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# On the Consistent Meaning of Local Realism

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**Abstract**

We analyze the different meanings currently assigned to the term "local realism" in the context of the conceptual and empirical violations of Bell-type inequalities. We point out that most of them are inconsistent and propose a possible correct connotation.

## Contents



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# 1 Introduction

In the field of the Bell inequality and its experimental tests, the term local realism has become almost universal, albeit proponents of quantum nonlocality vs. quantum locality have very different opinions of its meaning.

A poll carried out in 2011 [1] reported that 64% of the surveyed scientists interpret the observed violations of Bell's inequalities as the untenability of local realism. However, most proponents of quantum nonlocality strongly resist the expression of local realism [2–4], while quantum localists are very fond of it but do not always agree on its precise meaning.

We analyze whether the experimental Bell-type inequalities violations can falsify *local realism* (LR) according to its usual assigned meanings. But we explicitly avoid discussing quantum nonlocality. That discussion constitutes a different matter [5] and would only obfuscate our analysis.

Nicolas Gisin has performed a similar analysis [4], and we agree with some of his conclusions, but we disentangle the study from the quantum nonlocality conundrum facilitating its clarification.

# 2 LR and Preexisting values

When we understand LR as the conjunction of locality and realism

$$LR \equiv \text{Locality} \wedge \text{Realism} \tag{1}$$

often realism means that physical systems possess definite properties whether or not we observe them and that measurements eventually passively disclose those pre-existing properties [6–9]. That metaphysical kind of realism is a consequence of the *Einstein, Podolski, Rosen* (EPR) [10] argument for quantum incompleteness. Einstein rejected such speculation and replaced it with his far better separation principle argument [11].

The problem with that kind of realism is that it is unfalsifiable or, at least, the Bell inequality cannot falsify it. Indeed, in 1964 Bell [12] employed a similar EPR reasoning to conclude that locality required a deterministic hidden variable model of quantum mechanics. It is essential to realize that Bell's reasoning led him to determinism, which only means that we can predict the results of measurements with certainty but does not imply the existence of unobserved properties unless, of course, we accept the metaphysical EPR speculation.

Bell's insight allowed him to mathematically prove the incompatibility of non-conspiratorial local hidden variables with quantum mechanics, also opening the possibility of empirically testing the plausibility of local hidden variables.

However, the Bell inequality is silent regarding the existence or nonexistence of unobserved physical properties. Since any actual experiment can only yield results that are indeed measured, it is a remarkable extrapolation to claim that such experiments falsify what existed (or did not exist) before the measurement.

Admittedly, the Copenhagen view claims physical properties arise due to observation and do not exist before measurement. On the other hand, the kind of realism we are considering asserts the existence of well-defined physical properties independent of observation. So far, so good, but the empirical violations of Bell-type inequalities can falsify neither of the former metaphysical speculations.

Since the claim that experimental violations of Bell-type inequalities rule out pre-existing properties seems to be a very ingrained prejudice, we review a more formal argument in Appendix 7.

# 3 LR and Determinism

Since EPR identified determinism with pre-existence through the "elements of physical reality" and, as we explained in section 2, pre-existence is unfalsifiable, perhaps what Bell-type experiments indeed falsify is determinism.

The 1964 Bell theorem relies on a deterministic hidden-variable model. Given that quantum mechanics is essentially not deterministic, a possible interpretation for local realism could be local determinism. Thus, it is possible to identify realism with determinism and claim that experiments rule out local determinism.

That could have been a possible correct interpretation until 1974. In that year, Clauser and Horne [13] enlarged the scope of Bell-type inequalities to not deterministic hidden variables models. The date of the appearance of such models can even be pushed back to 1971 by Bell himself [14].[1]

Although we do not know when the term local realism became fashion-

[1] Only in a footnote Bell observed that his model could be interpreted as not deterministic.

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able,[2] from 1974, or perhaps 1971, onwards, local realism cannot mean local determinism.

## 4 LR and Counterfactual Reasoning

The metaphysical EPR speculation about the "elements of physical reality" gave rise to the invention of an *ad hoc* principle, namely, counterfactual definiteness [16–20]. This fanciful "realism" is particularly convenient to present pre-existence as opposed to the orthodox quantum interpretation stating that physical properties arise from the act of measurement.

The problem with those kinds of arguments is that Bell inequality only makes sense when predicting the results of actually performed measurements. It says nothing about the results of imaginary and unrealizable experiments; otherwise, the inequality would be unfalsifiable. Of course, determinism allows the prediction of counterfactual experiments. However, in the case of the Bell inequality, such predictions become untestable, i.e., there is no relation between the counterfactual predictions and what actual experiments do. The untenability of counterfactual definiteness, when used to derive the Bell inequality, is extensively discussed in Refs. [21–24].

The obvious conclusion is that, whatever it is that Bell-type experiments falsify, it cannot be the counterfactual existence of not performed experiments' results. Thus the claim that the empirical violations of Bell-type inequalities disprove local realism because they disprove counterfactual definiteness is devoid of logical and physical sense.

## 5 LR and Hidden-Variables

Although we avoid discussing the contentious issue of quantum nonlocality, we point out that an objective reading of Bell's papers [12, 25, 26] shows that he interpreted his inequalities as ruling out non-conspiratorial local hidden variables and not as ruling out orthodox quantum mechanics' locality. Of course, he believed that quantum mechanics is nonlocal but did not claim that his inequality proves it [5].

