The Bell Inequalities, Contextualized

The mathematical predictions of quantum mechanics are stupendously precise. However, many of those predictions are statistical, giving only the *probabilities* of various outcomes. For example, a circularly polarized photon has a 50% chance of passing through an ideal linear polarizer. Did an individual photon, previous to the encounter, possess a property that determined whether it would pass through the polarizer? Or did the photon 'make up its mind' at the last minute, at the moment when it encountered the polarizer?

If we believe that the photon possessed, before the fact, the property we end up measuring – that the measurement merely revealed a pre-existing trait -- then we believe in *realism*, and we might say that the photon is characterized by a hidden variable. We call it 'hidden' because it makes no appearance in present-day quantum mechanics. If the hidden variable exists, then quantum mechanics must be incomplete, as Einstein, Podolsky, and Rosen argued in 1935. If the hidden variable doesn't exist, then the photon is in some kind of undecided state prior to measurement. Prior to measurement, the photon's linear polarization is not merely unknown, but perhaps even unknowable, because it's actually non-existent.

The argument in favor of hidden variables was supported by a common-sense analysis of entangled particles. For example: it's possible to create pairs of 'entangled photons', traveling away from each other, with correlated polarizations, in the sense that either both photons will pass through horizontal polarizers, or both will be blocked by horizontal polarizers. Each of these outcomes is equally likely. If the photons 'make up their minds' at the last minute in encountering the polarizers, it would seem they have to communicate this decision to each other instantaneously, over an arbitrary separation, to ensure that they both do the same thing.

A seemingly more plausible assumption is *locality*: the measurement of one photon, or the results of that measurement, does not affect the other photon, or the results of its measurement. If we assume both locality and realism, then each photon is pre-programmed (with a hidden variable) either to pass through its polarizer or get blocked, and the two photons in a pair are identically pre-programmed, to account for the observed results. Some people argue that locality, combined with the observed correlations, implies realism. Alternatively, we may view locality and realism as separate assumptions.

Although the hidden variables -- factors that predetermine measurement outcomes -- are absent in standard quantum theory, some physicists initially hoped that an enhanced quantum theory might one day elucidate the hidden variables. Someday, quantum mechanics might then become a theory of particles that chart their own courses, free of distant influences and last-minute decisions; it might even become a theory of certainties, not probabilities.

But in 1964, John Bell showed that this was impossible. The assumption of locality, with the concomitant assumption of realism, imposes a constraint on a measurable quantity. Bell showed that quantum theory predicts a violation of the constraint (now called a Bell inequality). Thus, quantum theory is irremediably incompatible with the common-sense assumption of local realism. The question, finally, became a matter of experimental fact, rather than philosophical speculation: does experiment satisfy the Bell inequality (and thus contradict quantum theory), or does it violate the Bell inequality (and thus overturn local realism)?

The first experimental test of a Bell inequality was performed in 1972. Increasingly sophisticated tests have been performed ever since. And the results? Bell inequalities are certainly violated, and they are violated in just the way predicted by quantum theory. Hence there must be at least one false assumption in the derivation of the Bell inequality.

But which is the false assumption? If locality is the false assumption, then the measurement of one photon might instantaneously affect the other photon over any distance. It turns out that this sort of superluminal influence cannot be used to transmit messages, because the common outcome of the two measurements is random. Therefore 'spooky action at distance,' as Einstein called it, is actually compatible with special relativity.

Some believe that these results ultimately boil down to illustrating 'correlation without cause,' or what physicist Abner Shimony has called 'passion (i.e. feeling) at a distance' in place of 'action at a distance'. The relatively new quantum interpretation called *QBism* rejects realism and preserves locality by asserting a kind of correlation without cause.

But let's not be too hasty. Bell inequalities depend on other assumptions than just locality and realism. One implicit assumption is that the experimenter can freely choose measurement settings. If this assumption is incorrect, then we might have saved local realism, but at what price? Without free choice, we live in a 'superdetermined' universe in which free will is an illusion.

Another assumption, *counterfactual definiteness*, is that we can meaningfully discuss what particles would have done under conditions different from those they actually encounter. Again, we might save local realism by rejecting a different everyday assumption, but it's unclear whether we've gained anything.

What, ultimately, is the significance of a Bell-inequality violation? It falsifies one of our everyday assumptions, possibly locality or realism, but possibly something else.

The trouble with surviving quantum interpretations is that all of them conform to available data -- otherwise, they would have been eliminated by now. For example, if one claims that the measurement of one photon affects a distant photon, then one would like to watch this effect take place. But that's impossible, because the claim is really that the first measurement of *either* photon affects the other, and there's no way to make any measurement prior to the first measurement. 'Spooky action at a distance' can never be directly confirmed or denied.

The meaning of quantum physics has been debated for decades and remains a subject of active interest. In 2018 alone, multiple popular-level books about quantum interpretations were published, including *Beyond Weird*, *Totally Random*, and *What Is Real?* The last word has not been written about the meaning or interpretation of quantum mechanics. Today's students inherit our beautiful mess, and all its opportunities for advancement. Your first plunge into Bell inequalities might even be in a laboratory course, where theory meets reality…whatever *that* is.

Jed Brody
Author of *Quantum Entanglement* (forthcoming from MIT Press)
Senior Lecturer in Physics, Emory University