Nonlocality and Ontology: What Bell and Einstein, Bohm, and Ghirardi showed

Fundamental Problems in Quantum Physics

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I will briefly discuss three issues of fundamental physical significance for our quantum world, issues on which GianCarlo Ghirardi has worked long and hard and with great success: quantum nonlocality, the measurement problem, and the importance of local beables.

Quantum Nonlocality

Fifty years ago John Stewart Bell published "On the Einstein-Podolsky-Rosen Paradox," which contained his proof of Bell's inequality. Almost all physicists agree that this is a very important result. But they don't agree on what that result actually shows. I first discuss here what Bell showed, what he thought he showed, and why he showed it.

Nonlocality

Hidden variables are impossible in QM.

This [hidden variables] is an interesting idea and even though few of us were ready to accept it, it must be admitted that the truly telling argument against it was produced as late as 1965, by J. S. Bell. . . . This appears to give a convincing argument against the hidden variables theory. (Wigner, 1983, p. 53)

Einstein's view was what would now be called a hidden variable theory. Hidden variable theories might seem to be the most obvious way to incorporate the Uncertainty Principle into physics. They form the basis of the mental picture of the universe, held by many scientists, and almost all philosophers of science. But these hidden variable theories are wrong. The British physicist, John Bell, who died recently, devised an experimental test that would distinguish hidden variable theories. When the experiment was carried out carefully, the results were inconsistent with hidden variables. (Hawking, 1999)

We now know that the moon is demonstrably not there when nobody looks. (Mermin, 1981)

In 1935 Einstein, Podolsky, and Rosen argued that the quantum mechanical description is incomplete, i.e., that there are hidden variables. Bell showed in 1964 that the EPR argument is fundamentally flawed. However, in so doing Bell also provided strong support for the conclusion of that argument.

Two Part Argument

Part 1 (EPR): QM + Loc $\Rightarrow$ HV

Part 2 (Bell): QM $\Rightarrow$ not HV

Conclusion: QM $\Rightarrow$ nonlocality

Einstein Podolsky Rosen (Bohm)

singlet state: $\frac{|\uparrow\rangle_z|\downarrow\rangle_z - |\downarrow\rangle_z|\uparrow\rangle_z}{\sqrt{2}}$

spin components: $\mathbf{a}\cdot\boldsymbol{\sigma}_i, \; i=1,2$

$$\mathbf{a}\cdot\boldsymbol{\sigma}_1 = -\mathbf{a}\cdot\boldsymbol{\sigma}_2$$

Now we make the hypothesis, and it seems one at least worth considering, that if the two measurements are made at places remote from one another the orientation of one magnet does not influence the result obtained with the other. Since we can predict in advance the result of measuring any chosen component of $\boldsymbol{\sigma}_2$, by previously measuring the same component of $\boldsymbol{\sigma}_1$, it follows that the result of any such measurement must actually be predetermined. (Bell, 1964)

Pre-existing values:

$$A^{(i)} \quad \leftrightarrow \quad \mathbf{a} \cdot \boldsymbol{\sigma}_i$$

Bell

Three directions: **a** and **b** and **c**

Spin components: $A^{(i)}$ and $B^{(i)}$ and $C^{(i)}$

$$A^{(i)} = \pm 1 \quad \text{(2 more)}$$

$$A^{(1)} = -A^{(2)} \quad \text{(2 more)}$$

single particle

$$\{A = B\} \text{ or } \{B = C\} \text{ or } \{C = A\}$$

$$\mathsf{Pr}(A = B) + \mathsf{Pr}(B = C) + \mathsf{Pr}(C = A) \geq 1$$

$$\mathrm{Pr}\left(A^{(1)} = B^{(1)}\right) + \mathrm{Pr}\left(B^{(1)} = C^{(1)}\right) + \mathrm{Pr}\left(C^{(1)} = A^{(1)}\right) \geq 1$$

$$\boxed{\mathrm{Pr}\left(A^{(1)} = -B^{(2)}\right) + \mathrm{Pr}\left(B^{(1)} = -C^{(2)}\right) + \mathrm{Pr}\left(C^{(1)} = -A^{(2)}\right) \geq 1}$$

(Bell's inequality)

quantum mechanics:

$$\mathrm{Pr}(\boldsymbol{\alpha} \cdot \boldsymbol{\sigma}_1 = -\boldsymbol{\beta} \cdot \boldsymbol{\sigma}_2) = (1 + \boldsymbol{\alpha} \cdot \boldsymbol{\beta})/2 = \cos^2(\theta/2) = 1/4 \ (120^\circ)$$

Two Part Argument

EPR: $\quad QM + Loc \Rightarrow HV$

Bell: $\quad QM \Rightarrow \text{not } HV$

Conclusion: $\quad QM \Rightarrow \text{nonlocality}$

It is important to note that to the limited degree to which *determinism* plays a role in the EPR argument, it is not assumed but *inferred*. What is held sacred is the principle of ‘local causality’ – or ‘no action at a distance’. . . . It is remarkably difficult to get this point across, that determinism is not a *presupposition* of the analysis. (Bell, 1981)

