JOHN BELL'S APPROACH TO THE EINSTEIN-BOHR DEBATE

Bell built his theorem on the idea of EPR, imagining the results of measurements on two particles formed from the decay of a single parent particle. Since they start out as one, such particles, once they are separated, are referred to as "entangled," and, by the laws of quantum mechanics, if we now measure the properties of one of the entangled particles, we instantly know the properties of the other. In addition to features like position and momentum, for example, quantum particles also exhibit a property called "spin." The total spin of a system of particles must be conserved; that is, if one of the entangled particles exhibits what is called "spin up" the other necessarily exhibits the property called "spin down." As a result, if we know the spin of one, we automatically know the spin of the other—it will be the opposite—and in this sense the two entangled particles are perfectly correlated with each other.[4] As the French physicist Alain Aspect remarks: "When a measurement is carried out on one of the entangled particles, it is as if its twin immediately felt this and adopted a physical state corresponding to that of its partner."[5]

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[4] Strictly speaking, this particular case is called "anti-correlation." The distinction is unnecessary for our purposes, however, since the important point is that there is perfect correspondence and predictability between the spins of the two particles.

[5] Alain Aspect, "The Bohr-Einstein Debate and Quantum Entanglement Tested Experimentally," *Centre National de la Recherche Scientifique* (National Center for Scientific Research), 2005, 5; available at

http://www2.cnrs.fr/sites/communique/fichier/bohr_eisntein_en.pdf. It was the physicist David Bohm who, more than fifteen years after EPR, first cast Einstein's thought experiment in terms of "spin" rather than position and momentum. See David Bohm, *Quantum Theory* (New York: Prentice Hall, 1951). Bell incorporated this emendation in his theorem, and the experiments that followed have done likewise in one form or another. Accordingly, such experiments are often referred to as EPRB experiments, recognizing Bohm's formative role.

This seems reasonable enough on the surface, but notice the puzzle it creates. The perfect correlation between the particles would be one thing if they were still in close proximity to each other when one of them was measured. Then we could imagine the particles influencing one another in the same way that two billiard balls affect each other upon colliding. In the case we are considering, however, that is not the situation at all; the particles are actually far apart. So it seems that the measurement of one particle influences the physical state of the other, *despite the distance between them*. In Einstein's view, not to mention in our ordinary intuitions, that's the puzzle: How can the measurement of one particle possibly determine the physical state of another, when the two are nowhere near each other?

Einstein believed that this could not in fact happen. He believed that the two particles' properties are correlated with each other simply because those properties were acquired at the beginning, when they were still a single particle, and that they then simply carry those properties forward as fixed, stable characteristics until the time of measurement. This seems reasonable enough. Another appealing explanation is that the particle that undergoes measurement somehow "communicates" with its twin when it is measured, whereupon the twin particle then adopts the proper physical state in response. As suggested above, however, this seems odd if the distance between the particles is at all significant, and it is considered impossible if the distance between the particles is so great that such communication would have to occur at faster than the speed of light: By the principles of special relativity, communication at such speed is not possible. So, according to Einstein's view, the only real possibility is that the two entangled particles simply possess their properties from the beginning—*that* is what explains the correlation between them—and that those properties are not influenced by the subsequent act of measurement at all.

Bohr, on the other hand, believed that the correlation between the properties must be due to the entangled particles' continuation as *one system*. In this view, the two particles actually possess an overall quantum state between them—a single, nonseparable system—so that measurement of one of the particles automatically has an effect on the other. In that case, it is still true that no physical properties exist until measurement, but it is also true that a single measurement actually affects both of the particles—and that is why there is a correlation between them. In this scenario, a measurement on one particle affects the other precisely because they are *not* separated by space in any ordinary sense; the two are entangled, and it is simply not possible to talk about one without talking about the other.

In constructing his theorem, Bell proceeded on the assumption that Einstein was correct in these two ways: (1) quantum-level particles actually are similar to ordinary objects in our experience and possess states that are fixed (states that are independent of our observations of them), and (2) such objects cannot influence each other when separated by space (specifically, again, space so large that it would have to be traversed by an influence traveling faster than the speed of light).[6]

Making these assumptions, Bell identified the range of correlations that would be achieved by simultaneous measurements of the two entangled particles under various conditions: If we measure the two particles under condition x, what correlation would

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[6] This is no small requirement. A recent study demonstrates that, given certain conditions, the velocity of any communication or influence between the two particles would have to be greater than the speed of light—if that is possible at all—*by four orders of magnitude*. In other words, it would have to be 10,000 times faster. See Daniel Salart, Augustin Baas, Cyril Branciard, Nicolas Gisin, and Hugo Zbinden, "Testing the Speed of 'Spooky Action at a Distance,'" *Nature* 454 (2008): 861–64; available at http://www.nature.com/nature/journal/v454/n7206/full/nature07121.html.

we expect between their properties? If we measure them under condition y, what correlation would we expect between them? And so on, ultimately establishing an absolute range for the correlations required by Einstein's view and that were different from those that would be required by Bohr's. Universally acclaimed as an achievement of the most remarkable subtlety and elegance, this was the conceptual foundation that permitted Aspect, and others since him, to conduct empirical tests of the deep theoretical divide between Einstein and Bohr. The results of these experiments have been a major source of support for Bohr's view, that is, that activity at one quantum location can indeed influence activity at another location without any apparent interaction between them.