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LEARNING FROM THE BELL-INEQUALITIES: CAUSALITY, LOCALITY AND REALISM[1]

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1. *Introduction*

In Bohm's version of the Einstein-Podolsky-Rosen (EPR) paradox, a quantum system prepared in a total spin zero or singlet state falls apart in two spin ½-particles which go in opposite directions. If the two particles are sufficiently spatially separated, the value of the spin is measured on a separate particle. For every direction or 'setting' of the measuring instrument, one of the following results will be the case: *the spin is up* or *the spin is down*. Let A ($\sim A$) and B ($\sim B$) respectively be the left and right measuring results where the spin is up (down). Let Ψ represent the spin singlet state of the two well-separated particles (e.g. electrons). Finally, let a_m and b_n denote possible states of respectively the left and the right measuring instrument, that is the a_m's and b_n's are two sets of different possible measuring directions.

Quantum mechanics predicts that, if the value of the spin is measured in the *same direction*, there will be a perfect anticorrelation between A and B for each member of the ensemble. The measuring results A and B will each have a probability of 0.5. This means that with spin measurements in the same direction:

For all Ψ, a_m and b_m
$Pr(B/\Psi.a_m.b_m.A) = 0$

[1] I should like to thank D. Batens, E. Weber, J.P. Van Bendegem, P. Van Loocke and W. De Baere for their generous comments on an earlier version of this paper.

$$Pr(B/\Psi.a_m.b_m.\sim A) = 1$$
$$Pr(A) = Pr(B) = 0.5.$$

The dot (.) means logical 'conjunction'.

If the value of the spin is *not measured in the same direction*, quantum mechanics makes the following predictions for the correlation between A ($\sim A$) and B ($\sim B$):

$$Pr(A.B) = \tfrac{1}{2} \sin^2 \tfrac{1}{2}\alpha_{ab},\ Pr(A.B) = \tfrac{1}{2} \cos^2 \tfrac{1}{2}\alpha_{ab}$$
$$Pr(A.B) = \tfrac{1}{2} \cos^2 \tfrac{1}{2}\alpha_{ab},\ Pr(A.B) = \tfrac{1}{2} \sin^2 \tfrac{1}{2}\alpha_{ab}$$

where α_{ab} is the angle between the different directions a and b in which the spin is measured. These correlations between results of distant spin-measurements show a sharp break with the philosophical ideas of classical physics. According to a realistic account of these correlations, the spin components of the particles exist in each direction before a measurement is made. This means that whether or not we measure in a given direction, the particle has a definite spin-value in that direction. Quantum mechanics however says that the spin components of different directions are incompatible. No state in quantum mechanics can express the well-defined spin-values of a particle along different directions. That is why Einstein, Podolsky and Rosen criticized the ordinary understanding of quantum mechanics, namely the Copenhagen interpretation and accused the theory of incompleteness (Einstein, Podolsky and Rosen 1935).

The EPR-debate reflects the notorious realism problem in quantum mechanics: quantum systems do not have all the classic dynamic properties they should at any one time (cf. a familiar case is the incompatibility between position and momentum). The first aim of this paper is to clarify the meaning of the famous inequalities of J.S. Bell for this kind of realism. In section 3 I will argue that the Bell-inequalities and their subsequent experimental tests relate directly to the realism issue: they show that Einstein, Podolsky and Rosen were wrong. I regard the Bell-experiments as refuting quantum realism, which I summarize as follows:

(QR) There is a theory that provides scientific knowledge about the existence and the behaviour of the unobservable physical entities at submolecular level (i.e. quantum objects have all their dynamic properties at any one time).

Remark that (QR) is entailed by scientific realism in general, for which I give the following definition:

(SR) There is a theory that provides scientific knowledge about the underlying unobservable structure of the world, more precisely about the entities that exist and about their behaviour.

I will show that we have strong experimental evidence that quantum theory is incompatible with (QR), so that (SR) cannot be generally valid.

Another issue that still troubles many philosophers of science, is the so-called causal 'anomaly' of the Einstein-Podolsky-Rosen paradox. This causal problem consists in the fact that

(i) the Bell-inequalities are commonly taken to show that there cannot be a common cause of the EPR-correlations.