Despite my insistence that the determinism was inferred rather than assumed, you might still suspect somehow that it is a preoccupation with determinism that creates the problem. Note well then that the following argument makes no mention whatever of determinism. ... Finally you might suspect that the very notion of particle, and particle orbit ... has somehow led us astray. ... So the following argument will not mention particles, nor indeed fields, nor any other particular picture of what goes on at the microscopic level. Nor will it involve any use of the words 'quantum mechanical system', which can have an unfortunate effect on the discussion. The difficulty is not created by any such picture or any such terminology. It is created by the predictions about the correlations in the visible outputs of certain conceivable experimental set-ups. (Bell, 1981)

Why?

. . . in this theory an explicit causal mechanism exists whereby the disposition of one piece of apparatus affects the results obtained with a distant piece. . . .

Bohm of course was well aware of these features of his scheme, and has given them much attention. However, it must be stressed that, to the present writer's knowledge, there is no *proof* that *any* hidden variable account of quantum mechanics *must* have this extraordinary character. It would therefore be interesting, perhaps, to pursue some further "impossibility proofs," replacing the arbitrary axioms objected to above by some condition of locality, or of separability of distant systems. (Bell, 1966)

...as a professional theoretical physicist I like the Bohm theory because it is sharp mathematics. I have there a model of the world in sharp mathematical terms that has this non-local feature. So when I first realized that, I asked: "Is that inevitable or could somebody smarter than Bohm have done it differently and avoided this non-locality?" That is the problem that the theorem is addressed to. The theorem says: "No! Even if you are smarter than Bohm, you will not get rid of non-locality," that any sharp mathematical formulation of what is going on will have that non-locality. (Bell interview with Renee Weber)

The Measurement Problem

$$\Psi = \Psi_{\text{left}} + \Psi_{\text{right}}$$

$$\Psi = \Psi_{\text{alive}} + \Psi_{\text{dead}}$$

$$|\Psi\rangle = |\text{cat alive}\rangle + |\text{cat dead}\rangle$$

A symptom—not the real problem

The basic variables of a fundamental physical theory don't refer to macroscopic objects, let alone to cats. A state "cat alive" should refer to a state in which there is an arrangement in space of fundamental stuff in the shape of a living cat (and which behaves like a living cat). But for this one would need to have, in the theory, variables providing an arrangement of things in space; that is, one needs local beables.

BM

Beables: $\psi, \quad Q = (Q_1, \ldots Q_N)$

$$i\hbar\partial\psi/\partial t = H\psi$$

$$dQ/dt = v^{\psi}(Q)$$

SL

Beables: ψ, $m = m(\vec{x})$

$$i\hbar\partial\psi/\partial t = H\psi + NT(\psi)$$

$$m(\vec{x}) = m^{\psi}(\vec{x}) = \langle\psi|\widehat{m}(\vec{x})|\psi\rangle$$

HV vs HV

L(HVT) vs (LHV)T

locality vs local beables

But even supposing that somehow abandoning realism in quantum theory could preserve locality, we would have to wonder about the point of making such a bargain. Physicists have been tremendously resistant to any claims of non-locality, mostly on the assumption (which is not a theorem) that non-locality is inconsistent with Relativity. The calculus seems to be that one ought to be willing to pay *any* price—even the renunciation of pretensions to accurately describe the world—in order to preserve the theory of Relativity. But the only possible view that would make sense of this obsessive attachment to Relativity is a thoroughly realistic one! These physicists seem to be so certain that Relativity is the last word in space-time structure that they are willing even to forego any coherent account of the entities that inhabit space-time. (*Tim Maudlin*)

But

Bell: QM $\Rightarrow$ not HV

Like all hidden variable theories, the de Broglie-Bohm theory requires accepting the contextual nature of the greater part of the observables.
(*GianCarlo Ghirardi*)

contextuality of observables

vs

local beables

Contextuality is basically a triviality. That it should seem like more is a reflection of ontological carelessness and complacency. It becomes interesting only when it is elevated to nonlocality.

But quantum nonlocality is not a problem to be solved, but an established fact that needs to be appreciated. Among the radical ideas claimed by quantum physicists to be demonstrable consequences of quantum experiments, it is distinguished in at least two ways:

1] It is the least radical and most understandable of these ideas.

2] It is the only one of these ideas for which there is any genuine evidence.

In fact Bell's argument for quantum nonlocality is remarkably simple. It is quite astonishing that it should be so controversial.

I believe it can be said that the uncritical acceptance of the Copenhagen ideology represented a brake on the development of new ideas, on the elaboration of alternative models, and above all on the very comprehension of the revolutionary aspects of reality that were emerging. It became very difficult for dissenting voices to be taken seriously, and all too easy for those who shared the “victorious” position to take things that really required further serious analysis to be accepted for unequivocally stable truths and principles. (*GianCarlo Ghirardi*)