without being in the singlet state. Hence, quantum theory violates both the requirements of separability.

If we accept that a measurement results in a definite numerical value of the measured observable as its outcome, we have to concede that we do not have an overall convincing account of the dynamics that lead to such a definite outcome at our disposal. The most elaborate suggestion goes back to Ghiradi, Rimini and Weber (1986). Nonetheless, in this paper, I am concerned only with the additional problems that the correlations between space-like separated measurement outcomes raise.

The most prominent strategy for explaining the correlations between the measurement outcomes without coming into conflict with local action consists in the following idea: since the two systems do not have a separate spin state each, a measurement interaction with the one system directly changes the state of the whole. Qua change of the state of the whole, this local interaction is relevant to the probabilities for the outcome of a measurement on the other system. But this change of the state of the whole is not a local change in the other system. That is to say: it is not a change of intrinsic properties of the other system. We have to give up the assumption that the probability distribution of spin in any direction is an intrinsic property of a system. A local change in the other system occurs only in a local interaction of that system with a measurement device. Instead of countenancing a superluminal interaction, this idea suggests that the world is more tightly interwoven than just by spatio–temporal relations between physical entities that are localized at space–time points or arbitrarily small space–time regions. (This idea hence contradicts Lewis' conception of Humean supervenience; see Lewis (1986), pp. IX–XI).

One proposal along these lines is put forward by Healey. This proposal is in the framework of the so-called modal interpretation. It yields definite numerical values as measurement outcomes without working with the assumption that a state-reduction of the singlet state to a product state occurs in measurement. Healey, however, envisages the possibility that his proposal is a causal explanation of the Einstein–Podolsky–Rosen correlations (see Healey (1989), pp. 129–136, 148–173, and (1994), pp. 359–373). Another proposal is the [185] one of Shimony (1993), pp. 151–154: he acknowledges state reductions and conceives measurement as an actualization of potential properties of quantum systems; but he maintains that in a Bell experiment a measurement of the spin of the one system is not sufficient for an actualization of a definite numerical value of the spin in the same direction of the other system too, even if one such value of the other system has probability one. (See also Rohrlich (1987), p. 175, and furthermore Hawthrone and Silberstein (1995) who employ the notion of holistic connections between events (pp. 115–117)).

Even if we acknowledge that there is a state reduction in measurement, according to the idea under consideration, there is no question of a relation of physical interaction between, say, the one system acquiring a state in which it has spin up and the other system acquiring a state in which it has spin down. For these are not changes in separate states of the two systems, but a change from a non-separable state of the whole to separate states of the parts. As remarked above, the principle of local action presupposes separability: local action is a constraint on the way in which changes in the separate states of physical systems are carried out. Applied to this case, that is to say: the question of a superluminal physical interaction on the quantum level can arise only if we presuppose, contra quantum theory, that the two systems have a separate spin state each prior to measurement.

Furthermore, if the measurements in the two wings of a Bell experiment are separated by a space-like interval, there is no fact of the matter as to which of these measurements occurs first. To accommodate this point within an account that acknowledges state reductions, there is an elaborate suggestion by Fleming (1996) according to which the local observables of spin of the photons in the Bell experiments are properties which are relative to a reference frame – in the sense that they are relative to a space-like hyperplane. (For a non-technical description and critical evaluation of this view, see Maudlin (1994) pp. 204–212, 233–234; (1996), pp. 298–303. See furthermore the criticism of Dorato (1996), pp. 593–595).

Again, this suggestion highlights the following point: if we are to employ the notion of non-separability in order to avoid a conflict with local action as well as special relativity, we cannot conceive those properties that are affected by quantum entanglement as intrinsic properties, but have to conceive them as relational ones. I do not have the space here to enter into an examination of the mentioned proposals. The only point I need is that, based on quantum non-separability, there is a strategy available for explaining the correlations between the outcomes of a Bell experiments which does not have to assume superluminal interaction on the quantum level.

[186] *5. A brief evaluation*

This confrontation of Lewis' causation with an option in the interpretation of quantum theory shows the following: we have to envisage that not all cases of causation à la Lewis are realized as some sort of a physical interaction. There are two main options to accommodate this result:

1. One can divorce Lewis' causation from physical interaction. Lewis' counterfactual criterion tells us when there is causation, but it leaves entirely open what the means of causation is. In this perspective, if one acknowledges definite measurement outcomes, quantum entanglement or non-separability simply is a means of causation that is distinct from physical interactions (forces). This is not to say that quantum entanglement is itself a causal relation. But if a measurement interaction occurs, quantum entanglement can act as a means of causation. Berkovitz (1998a), pp. 203–219, and (1998b) argues for a position along these lines. However, one can object to this strategy that by divorcing causation from a realization in terms of a physical interaction, one divorces this concept from widespread pre-philosophical intuitions about what causation is.
2. One can take the correlations between the measurement outcomes in a Bell experiment as a case that calls for an amendment of a theory of causation such as the one of Lewis:

a) One possibility is to include further physical conditions for a relation of causal dependence which can be formulated within a theory such as the one of Lewis. This is the strategy of, for instance, Redhead. As a necessary condition for a causal relation, he introduces a condition of robustness against differences in the way in which the cause comes into existence. On the basis of this condition, Redhead maintains that there is no causal link between the two wings in a Bell experiment (see, in particular, Redhead (1987), pp. 102–106; (1989), pp. 148–151; (1992); for a criticism of Redhead's proposal, see in particular Cartwright and Jones (1991), Healey (1992), and Maudlin (1994), pp. 150–154).

b) One can go beyond the framework of a theory such as the one of Lewis and demand outright that physical interaction is a necessary condition for causation over and above counterfactual dependence. However, if one introduces physical interaction into the definition of causation, then one can maintain that physical interaction is sufficient on its own to do the job of accounting for causation. Thus, for instance, Dowe (1992), pp. 210–215, and (1995) as well as Salmon (1998), essay 16, advance a theory of causation according to which a causal process posseses or transmits a conserved [187] quantity, and an interaction is an exchange of a conserved quantity. This theory is a sophisticated regularity account of causation.

Whatever stance one takes on this issue, this case study highlights Quine's thesis in “Two Dogmas of Empiricism” (in Quine (1980), essay 2) that science and metaphysics are interwoven: which stance one takes on this issue depends on which way one regards as most plausible when it comes to outbalancing new scientific evidence with metaphysical considerations such as those ones that speak in favour of a counterfactual account of causation.

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