(ii) there is a spacelike separation between the two detection-events; thus a direct causal link between these events is unacceptable on relativistic grounds.

This would mean that the only two possibilities for a causal explanation of EPR-correlations are ruled out. The justification for (i) is Reichenbach's criterion for common causes. Section 4 will show that this criterion is not appropriate for 'hunting' common quantum causes. Though (QR) fails, I will show that the Bell-inequality does not exclude a local causal explanation of EPR-correlations. But first, in section 2, I give as preparation an explanation of the Bell-inequalities.

2. *The Bell-inequalities.*

2.1 The debate between the advocates of the Copenhagen interpretation and its opponents reached its heyday in 1964. Since then, J.S. Bell is supposed to have shown that no local-hidden-variables theory is possible in quantum mechanics (Bell 1964). For this he construed inequalities, the so-called Bell-inequalities, that say how the spins of the EPR-experiment must be correlated if they are governed by two sets of hidden variables, each set applying to each particle separately. Hence it is said that predictions of local-hidden-variables theories will always satisfy these inequalities. Quantum physics, on the contrary, predicts that the Bell-inequalities in certain experimental circumstances will be violated.

We have to notice however, that the term 'local' is used here in a peculiar sense. In recent Bell-literature it is proved that the Bell-inequalities require a statistical condition that is not equivalent with the local constraints of relativity theory. After I have given the argument, I will try to answer the question what we will have to give up.

2.2 Bell's point of departure is Bohm's version of the EPR-paradox. For the n-th pair of particles emitted from the source, A_n is the value of the spin of the particle of which the spin is measured in direction a; A'_n is the value of the spin of the particle of which the spin is measured in direction a'. Analogously for B_n and B'_n. For the values of the spin, respectively corresponding to a value $\hbar/2$ or $-\hbar/2$ of the spin-component in the well-determined directions we always have $+1$ ('spin up') or -1 ('spin down').

According to Bell, a local-hidden-variables theory asserts that the particles have independent well-determined values of the spin in directions a, a', b and b' which coincide with the outcomes of a measurement on each particle in the corresponding directions; we will call this the *Bell-locality condition*. J.P. Jarrett has proved that Bell-locality is the conjunction of two logically independent conditions (Jarrett 1984):
(1) According to the first condition the measuring result on particle one is statistically independent of the direction in which we decide to measure the spin of particle two. More precisely, the probability of a measuring result in any direction on particle one is equal to the probability of that measuring result in that direction given any direction of a measurement on the other particle. This condition is called *locality* (Jarrett) or *parameter independence* (Shimony):

For all Ψ, a_m and b_n

$$Pr(A/\Psi.a_m) = Pr(A/\Psi.a_m.b_n)$$
$$Pr(B/\Psi.b_n) = Pr(B/\Psi.b_n.a_m)$$

(2) The second condition says that the measuring result on particle one is statistically independent of the measuring result on particle two. More precisely, the probability of a measuring result in any direction on par-

ticle one is equal to the probability of that measuring result in that direction given the measuring result on particle two. This condition is called *completeness* (Jarrett) or *outcome independence* (Shimony):

For all Ψ, a_m and b_n
$Pr(A/\Psi.a_m.b_n) = Pr(A/\Psi.a_m.b_n.B)$
$Pr(B/\Psi.a_m.b_n) = Pr(B/\Psi.a_m.b_n.A)$

Bell-locality (i.e. the conjunction of Jarrett-locality and completeness) requires that the measuring result on particle one is statistically independent of both the direction and the result of the measurement on particle two. Formally, the Bell-locality condition can be expressed as factorizability:

For all Ψ, a_m and b_n
$Pr(A.B/\Psi.a_m.b_n) = Pr(A/\Psi.a_m) \text{ x } Pr(B/\Psi.b_n)$

This means that according to the Bell-locality condition, A_n is the same whether we are measuring B_n or B'_n; in other words, the change in measure-direction from b to b' or the result of that measurement do not affect A_n (the trick here is that A_n denotes at the same time a direction and a measuring result, namely A_n is the measuring result in direction a). Thus we easily see that

$$A_nB_n + A_nB'_n + A'_nB_n - A'_nB'_n = \pm 2 \qquad (1)$$

where

$$A'_nB'_n = A_nB_n \times A_nB'_n \times A'_nB_n = A_n^2 \times B_n^2 \times A'_nB'_n$$

Since both occurences of each measuring result in (1) have the same value, we can rewrite (1) as

$$A_n(B_n + B'_n) + A'_n(B_n - B'_n) = \pm 2 \qquad (2)$$

for B_n and B'_n must have either the same or opposite sign. According to the Bell-locality condition the values of the spin in each individual experiment must satisfy this equality.

