Michelle Wellman
3/24/19
Phil-222, Professor Nina Emery
Bell's Theorem Paper

While it is not unusual for physicists to encounter strange phenomena when studying the universe, it is rare for them to observe something as surprising as the results of the EPRB experiment. What is so surprising about this experiment is that the results show a perfect anti-correlation which cannot be explained by any regular means of explaining a correlation. One theory put forth to explain this perfect anti-correlation is known as hidden variables theory, which uses a common cause explanation to make sense of the results. In response to hidden variables theory, John Stewart Bell made the argument that if one accepts two assumptions known as no-conspiracy and locality, the hidden variables' theory cannot be used as an explanation for the perfect anti-correlation because it contradicts predictions derived from mathematics. This argument is known as Bell's Theorem. The best way to respond to Bell's Theorem is to give up the locality assumption, which would allow us to keep hidden variables theory and explain the perfect anti-correlation using a common cause explanation. This paper argues for this statement by detailing Bell's Theorem, the three ways of responding to it, making an argument for giving up locality, and finally discussing a possible objection to the argument and determining that the objection is unconvincing.

In order to understand Bell's Theorem, the EPRB experiment must be understood. The EPRB experiment was inspired by a thought experiment published by Einstein, Podolsky, and Rosen in 1935. The set-up of the experiment has a source emitting pairs of spin-1/2 particles simultaneously so that one goes to the left side of the set-up and the other one goes to the right. Both particles travel through Stern-Gerlach magnets, and then hit a detection screen which will show whether the particles were deflected up or deflected down when going through the magnets. The magnets can be oriented at any angle, however when they're both oriented at the same angle, the only two observed outcomes are either the particle on the right is deflected up and the left particle is deflected down, or the particle on the right is deflected down and the left particle is deflected up. These results are described as a perfect anti-correlation because the outcome on the right side always takes the opposite value of the outcome on the left. It doesn't matter what the angle the magnets are oriented at. If they are oriented at the same angle, the perfect anti-correlation will be observed (Emery and Hall, 21).

Einstein, Podolsky and Rosen devised an explanation for the results of the EPRB experiment known as hidden variables theory, which states that before the particles leave the source, they are each assigned an instruction set that determines whether they are certain to go up or certain to go down through any possible angle the magnets can be oriented at. These instruction sets come with three properties: The first property is that the instruction sets are complete, which means that the particles are given instructions for every possible angle the magnets can be oriented at. The second property is that the instruction set are deterministic, which means that for every possible angle the magnets can be oriented at, the particle will be certain to go up or certain to go down through the magnets. The third property is that the instruction sets are anti-corelated, which means that for every possible angle, the particle pairs will be given instruction sets that are the exact opposite of each other. So, if the left particle is instructed to go up through a certain angle, the right particle will be instructed to go down through that same angle. These instruction sets are known as hidden variables, and they must possess all three of these properties in order to explain the perfect anti-correlation (Emery and Hall, 23).

In response to the EPRB experiment as well as hidden variables theory, Bell came up with a proof to argue that hidden variables theory can’t be used to explain the perfect anti-correlation if the following two assumptions are true: The first assumption is known as no-conspiracy, which states that the pair of particles themselves do not have any influence over the orientation of the magnets. The orientation of the magnets is left up to the free will of the experimentalist. The second assumption is known as locality (also known as independence), which states that the outcome on one side of the experiment has nothing to do with whether or not a measurement has been performed on the other side of the experiment, or what that measurement is (Emery and Hall, 24).

Assuming a hidden variables theory that explains the perfect anti-correlation, and that does not violate no-conspiracy or locality, Bell used algebra to prove that hidden variables does not align with predictions made by the cos-squared law, a formula that was derived from standard mathematical formalism (Emery and Hall, 30). The cos-squared law makes predictions on the probability of a particle going up or going down through a magnet at a given orientation using a simple formula involving cosines (Emery and Hall, 8). To begin the proof, Bell considered a set of three different cases for the EPRB set up, as well as a complete list of possible pairs of instructions that could be given to the particles by the source. Each pairing was assigned an unknown variable corresponding with hidden variables theory that represents the probability of seeing that set. Using this table, Bell came up with the probabilities of seeing different outcomes on both sides of the experiment (one particle goes up and the other particle goes down) for each of the three cases considered in terms of the probability variables assigned to each instruction set. Bell also calculated the probabilities of seeing different outcomes on both sides of the experiment using the cos-squared law for all three cases. From the results obtained by hidden variables and the cos-squared law, Bell used algebra to prove that these theories do not make the same predictions on whether or not different outcomes will be seen in each of the three cases (Emery ad Hall, 27-30).