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[2]Norsen traced back the appearance of LR to 1979 [2]. But Clauser and Shimony already used the expression "local realistic theories" in 1978 [15]

Our point is that perhaps the only way to make sense of the expression of local realism when claimed to be falsified by the empirical violations of Bell-type inequalities is

$$LR \equiv \text{non-conspiratorial local hidden-variables.} \tag{2}$$

# 6 Conclusions

Most of the recently relevant experimental violations of Bell-type inequalities report having ruled out local realism [6, 8, 27, 28], considering local realism as locality plus the assumption of preexisting properties in the EPR sense of elements of physical reality, meaning that properties exist independently of observation. However, the realism assumption they report to have falsified is untestable by Bell-type inequalities. Those remarkable experiments indeed prove what Bell insistently explained from 1964 [12] to 1990, the year of his death:

> Quantum mechanics cannot be embedded in a locally causal theory. [26]

Implicit in the former assertion is that "locally causal theory" means hidden variable theory. Although some interpret it as proof of quantum nonlocality, its unambiguous meaning is that a local hidden variable theory (either deterministic or stochastic) cannot reproduce the experimental findings when statistical independence is assumed. We believe there are good reasons to sustain quantum nonlocality,[3] but the Bell inequality is not one of them [5].

In 1964 John Bell turned a previously metaphysical conjecture, namely, the possibility of local hidden variables, into a concrete physical problem decidable in the experimental arena. However, experiments cannot falsify what they usually report they have proved, confirming Einstein's dictum:

> It is the theory which decides what we can observe. [30]

Thus, an adequate interpretation of experiments requires an scrupulous conceptual and theoretical analysis. A similar problem occurred in the 19th century when interpreting the Michelson-Morley experiment.

Although the shut up and calculate philosophy may disgard our considerations as irrelevant, the elimination of ambiguities and inaccuracies from scientific parlance may justify them.

[3] See for instance [29].

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# APPENDIX

## 7 The Influence the Apparatuses on Measurements

We can include the influence of the measuring devices in the derivation of the Bell inequality. Their explicit inclusion makes it more evident that the Bell inequality cannot falsify pre-existing values. On the contrary, we can surmise the inclusion of such influences is according to the orthodox Copenhagen dictum that observation creates such values. Of course, all about pre-existence is mere speculation, but the explicit inclusion of apparatuses' hidden variables may help us get rid of such prejudices.

In 1971 Bell showed [14] how to include the uncontrollable influences the measuring devices may have on the results. That is according to Bohr's views:

> Indeed the *finite interaction between object and measuring agencies* conditioned by the very existence of the quantum of action entails – because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose – the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. [31]

In [14], Bell explained that "If we average first over these instruments variables", but did not give a detailed explanation [32]. We start with the expression for the joint probability of a stochastic local non-conspiratorial hidden variable model

$$P(A, B \mid a, b) = \int_{\boldsymbol{\Lambda}} P(A \mid a, \lambda) P(B \mid b, \lambda) P(\lambda)\, d\lambda \tag{3}$$

In (3), $A, B \in \{-1, 1\}$ are the results, and $a, b$ are the measurement settings. The hidden variables $\lambda$ are the local common causes, and $\boldsymbol{\Lambda}$ is the space of these variables. We include the apparatuses' effects assuming hidden variables $\xi \in \boldsymbol{\Lambda}_1$ for Alice's measuring device and $\eta \in \boldsymbol{\Lambda}_2$ for Bob's. The probabilities for the measurement results respectively become

$$P(A \mid a, \lambda, \xi) \quad \text{and} \quad P(B \mid b, \lambda, \eta)$$

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The $\lambda$ represents common causes lying at the causal past of the measuring events while $\xi$ and $\eta$ describe the local instruments. Therefore all these variables are independent of each other and are independently distributed. Putting $P_\lambda = P(\lambda)$, $P_\xi(a) = P(\xi, a)$, $P_\eta(b) = P(\eta, b)$. The fact that $P(\lambda)$ is independent of $a$ and $b$ is a consequence of the non-conspiratorial hypothesis.

$$P(A, B \mid a, b) = \int_{\mathbf{\Lambda}} P_\lambda d\lambda \int_{\mathbf{\Lambda}_1} P_\xi(a) d\xi \int_{\mathbf{\Lambda}_2} P_\eta(b) d\eta P(A \mid a, \lambda, \xi) P(B \mid b, \lambda, \eta) \quad (4)$$

Integrating first over the instruments variables $\xi$, $\eta$

$$\int_{\mathbf{\Lambda}_1} P_\xi(a) P(A \mid a, \lambda, \xi)\, d\xi = \overline{P}(A \mid a, \lambda) \quad (5)$$

$$\int_{\mathbf{\Lambda}_2} P_\eta(b) P(B \mid b, \lambda, \eta)\, d\eta = \overline{P}(B \mid b, \lambda) \quad (6)$$

Taking (5) and (6) into (4) we have

$$P(A, B \mid a, b) = \int_{\mathbf{\Lambda}} \overline{P}(A \mid a, \lambda) \overline{P}(B \mid b, \lambda) P_\lambda \, d\lambda \quad (7)$$

Since $\overline{P}(A \mid a, \lambda)$ and $\overline{P}(B \mid b, \lambda)$ range between 0 and 1, the derivation of the Bell inequality goes through as usual.

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