Since correlations are average values of expressions of the form $A_n.B_n$ taken over a lot of cases, we can write (1) in the limit $N \to \infty$ as

$$|P(a.b) + P(a.b') + P(a'.b) - P(a'.b')| \leq 2 \qquad (3)$$

in which the correlations are defined as

$$P(a.b) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} A_n.B_n$$

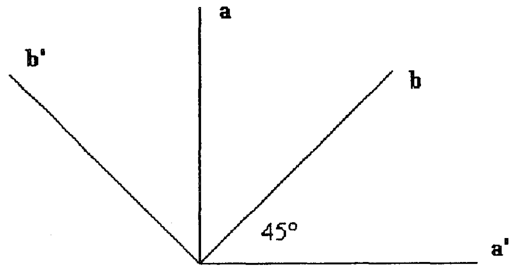
$$P(a.b') = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} A_n.B'_n$$

$$P(a'.b) = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} A'_n.B_n$$

$$P(a'.b') = \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} A'_n.B'_n$$

(3) is a typical example of an inequality that the correlations in a Bell-local-hidden-variables theory must satisfy.

2.3 Quantum mechanics makes a quantitative prediction for the correlation between the measuring results, namely $P_{qm}(a.b) = -\cos \alpha_{ab}$, in which α_{ab} is the angle between a and b. If $\alpha_{ab} = 0$, then the correlation equals -1, and as a consequence measuring results in the same direction must have an opposite sign. Now the crucial point is that the quantum mechanical correlation function does not satisfy the Bell-inequality. Suppose that the mutual orientation of the directions a, a', b and b' is the following:



Then we have

$$\left|P_{qm}(a.b) + P_{qm}(a.b') + P_{qm}(a'.b) - P_{qm}(a'.b')\right| = 2\sqrt{2}$$

The Bell-inequality (3) is obviously violated by the quantum mechanical predictions. Because quantum mechanics and a Bell-local-hidden-variables theory can never be empirically equivalent, an experimental decision between both is possible.

2.4 Recent experimental tests, the so-called Bell-experiments, have confirmed the predictions of quantum mechanics and proved that correlated spins violate the Bell-inequalities. The most convincing results are reported by A. Aspect, J. Dalibard and G. Roger (Aspect et al. 1982). A source simultaneously sends out photons with correlated polarization in opposite directions. The setting of the measuring instrument, like every quantum mechanical observation, determines the measuring result. New in Aspect's experiment is that the directions or 'settings' of the polarization-meter are determined by a switch that changes into another position when the pair of photons has left the source. So there cannot be fixed measuring results on the moment they are leaving. Though it is impossible for one photon to know what happens with the other by exchange of signals in space-time, the experiment confirmed that the polarization measurement on one photon is determining for the polarization of the other photon. Hence there cannot be local-hidden-variables that control the behaviour of photons on the moment they leave the source. One may conclude that Bell-local-hidden-variables theories are unfit for the description of the experimental founded results. The Copenhagen interpretation so far has stood the test.

2.5 The violation of Bell-locality by the Bell-experiments implies by *modus tollens* that one of the two conditions Jarrett-locality or completeness must be false. Since quantum mechanics is able to predict very accurately the experimental results, it is obvious that we use the quantum mechanical predictions to answer the question which one is false.

The predictions of quantum mechanics are in agreement with Jarrett-locality. When $\alpha_{ab} = 0$ (and therefore index n equals m) or $\alpha_{ab} > 0$, the statistical frequency of the measuring result on particle one is independent of the measuring direction on particle two:

$$\begin{aligned} Pr(A/\Psi.a_{\mathrm{m}}) &= Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}) \\ &= Pr(A.B/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}) + Pr(A.\sim B/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}) \\ &= \tfrac{1}{2}\sin^2 \tfrac{1}{2}\alpha_{ab} + \tfrac{1}{2}\cos^2 \tfrac{1}{2}\alpha_{ab} \\ &= \tfrac{1}{2} \end{aligned}$$

Since the Jarrett-locality condition is satisfied both when the spins are measured in different and in the same directions, we have no reason to think that Jarrett-locality is violated by quantum mechanics.