To conclude, Bell's Theorem states that if the no-conspiracy and locality assumptions are true, hidden variables theory must be false since it does not make the same predictions as the cos-squared law. This is important because physicists agree with the cos-squared law since it was derived from mathematical formalism. Additionally, when the experiment is run, the outcomes match the predictions made by the cos-squared law. Therefore, the contradiction between hidden variables and the cos-squared law must be taken seriously.

There are three ways one could respond to Bell's Theorem. The first possible response is to give up the no-conspiracy assumption. This would imply that the source is in some way either anticipating or constraining a person's choice on the orientation of the magnets, meaning that they have no free will in the experimental set-up. The second possible response is to give up the locality assumption. This would imply that the outcome on the left side of the experiment is dependent on the outcome on the right, and vise-versa. While this may be possible, a good explanation is owed for how this happens. The third possible response would be to give up hidden variables' theory, which would imply that the perfect anti-correlation cannot be explained by a common cause explanation. This would require a different method of explaining the perfect anti-correlation (Emery and Hall, 31).

Out of these three possible responses to Bell's Theorem, the best one is to give up the locality assumption. This is the best response because it doesn't require the consideration of the absence of free will, nor does it imply a direct causal connection which would be the most plausible way of replacing hidden variables theory. Hidden variables theory does not agree with the mathematical formalism; however, this disagreement remains as long as no-conspiracy and locality are kept. Giving up hidden variables' theory would require the consideration of a direct causal connection, which would most likely mean that one of the particles is being influenced by a signal coming from the other particle instructing it to go in the opposite direction. This is not a good explanation because it violates special relativity since it would require signals that could travel faster than the speed of light. Additionally, physicists have not been able to detect or block a signal of any kind between the two particles when running the experiment.

Giving up the locality assumption is surprising because based on every day experience, it seems obvious that the cause of any event would always be spatially adjacent to it. However, there is a theory in classical mechanics known as Newtonian gravitational theory that allows causation at a distance. According to Newtonian gravitation, every massive particle exerts a gravitational force on every other particle, even particles that are light years away. Knowing that even a small gravitational force has an influence over particles that are so far apart from each other makes quantum causation seem less surprising (Maudlin, 21).

One could object to this argument for giving up locality by demonstrating that the connections made between Newtonian gravitation and quantum causation are invalid. Proving that this connection is invalid could rule out this justification for giving up locality. They could do so by pointing out three important properties that are observed in quantum causation but not seen in gravitation. The first property is that quantum causation is unattenuated. The gravitational force between two particles becomes weaker when there's a greater distance between them. This property is not seen in quantum causation. The strength of the effect of quantum causation remains the same even at a large distance where gravitational forces would be so small, they would be negligible (Maudlin, 22). The second property is that quantum causation is discriminating. The gravitational force created by one particle will affect any and every other particle, decreasing in strength with distance. However, with quantum causation, particles will only affect each other if they have interacted in the past. Therefore, quantum causation is discriminating, meaning it only affects certain particles, whereas gravitation has the opposite effect since it affects all particles (Maudlin, 22). The third concerning property with quantum causation is that its effects appear to exceed the speed of light. Although classical forces such as gravitation were originally described as instantaneous, special relativity rules this out by dictating that nothing can be faster than the speed of light. Quantum causation appears to violate special relativity since the effects are instantaneous even at a large distance. A large enough separation between the particles would require any communication between the particles to exceed the speed of light (Maudlin, 22-23). These properties of quantum causation contradicted by gravitation draws concern on giving up locality and keeping the hidden variables' theory.

This objection to the argument on giving up locality is unconvincing because we do not need to worry about whether quantum causation shares the same properties as Newtonian gravitation. The argument does not state that quantum causation has any of the same properties as Newtonian gravitation, and does not attempt to make a completely direct comparison to it. The reason for comparing quantum causation to Newtonian gravitation is to illustrate the fact that causation at a distance is physically possible. This is accomplished by pointing out that causation at a distance has been seen before in gravitation, a phenomenon that everyone is already familiar with. The properties possessed by gravitation such as it being attenuated, and non-discriminating isn't necessary for causation at a distance to be possible. While the fact that quantum causation is observed to be very different from Newtonian gravitation does make it less plausible, it does not make it impossible. Ruling out this objection proves that giving up locality is possible and giving up locality makes it possible to keep hidden variables theory. This theory might not be perfect, but it’s the best explanation for the perfect anti-correlation seen in the EPRB experiment.

Works Cited

Emery, Nina, and Ned Hall. “*Notes on the Philosophy of Quantum Mechanics*”.

Maudlin, Tim. “*Quantum Non-Locality and Relativity: Metaphysical Interpretation of Modern Physics*” 3rd Ed. Blackwell Publishing Ltd, 2011.