“Ethereal Non-Locality” and Causal Influence in Quantum Mechanics

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1 Introduction

In 1935, Einstein, Podolsky, and Rosen (EPR) published a paper, Einstein et al. (1935), which set up the first half of a conundrum in quantum mechanics. EPR argued through a thought experiment that assuming locality in quantum mechanics meant that the ψ-function could not provide a complete description of a physical system — that there must be hidden variables that pre-determine the outcomes of measurements. Thirty years later Bell (1964) showed there could be no such hidden variables. Together, these two papers can be thought of as setting up the following argument: if the predictions of quantum mechanics are correct, then quantum mechanics is an inherently non-local theory.

What is troubling about non-locality? Einstein was famously opposed to it, naming the implied non-locality of quantum mechanics “spooky action at a distance.” This “action at a distance” is the idea that two particles can be space-like separated, and yet still be correlated in a way that is not deterministic. This notion directly conflicts with a natural understanding of causality, inspiring the resistance against it. Yet perhaps not all is lost. A general attitude towards this non-locality is shown by this quote from Griffiths and Schroeter (2020): “Causal influences cannot propagate faster than light, but there is no compelling reason why ethereal ones should not. The influences associated with the collapse of the wave function are of the latter type, and the fact that they ’travel’ faster than light may be surprising, but it is not, after all, catastrophic.”

In this essay, I will explore the concept of “ethereal non-locality” and its implications for causal influence in quantum mechanics. I will challenge Griffiths’ claim that ethereal influences are not catastrophic (catastrophic to whose or what’s ends?) and argue that the non-locality of quantum mechanics does indeed pose a major challenge to either our understanding of physics or our philosophy of causality.

I will first present the EPR argument and Bell’s theorem, and demonstrate the relevant technical details of quantum theory. I will then discuss the dominant theory of causation and approach to causal inference, and show how they are challenged by the non-locality of quantum mechanics. Finally, I will argue that rather than accepting ethereal non-locality as a benign feature of quantum mechanics and arguing that it is not catastrophic, we should instead take it as a serious challenge to be addressed by future research in the philosophy of physics, with consequences not only for our understanding of quantum mechanics, but also for our understanding and broader application of causal inference.

2 The EPR-Bell Argument

The EPR and Bell arguments both deal with the concept of entanglement. Entangled particles are those which have been prepared such that they are described by a wave function that is not separable into the wave functions of the individual particles, resulting in a correlation between the two particles. For simplicity, we will sum up both EPR and Bell using the same example of an entangled system, the GHZ state given in Greenberger et al. (2007). The GHZ is a three-particle entangled state, with the following properties:

- If spin is measured along the x-axis for all three particles, the number of particles with spin up will always be odd.
- If spin is measured along the x axis for the one particle, and along the z-axis for the third particle, the number of particles with spin up will always be even.

On this experimental setup, the EPR argument would ask us to consider the following: In the case of either measurement, all x spin or one x and two z spins, if we measure the first two outcomes, we can predict the third outcome with certainty. *Before I ever measure* the third particle, I know what the outcome of the measurement will be. However, I could not predict this outcome from the preparation of the state alone. This means that one of two things happened: either the state of the third particle was determined at the time of preparation, or the measurement of the first two particles somehow influenced the outcome of the third particle instantaneously. EPR assume locality to hold, and so they conclude that the state of the third particle must be determined prior to measurement. However, the key takeaway is that if quantum mechanics is local, then the ψ-function cannot provide a complete description of the physical system — there must be some hidden variable which determined the outcome prior to the measurement which was not captured in the ψ-function.

Bell's work, on the other hand, shows that there can be no such hidden variable. If the outcomes of the measurement are determined by some hidden variable prior to measurement, then there must be some way to assign outcomes of measurements to each of the particles in the state before measurement. Bell showed that this cannot be done — There is no way to assign the states of the particles in the GHZ state so that the parities of the outcomes of the measurements are consistent with the predictions of quantum mechanics.

EPR and Bell put together show the following: If the relevant predictions of quantum mechanics are correct, then the theory is non-local. The wealth of experimental evidence put together since the 1960s has shown that the predictions of quantum mechanics are indeed correct, and therefore, quantum mechanics is a non-local theory.

3 Non-local Causation?

As previously mentioned, Griffiths acknowledges the locality given by EPR-Bell, but refers to this non-locality as "ethereal" and not causal. This begs the question of what we mean by causality, and when we can conclude that an interaction is or isn't causal. Until we have a clear account of causality, we cannot say whether or not the correlation between the measurements in the GHZ state is causal.