It is easy to see that the predictions of quantum mechanics violate the completeness condition. Indeed, for correlated spins in the same direction, we have:

$$\begin{aligned} Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{m}}) = 0.5 &\neq Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{m}}.B) = 0 \\ &\neq Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{m}}.\sim B) = 1 \end{aligned}$$

The completeness condition is also violated when the spins are measured in different directions:

$$\begin{aligned} Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}) = 0.5 &\neq Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}.B) = \sin^2 \tfrac{1}{2}\alpha_{ab} \\ &\neq Pr(A/\Psi.a_{\mathrm{m}}.b_{\mathrm{n}}.\sim B) = \cos^2 \tfrac{1}{2}\alpha_{ab} \end{aligned}$$

Now we can conclude that no hidden-variables theory that satisfies the completeness condition could ever be compatible with the quantum mechanical predictions. Bell-local-hidden-variables theories are violated because quantum mechanics predicts that the statistical frequency of the measuring result on particle one depends on the measuring result on particle two, and not because these theories satisfy Jarrett-locality.

3. *Nonseparability and Quantum Realism.*

3.1 The principle of separability has played an important role in Einstein's realism as a fundamental ontological claim. Einstein has formulated it as the *mutually independent existence of spatially distant objects* (Einstein 1948). More precisely, separability asserts (i) that spatially distant objects have each well-defined separated physical states and (ii) that the state of a composite system is determined by the states of the composing parts. Since this principle is refuted in quantum mechanics, I think that there is a decisive argument in the debate about the relation between theory and reality.

First, I will show how nonseparability emerges in quantum mechanics, and argue that this can be used as an argument against quantum realism. Secondly, I will argue that separability is implicit in the derivation of the Bell-inequality and that it is refuted by the Bell-experiments.

3.2 Consider an ensemble of composite quantum systems ($S = S_1 + S_2$) that can be written as the superposition

$$\Psi = \sum_{ij} c_{ij}\varphi_i \chi_j , \qquad \sum_{ij} |c_{ij}|^2 = 1 \tag{1}$$

where φ_i and χ_j are complete orthonormal sets of states for S_1 and S_2, and where c_{ij} is a complex coefficient. It is well known that if factorization condition

$$c_{ij} = x_i y_j \tag{2}$$

fails for at least one member of the c_{ij}'s, then quantum nonseparability emerges. It consists in the fact that S_1 and S_2 are so coupled that if S_1 is in one of its possible states then there is a strict or less strict correlation between this state and the state in which S_2 is. In other words, it is impossible to ascribe to the individual subsystems S_1 or S_2 a complete set of definite (though possibly unknown) values of their own.

When a composite system S cannot be described by a factorized state, i.e. by a state product of two states, the composing parts cannot have separated physical states. This holds true independently of the fact that the two subsystems are widely spatially separated. It is obvious that this fact is imposing very severe limitations upon any realistic account of these subsystems: if the state vector is the only link between the quantum mechanical formalism and the microphysical reality, i.e. there is no alternative (hidden) description of Ψ, then quantum theory does not ascribe any separated reality to S_1 or S_2. Moreover, since nonseparability can only be broken when an observation is made, we have that in the case of two correlated spin ½-particles, the spin of particle one has no existence independent of the observation of the spin of particle two. This means that quantum mechanics provides no state vector for the behaviour of a spin ½-particle which has an existence independent of an observation, so (QR) fails.

Of course fervent realists can object that nonseparability is in fact an argument against local realism without affecting some other (nonlocal) realistic interpretation. One may say that the real object consists of two spatially separated parts, i.e. the two particles, that depend on each other. In other words, we get a holistic version of realism that assigns reality to the composite system and not to the composing parts. Realism defined as weak as that could be compatible with quantum theory, however at a high price: one can only vindicate the realistic picture by invoking some very mysterious features of the world. So it clearly is hard to avoid triviality with that sort of definitions. Therefore quantum realism in a serious sense must entail separability. Moreover, it is misleading to use the term 'local' for quantum realism as defined by myself. Nonseparability is not equivalent with violation of local (relativistic) constraints, but it merely indicates that the submolecular particles cannot have all their dynamic properties at any one time.

