Bell's Theorem: An example of experimental metaphysics

1. <u>Introduction</u>

For many, the Bohr-Einstein debates on the nature of quantum mechanics over the first half of the 20th century represent the highest points of scientific research and philosophical discourse in recent history, not only due to their profound nature but also due to the timbre of mutual respect under which they took place.

The realization, then, that the heart of the matter was largely settled in the year 1964 in a short article[1] of not more than 5 pages written by a physicist on a Sabbatical mulling over the matter as a "hobby"[2], should be more than a little startling.

John S. Bell was a physicist from Northern Ireland whose work on the foundations of quantum mechanics which is often best characterized as *experimental metaphysics*[3]: An apparent contradiction in terms.

To wholly grasp why the invocation of this strange category is justified is, perhaps, to understand the remarkable and profound advancement Bell precipitated in quantum theory. Thus, we shall, to begin with, explain in the historical context not only why Bell's work is experimental, but also why it is indubitably metaphysical.

Realism and *completeness* are the two primary notions with metaphysical import which John Bell dealt with; and both these notions go back to (insofar as Bell is concerned) none other than Einstein. In a now-legendary article titled "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?", Einstein (along with Podolsky and Rosen) attempted to argue that quantum mechanics was an *incomplete* theory.

And what, precisely, is meant by the word "incomplete" here? Intuitively, we would agree that a physical theory of the kind quantum mechanics purports to be can be considered complete only if it does not *miss out on* or *fail to describe* some aspect of *reality*.

This, in turn, begs the following question: Precisely what objects can we consider to be an "aspect of reality"?

Here, I quote directly from the original paper EPR's characterization/operational definition of physical reality[4]:

"We shall be satisfied with the following criterion, which we regard as reasonable. *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.* It seems to us that this criterion, while far from exhausting all possible ways of recognizing a physical reality, at least provides us with one such way, whenever the conditions set down in it occur. Regarded not as a necessary, but merely as a sufficient, condition of reality, this criterion is in agreement with classical as well as quantum-mechanical ideas of reality."

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This covers the metaphysical definitions we need equip ourselves with. For the experimental side of the coin, we need to recognize only two notions, fairly elementary and familiar to most: *Separability* and *locality*.

Locality is merely the relativistic principle which states that no signal can travel faster than the speed of light.

The separability principle refers to the assumption that two dynamically independent systems cannot influence each other.[5]

It appears that the two principles amount to the same thing: If two dynamically independent systems could influence each other (one may argue), the influence in question would have to be a nonlocal one. In other words, a violation of separability seems to entail a violation in locality, and vice-versa. However, as we shall see later, they are fundamentally disparate: There is a gap between the two which is as subtle as it is shocking.

2. Einstein's defeat

The EPR paper tried to argue that the criterion of physical reality provided, in conjunction with the principle of *separability,* entails that quantum theory is incomplete.

Before getting into the specifics of this argument, I will make clear the result from the outset. The fact is that we now know that this argument, beyond all doubt, *fails.* And it is precisely at *this* stage that John Bell enters the picture.

For suppose now that quantum mechanics were incomplete. Typically, the hypothetical complete theory that would replace it was considered to be a 'hidden variable' theory: A theory which could, in principle, deterministically predict with certainty the evolution of every "aspect" of physical reality, if only we know all the parameters required to do the same. To contrast, quantum theory claimed that, for example, it was an in-principle impossibility to predict (say) the position and momentum of a given particle beyond a certain limit of uncertainty.

Of course, this theory supposed to be a *separable* one, for locality and separability were thought equivalent, and non-locality would violate relativity.

Now, since these variables are classical parameters, they must satisfy certain *statistical* constraints (based on the facts that the sum of the probabilities of an outcome must be unity, etc.).

But at the same time, they must also satisfy another set of *deterministic* constraints: These are consequences of experimentally established aspects of quantum-mechanical formalism (such as the form of the "expectation value" of an observable, etc.).

And John Bell's great contribution lay in showing that these two sets of constraints were *completely incommensurable: It was not possible to satisfy both these sets of constraints.*

In other words, a deterministic hidden variable theory satisfying separability and locality, of the kind Einstein envisioned, was ruled out.

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3. Einstein's victory

Since we have achieved a *reductio ad absurdum* of sorts regarding the EPR argument's conclusion of there being a "local/separable realism"-flavored theory extending quantum mechanics, this implies that one of the two assumptions of the EPR argument are incorrect: Either the criterion of physical reality provided, or the principle of separability postulated.

It is interesting to note that historically, Niels Bohr attacked the former assumption, while Erwin Schrödinger argued against the latter. Ultimately, Schrödinger's argument proved to be on the right track: It was the principle of separability which was flawed.

At this stage of the discussion, we enter the most important point of it all, what should perhaps be the primary takeaway from the whole series of events: The distinction between non-locality and non-separability.

For what was found firsthand a few decades after the EPR paper was the fact that non-separability *does not* imply non-locality. This feature is related to the phenomenon of quantum entanglement, which exhibits locality in conjunction with non-separability, and which is beyond the scope of this article to discuss.

And what *this* amounts to is saying that two spatially faraway systems can interact and influence one another in a manner which does not consist of causal correlations and signal transmissions at all, but using some fundamentally different and hitherto unimaginable mode of interactions!

To be sure, the EPR argument was flawed, but what a heroic flaw it was: One which forced Mother Nature to expose one of her subtlest aspects; a chain of events which none of the more superficial contrarians of Einstein could have ever even dreamt of then. Truly, was it not more of a victory for Einstein than a defeat?

4. Conclusion

It is now time to catch our breath and refine what we have learnt from the above accounts.

The bottom line is typically summed up in the following manner: Bell's results offer us an option between a theory which is either of the form of local non-realism, or of that of non-local realism. To reiterate, this is because the statistical constraints a local realist theory must satisfy was in contradiction with the deterministic constraints imposed by quantum theory.

Of course, it is trivial to reconstrue a local quantum theory as satisfying realism if we take realism in the broadest, philosophical sense. However, it is usually given a more pragmatic meaning (such as the one put forth in the EPR paper).

In this context, one may understand realism to be the idea that (in conjunction with the EPR characterization) all measurable things have a value regardless of whether or not they are actually measured.

As a matter of fact, Bell himself was a realist, following Einstein, and believed that his results pointed towards the direction of a non-local world. However, the conventionally accepted result is that of a local theory failing to satisfy realism.

In 1982, French physicist Alain Aspect performed the Nobel prize-winning[6] experiment[7] which irrefutably showed the incommensurability of the statistical and the deterministic constraints.

Bell's theorem remains a unique and rare example of an advancement wherein experimentalism was enabled to extend a causal, effective tentacle all the way down to the substratum of metaphysics.

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