There are a number of philosophical theories of causation, but the dominant approach in the philosophy of science is the counterfactual theory of causation as formulated by Lewis (1973). On a simple telling, this theory states that A causes B if and only if B would not have occurred if A had not occurred while holding fixed all other variables. The statistical method of causal discovery, as formulated by Pearl (1995) relies on this theory, formulating a counterfactual as a conditional probability. The counterfactual probability of B given A is the probability that B would have occurred if A had occurred, while holding fixed all those variables which do not lie along a causal pathway from A to B. This method has been used to great success in a number of fields, including epidemiology, economics, and computer science.

To see how causal inference is conducted, consider the following example. Suppose we have a dataset of patients who have been treated with a new drug, and we want to know whether the drug is effective. We can use the counterfactual method to estimate the causal effect of the drug on the patients. We can compare the outcomes of the patients who were treated with the drug to the outcomes of the patients who were not treated with the drug, while holding fixed all other variables which may have influenced the outcome of the patients. This is called a randomized interventional trial, and is thought to detect causal relationships between variables.

This method of causal inference is based on the underlying assumption of the *causal markov condition*, which simply states that statistical dependencies in a causal system must be captured in the causal graph of that system as either causal relationships or as a product of a common cause. For causal inference to be valid, we must be able to construct a causal model of for which the Markov condition holds in every system, else the implication is that causal inference may detect spurious relationships between variables which should not be causally linked Geiger and Pearl (1990).

Let us consider the GHZ state in the context of this method of causal inference. If we consider the counterfactual probability of the outcome of the third particle given the outcomes of the first two particles, we find that the outcome of the third particle is perfectly correlated with the outcomes of the first two particles. By preparing the GHZ state specifically we have conditioned on the preparation of the state, and so, as in the EPR argument, we reach the following conlusion. Either there are some other variables to be considered in our causal model, or the correlation between the measurements in the GHZ state is causal according to our causal inference. Given Bell's work, there may be no hidden latent variable to consider, and so we must conclude that according to our common understanding of causality, this influence is causal.

We are now left with two options. Either we accept this relationship as causal, and thus must acccept causal influence that travels faster than the speed of light, or our dominant approach to causality is flawed. The nature of this flaw is concerning — we have a clear statistical dependency in our system which is we cannot account for in our causal model, indicating that we have found a violation of the Markov condition which underlies causal inference. As Griffiths points out, the first option is catastrophic (to special relativity) — however, I contend, so is the latter (to causality). If the critical underlying assumption of causal reasoning is shown to be violated by fundamental physics, then we are forced to reconsider our use of causal inference in a number of fields, and to reconsider our understanding of causality itself.

4 Discussion

Griffith's claim that the non-locality of quantum mechanics is not catastrophic is based on the idea that the non-local influences in quantum mechanics are not causal, meaning that we are not forced to accept any signal propagation faster than the speed of light. However, this idea neglects to consider the implications of concluding that the correlation between the measurements in the GHZ state are non-causal. If we, like Griffiths, wish to preserve locality of causation, then we must ask ourselves what changes we need to make to our understanding of causation.

One possible solution is to conclude that the Markov condition approximately holds. Perhaps it's the case that in all macroscopic systems, the Markov condition is viable, even though it is violated in quantum systems. This resolves our issue to a certain degree, but it raises the question of what exactly is the nature of the boundary between the quantum and classical worlds, and how should when know when it is appropriate to apply causal inference to a system, questions which require further research.

Another approach might be to turn to another theory of causation which can handle the exclusion of non-local causation. Process theory, as discussed in SEP (2008) is a theory of causation under which variables A ad B are allowed to have a causal relationship only if there is a process or mechanism through which we understand A to impact B. This theory provides us with a justification of rejecting non-local causation — two space-like sepatated particles cannot have a causal mechanism through which they influence each other if we are continuing to assume non0signalling, and so we can reject the causal relationship between the measurements in the GHZ state. However, this approach means that we need to reevaluate our use of counterfactual reasoning in causal inference, and to develop new methods of causal inference which are compatible with process theory.

In conclusion, the non-locality of quantum mechanics shown through the EPR and Bell arguments poses a fundamental challenge to the assumptions underlying our dominant theories of causation and causal inference. While we have theories of causation such as process theory which can handle the exclusion of non-local causation, the counterfactual approach which underlies techniques of causal inference and discovery is fundamentally challenged by the non-locality of quantum mechanics. While Griffiths may consider this challenge to be "non-catastrophic", I argue that it poses a critical challenge to our understanding of causality and requires further research in the philosophy of physics and causal inference.

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