3.3 Now I will show that separability is implicit in the derivation of the Bell-inequality and that the Bell-experiments can be held to refute it. This means that we have strong experimental evidence that there is no alternative description of Ψ that installs (QR) in quantum mechanics: the Bell-experiments tell us that (SR) cannot be generally valid. In my proof of this, I want to show that quantum mechanics reveals a remarkable connection between (QR) and determinism. Let us start with a theorem proved by Ghirardi, Rimini and Weber that states:

> *a necessary and sufficient condition in order that there exists a complete set of commuting observables of S_1 (or S_2) having probability 1 of giving a definite result if measured, is that the composite system ($S_1 + S_2$) be described by a factorized state, i.e. $c_{ij} = x_i y_j$.* (Ghirardi et al. 1977)

This means that having definite, though possibly unknown, values for a complete set of commuting observables is equivalent with the separability condition. Since hidden determinism, for present purposes, can be defined as the requirement that the spins always have probability one or zero of giving a definite result if measured, namely

For all Ψ, a_m, b_n, η_i and μ_i
$$Pr(A.B/\Psi.a_m.b_n.\eta_i.\mu_i) = 1 \text{ or } 0$$

where η_i and μ_i are two sets of deterministic hidden variables, each set applying to each particle separately, we can claim

$$\text{Hidden Determinism} \Leftrightarrow \text{Separability} \tag{3}$$

One can easily show that the assumption that the spins of particles are controlled by a deterministic-hidden-variables theory is implicit in the derivation of the Bell-inequality. Indeed, hidden determinism entails

$$Pr(A.B/\Psi.a_m.b_n.\eta_i.\mu_i) = Pr(A/\Psi.a_m.b_n.\eta_i) \text{ x } Pr(B/\Psi.a_m.b_n.\mu_i)$$

So

$$Pr(A/\Psi.a_m.b_n.\eta_i) = Pr(A/\Psi.a_m.b_n.\eta_i.\mu_i.B) \tag{4}$$
$$Pr(B/\Psi.a_m.b_n.\mu_i) = Pr(B/\Psi.a_m.b_n.\mu_i.\eta_i.A)$$

When (4) is called hidden completeness, i.e. the completeness condition is satisfied thanks to two sets of hidden variables, then

$$\text{Hidden Determinism} \Rightarrow \text{Hidden Completeness} \tag{5}$$

We know that conjunction of completeness and Jarrett-locality is equivalent with Bell-locality and that Bell-locality entails the Bell-inequality, so from (5) we have:

Hidden Determinism
& $\Rightarrow$ Bell-inequality (6)
Jarrett-locality

Since the Bell-inequalities are experimentally violated and Jarrett-locality is not, we must give up determinism. This means that we have experimental reasons to assert that no deterministic-hidden-variables theory could ever reproduce the predictions of quantum mechanics. There is no hope left to maintain that indeterminism in quantum mechanics has to be due to a failure of theory.

Because of (3) and the claim that hidden determinism is implicit in the Bell-derivation, we have

Separability
& $\Rightarrow$ Bell-inequality (7)
Jarrett-locality

So separability clearly is implicit in the Bell-derivation. Claim (7) and Jarrett-locality not being violated imply that separability cannot be the case. In other words, quantum mechanics does not satisfy the Bell-inequality because it does not satisfy the separability condition. According to the experimental correlations, the spins of particles cannot be described by a factorized state, i.e. the spins have no separated reality. Hence the Bell-experiments clearly show us that no deterministic or realistic-hidden-variables theory is possible.

4. *A local causal explanation of EPR-correlations.*

4.1 It is sometimes said that the understanding of causal mechanisms, imposed as a demand for scientific explanation, would lead to the postulation of the real existence of unobservable entities that thus can be scientifically established. (Russell 1948; Cartwright 1983; Salmon 1978, 1984; Van Fraassen 1980). I disagree.

