Clear as a Bell

John Bell's famous paper of 1964 significantly deepened a controversy over the foundations of quantum theory dating back to Einstein and Bohr in the early 20th century. This year is the 50th anniversary of Bell's momentous achievement — his proof of what subsequently became known as Bell's Theorem. What was it that he actually demonstrated? Surprisingly, physicists still don't completely agree.

Last month, the *Journal of Physics* published a special issue commemorating Bell's paper (http://go.nature.com/IqwLlx). Among many interesting works, philosopher Tim Maudlin offers a paper entitled simply 'What Bell did' (available at http://arxiv.org/abs/1408.1826). In it, he suggests that many physicists today don't really know, and often hold fast to beliefs about Bell's work having little basis in reality. The problem, he thinks, is a loss of context — much of the history that led Bell to his result has been all but forgotten.

The most common idea about Bell's analysis is that it rules out local, hidden variable theories — at least if taken in conjunction with later experiments confirming the relevant quantum mechanical behaviour for entangled pairs of particles. That is, Bell's theorem shows that no conceivable theory fitting the experimental facts can be both local and deterministic; there's no way to cling to the idea that some real physical states of affairs determine each quantum outcome in a way that respects locality.

I've certainly read this idea in many places, including prominent papers in *Nature* and *Physical Review Letters* over the past decade. Is it correct? Not at all, argues Maudlin. The theorem really says nothing about determinism or the possibility of hidden variables, but instead implies — profoundly — that nature is inherently non-local, regardless of anything else.

Bell was motivated, in part, by the famous 1935 paper of Einstein, Podolsky and Rosen (EPR), which made a simple and powerful argument about why the description of nature offered by quantum theory is incomplete. Consider two electrons in a singlet state, the particles located respectively in regions R1 and R2, which are separated by a great distance. By measuring the spin of the particle in R1, we immediately learn the spin of the particle in R2; that particle exists, we now know, in a state of completely definite spin. Yet the quantum description of the second particle, for an observer in R2, remains indefinite. Conclusion: if nature is local, and there is no action-at-a-distance, then quantum systems sometimes have definite properties that quantum theory simply does not describe.

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Note that this argument doesn't make any assumptions about determinism, only about the principle of separability — that something happening in one region of space should not immediately influence what goes on in regions far away. The EPR argument, Maudlin emphasizes, reflects what Einstein saw as the primary problem with quantum theory — not its indeterminism, but its non-locality. Despite the oft-heard quotation that "God does not play dice," Einstein objected more strenuously to the theory's implication that nature seems to use what he called "telepathic methods".

Bohr replied to the EPR paper in famously elliptic terms (*Phys. Rev.* **48,** 696–702; 1935). Although there is "no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure," he had to admit, "there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system."

This sounds a lot like defence by obscurity. Bohr wouldn't accept the EPR conclusion, but he certainly couldn't refute it either. His move was simply to assert that, in some way no one quite understands, there must be an influence between two separated systems, though not a physical influence — something more obscure, more quantum. Bohr's reputation and status were enough to convince a generation of physicists to mostly ignore the issue.

Further work set the stage for Bell. In the early 1950s, David Bohm produced an explicit theory showing how the predictions of quantum theory could be reproduced exactly in a hidden variables theory — one that was explicitly non-local. In doing so, he refuted an earlier 'mathematical proof' by von Neumann that such a theory was impossible. That earlier proof, though incorrect, was hailed by many physicists, again largely on the basis of reputation.

What Bell ultimately did, Maudlin argues, was to clarify the essential role of non-locality in any theory agreeing with the predictions of quantum theory. Which would include quantum theory itself. It's possible to tell the story one way — that Bell's work destroyed any hope for 'hidden variables' because this demand led immediately to non-locality. Who can accept that? He actually showed that you have to live with non-locality no matter what — determinism has nothing to do with it.

The EPR argument demonstrated plainly that, if you accept indeterminism, quantum theory must be non-local. Hence, the logical thing to wonder — setting aside the prevailing biases of the field — was if deterministic theories could do any better, removing the apparent non-locality, quite possibly by restoring determinism. Bell set out the logic very clearly (*Physics* **1,** 195–200; 1964), although this seems to have now been lost on many physicists:

> *"The paradox of Einstein, Podolsky and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality. In this note that idea will be formulated and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely, that the result of an experiment on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty."*

Note the final sentence especially. This was the significance of the result as Bell saw it. In the end, Bell's famous paper didn't prove the impossibility of hidden variables at all. Its point was that, whatever one may think about determinism or indeterminism, there's just no hope for retaining locality. Start thinking about how we might learn to live with it.

I think Maudlin is largely correct. Some other physicists, it should be said, do not agree (for example, see the reply to Maudlin's paper by Reinhard Werner in the same volume). The arguments and reinterpretations go on, in part because of the subtleties of the topic, but also, I suspect, because it's hard to discuss any of this with deep intuitions about how the world 'ought to be' getting in the way.

Bell worked very hard to make logic show him the way. ❐

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