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Book Review: *Quantum Non-Locality and Relativity*

Quantum Non-Locality and Relativity. T. Maudlin, Blackwell, 1994.

Here is a puzzle: two persons leave a room through opposite doors; at that point, each is asked a question. The precise nature of the question does not matter, but there are three possible questions. Each person must answer yes or no. The experiment is repeated many times. The two persons are allowed to decide, before leaving the room, to follow any strategy they want, but not to communicate with each other after they have heard the questions. Bell's theorem shows that there is no strategy whatsoever that will enable them to reproduce, in the long run, the statistics that have been observed in correlated photon pairs and that are predicted by quantum mechanics (for the photons, the question correspond to three different angles along which the polarization is measured and the yes/no answers correspond to the two possible results).

This is puzzling: if we cannot do it, how can the photons? It does not help to say that they come from the same source, since the humans also come from the same source where they are allowed to communicate and to choose their strategy in any way they like. So, the photons must somehow communicate with each other after being asked the questions, or, to use less anthropomorphic language, the experiment done at one door must have an influence on the other side. As far as the experiments tell, these influences travel faster than light. But doesn't this then enter into conflict with the special theory of relativity? This is the topic of Maudlin's book.

I think this is arguably the most important question in physics, yet the only book entirely devoted to it is written by a professional philosopher (but one very well trained in physics). Bell's theorem leaves many physicists indifferent, partly because it is widely misinterpreted as showing only that local hidden variable theories are impossible. One of Maudlin's goals is to convince the reader that the damage is much more serious. I learned the story told above from him and the point of telling it that way is to dispel various confusions about Bell's theorem. It is locality *tout court* which is

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refuted by Bell's arguments and the experimental evidence. To stress it again:

> But what is puzzling about the quantum statistics for pairs of photons is simply that they cannot be reproduced by any means, stochastic or deterministic, if there is no information transfer between the wings of the experiment. Those who doubt this claim are challenged to reproduce the statistics without such transfer, to play our game with one partner not allowed to communicate with the other. They may use whatever stochastic devices they like: decaying uranium atoms, flipped coins, et. They may use whatever modal logic appeals to them. They may invoke whatever standards of explanation they please. The bottom line is: can you get the numbers without having information about the setting of the distant polarizer available to one partner? The answer is that you cannot. This dependence on distant events does not violate any classical physical principles, if "classical" is taken in the usual way. It does at least seem to conflict with relativistic constraints. So we have had reason to be worried about our photons all along. (p. 183)

Another reason why Bell's theorem leaves many physicists cold is that the exact status of the wave function has never been properly clarified. On the one hand, it seems to be of a purely epistemic nature: it represents what we know about the system, or a way to predict results of "measurements." On the other hand, since it is supposed to be the "complete physical description" of the world, it had better have some objective status. If, for example, one takes the wave function as being only a way to predict results of "measurements," what does it mean outside of the laboratory, or before the existence of mankind? This is never made clear in the traditional approach and this ambiguity reinforces the prevailing confusion about the exact meaning of Bell's theorem. Indeed, one way to avoid facing the problem of nonlocality is to imagine that what Bell shows implies merely that when we perform the experiment on one side, we simply learn something about the state of affairs on the other side, but not that we influence that state of affairs. If that were all that is involved in those experiments, there would be nothing to worry about. It is easy to invent purely classical situations where a "measurement" on one side gives us some information about what happens on the other side (just cut a picture in two and send each half to a different person; upon reception, each of them learns which half the other person has gotten). However, the whole point of the analysis by Bell of the EPR situation is that such an account is *impossible* here and that, indeed, intervention at one place does influence affairs at the other.

Nevertheless, it is clear that one must be careful about the possible conflict with relativity. It is rather easy to see that neither the theory nor the experiments allows for an instantaneous transmission of signals. But so what? There is no obvious difficulty with causal loops, but is that all we should worry about? What other constraints does relativity imply? That nothing goes faster than light? What does nothing mean? Matter, energy, information, signals, influences, causation? Or does relativity mean simply the demand that our physical theories be Lorentz invariant?

The main goal of Maudlin's book is to analyze carefully the different constraints that relativity may impose. After a very nice introduction to the theory of relativity for nonexperts, he studies the following four types of "connections": transport of matter, transmission of signals, causal influences, and transmission of messages. Roughly, the upshot is that Bell's theorem does not demand (instantaneous) transmission of matter or of signals, but does imply a causal effect and a transmission of messages. The difference between a signal and a message is that the latter may be "secret," in the sense that one cannot decipher it without further information (think of a message written in an unknown language: information is transferred, since a dictionary allows one to decipher it). Bell's inequalities do indeed demand that secret messages be sent between the two wings of the experiment. Causation is a notoriously difficult notion to define. Maudlin provides a nice and convincing analysis which shows that the Bell "connections" actually imply an instantaneous relation of cause and effect.

Finally, how does all this square with relativity? Even to start the discussion, one must put oneself within a precise conceptual framework, i.e., a precise formulation of quantum mechanics (it is impossible to discuss subtle nonlocal effects in a "theory," such as some versions of the Copenhagen interpretation, which claims that the only goal of physics is to predict results of "measurements"). Maudlin clearly explains the problem faced by any such formulation. One might want the following two statements to hold:

— The wave function is the complete description of physical reality.

— Schrödinger's equation always holds.

But, then, measurements never have definite outcomes, and Schrödinger's cat never ends up alive or dead.

The author considers two precise formulations of quantum mechanics: Bohmian mechanics, where the wave function is not the complete description of reality (particles move along paths) and GRW-type theories,[3] where the Schrödinger equation is not always valid (there are spontaneous collapses of the wave function). Of course, because they are precise theories, neither of them fares very well when relativity is introduced. In each of them, there is a well-defined notion of cause and effect. But since, in the Bell-type experiments, a causal connection goes faster than light, the ordering between cause and effect is not Lorentz invariant, and that is basically the source of the trouble. For example, in a Bohmian approach, one may recover all the experimental results that are interpreted as evidence for the theory of relativity, but the theory is not Lorentz invariant. Similar problems occur in GRW-type theories. Maybe the situation is best summarized in the title of one of the last sections of the book: "Choose your poison."

However, not everybody is so pessimistic. Bell introduced the notion of relative time-translation invariance, which is a kind of nonrelativistic version of the nonexistence of absolute simultaneity. He showed that GRW-type theories can respect this relative time translation invariance and that "the model is as Lorentz invariant as it could be in the nonrelativistic version. It takes away the ground of my fear that any exact formulation of quantum mechanics must conflict with fundamental Lorentz invariance" (ref. 1, p. 209). A somewhat similar result can be obtained in a Bohmian approach.[2]

Maudlin's book is an important one. It discusses in very clear language some of the most puzzling conceptual problems in contemporary physics. It is not mainly a philosophy book, but a physics book, although the practice of philosophy may have helped the author to discuss carefully some conceptual problems which are often overlooked by physicists.

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