I claim that there is causality in the quantum domain but this cannot be invoked to support (QR). To prove this, I show in this section that, though (QR) fails, there is a local causal explanation of correlated spins. First, I explicate Reichenbach's criterion for common causes and I show why it is not appropriate for 'hunting' common quantum causes in EPR-correlations. Secondly, I use another criterion, borrowed from Salmon and I show that correlated spins do not violate the principle of the common cause. Finally, I show that there is not even sinned against any local constraint.

4.2 Suppose, for example, that we have two events *A* and *B* that stand for the disease of Lesh Nyhan in two brothers. Since this affliction is hereditary, occurences of Lesh Nyhan in male siblings are not independent. This means that there is a positive correlation between *A* and *B*: the probability of *A* and *B* is greater than the product of the respective probabilities of *A* and *B*. Reichenbach's common cause principle says that if there is such a positive correlation between two simultaneous events, there is a third event *C* in their common past that accounts for them. In the case of Lesh Nyhan, *C* is a defective gen on the X-chromosome that males get from their mother.

Reichenbach's principle stipulates that the statistical structure of common causes satifies the following conditions:

If (1) $Pr(A.B) > Pr(A) \times Pr(B)$

and there is no direct causal link, then there is a common cause *C* such that

(2) $Pr(A.B/C) = Pr(A/C) \times Pr(B/C)$
(3) $Pr(A.B/{\sim}C) = Pr(A/{\sim}C) \times Pr(B/{\sim}C)$
(4) $Pr(A/C) > Pr(A/{\sim}C)$
(5) $Pr(B/C) > Pr(B/{\sim}C)$

Conditions (2)-(5) form a conjunctive fork. An important way to look at conjunctive forks is that (2) and (3) entail

(6) $Pr(B/C.A) = Pr(B/C)$
(7) $Pr(B/{\sim}C.A) = Pr(B/{\sim}C)$

(6) and (7) say that *C* and $\sim C$ screen off *B* from *A*; that is the presence

or the absence of the common cause C makes each of the two effects A and B statistically irrelevant to one another. In the case of our example, this means that the probability of getting the disease of Lesh Nyhan only depends on the genetic defect inherited from the mother and not on whether or not other brothers have inherited the disease. When the genetic factor is not present in the mother, the illness of one brother will not be statistically relevant to the illness of the other.

4.3 It is easy to see why Reichenbach's principle is not appropriate for 'hunting' common quantum causes: the universal validity of Reichenbach's principle entails determinism. I use an example of Salmon to illustrate this (Salmon 1978). Suppose that an energetic photon collides with an electron in a Compton scattering experiment. Let us call this collision event C. The scattering process can be described as a collision between two particles with conservation law $E \approx E_1 + E_2$. Let E be the energy of the original photon, and let E_1 and E_2 be the energy of the photon and the electron after the collision. The events that the particles have energy E_1 and E_2 are called A and B.

Since the causation is genuinely *indeterministic*, for example $Pr(A/C) = 0.1$ and $Pr(B/C) = 0.1$, and since energy is conserved, i.e. $Pr(B/A) \approx 1$, we have $Pr(B/C.A) \approx 1 > Pr(B/C)$. So there is no screening off the one effect from the other. Reichenbach's principle clearly is not valid to cases where indeterministic causes produce their effects in pairs. On the other hand, if C is a *deterministic cause*, then Reichenbach's conditions are satisfied: $Pr(B/C.A) \approx 1 = Pr(B/C)$.

It is obvious that in some indeterministic systems the resulting effects are more strongly correlated with one another than is allowed by Reichenbach's principle. Salmon has described these statistical structures with reference to Compton scattering as interactive forks. For the definition of interactive forks: replace condition (2) by the inequality

(8) $Pr(A.B/C) > Pr(A/C) \times Pr(B/C)$

so that (6) becomes

(9) $Pr(B/C.A) > Pr(B/C)$

The other conditions remain the same.

4.4 Reichenbach's conjunctive fork condition is immediately violated by the Bell-experiments. Experimental violation of completeness shows that it is not possible to postulate a hidden variable λ in Ψ that screens the effects off from each other, so condition (2) of conjunctive forks cannot be satisfied. This does not mean that we already can conclude that EPR-correlations are not due to the action of a common cause! We can try to show that the described events of correlated spins form an interactive fork.

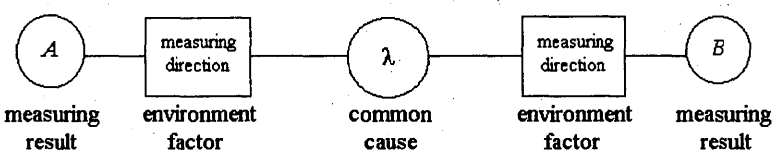
Consider a population of experiments (P_1) in which the directions of measurement are the same. If we now posit a hidden variable λ in Ψ, then whether these directions are varying or not, we can write for each member of the population: $Pr(\sim B/\lambda.A) = 1 > 0.5 = Pr(\sim B/\lambda)$. In this population a_m and b_m have no causal influence at all. The described events λ, A and $\sim B$ clearly form an interactive fork:

$$Pr(A.\sim B/\lambda) > Pr(A/\lambda) \text{ x } Pr(\sim B/\lambda)$$

But when, on the contrary, we have a population of experiments (P_2) in which the relative directions of measurement are allowed to vary, then the probability $Pr(\sim B/\lambda.A)$ will differ for each member of the population. This means that a_m and b_n can be considered as independent causally relevant factors for the quantum mechanical statistics of correlated spins.

Since any direction a_m is causally relevant in (P_2) and is not in (P_1), it cannot be considered as a causal interaction, i.e. an event where one causal (spatio-temporally) process intersects another and produces a modification in its structure; similarly for any direction b_n. Though the directions have an influence on the correlation between measuring results, there clearly cannot be a mark transmission from them. Hence let us call a_m and b_n *environment factors*: these factors merely determine which spin components we are measuring, so they are causally relevant for the correlation but are not causally interacting. To make quite clear what I mean with environment factors, I give another example. Several studies has established that exposure to nuclear radiation, as occur by an atomic blast, is a probabilistic cause of leukemia. Moreover the probability of getting leukemia is closely correlated with the distance from the explosion. People got leukemia because they were too close to the hypocenter at the time of the explosion. Hence the distance from the explosion clearly is causally relevant for getting leukemia, but is not causally interacting; so we call distance, in this case, an environment factor.

The only causal interaction in the EPR-experiment is λ that can be considered as a common quantum cause. When the environment factors or directions are the same for both particles, then the common cause acts in a homogeneous environment and satisfies the statistical conditions of an interactive fork. But when the environment factors or directions differ from each other, the statistical conditions of interactive forks will not always be satisfied because these factors determine which correlation appears between the effects that λ is producing. In this case the factors a_m and b_n form independently two different environments (or one non-homogeneous environment) for the causal paths from λ, so they must have a *local* influence on the correlations built into the composite system. Even the experiments of A. Aspect, J. Dalibard and G. Roger, where the directions are decided after the photons leave their source, can be causally explained without a temporal gap. The common cause precedes its effects in time and there is no need that the particles exchange signals during the period in between.



5. *Conclusions*

What lessons are we to draw from the Bell-inequalities? We had the intention to clarify a few of them. First of all, it is tenet among traditional realists that (SR) or (QR) have no empirical consequences. In other words, the (realistic or nonrealistic) interpretation of a theory would not affect the empirical claims of that theory. The Bell-inequalities show us that this is wrong: quantum mechanics is incompatible with a realistic interpretation on the submolecular level.

We have argued that quantum realism is refuted by the Bell-derivation: there is strong experimental evidence that the spins have no separated reality before they are measured. What is the bearing of this on the debate about the relation between theory and reality? Quantum mechanics tells us that if two realities (e.g. spin ½-particles) have once interacted and have no complete set of deterministic values of their own, then quantum realism must fail. Quantum realism clearly is not unrelated to determinism: 'the world must exist in a well-defined state'. Since this condition is not satisfied in the quantum domain, scientific realism cannot be generally valid.

Does this mean that local causality is excluded in EPR-correlations? Our answer is *no*. Once we accept that determinism is too restrictive as a necessary condition of common causes, we have to admit that the Bell-inequalities do not rule out a common quantum cause.

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