“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, in 1964, John Bell published a paper, Bell (1964), that 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 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 dominant theories of causation and 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* teh 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 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 two most relevant to this discussion are the counterfactual theory of causation and the process theory of causation. The counterfactual theory of causation, as formulated by Lewis (1973), states that A causes B if and only if B would not have occurred if A had not occurred. The process theory of causation, on the other hand, states that A causes B if and only if there is a causal process that connects A to B.

If one adopts a process theory of causation, then it seems that we may safely conclude that the correlation between the measurements in the GHZ state is not causal. One simply concludes that "processes" may not travel faster than the speed of light (this can be considered an outcome of the theory of relativity) and so the correlation between the measurements in the GHZ state cannot be causal.

However, the dominant theory of causation which underlies the process of causal discovery and inference is the counterfactual theory. 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 if 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.

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 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 and requires revision. As Griffiths points out, the former is catastrophic — however, I contend, so is the latter. If a dominant theory and approach to causation is marked flawed by fundamental physics, then we must interrogate our use of causal inference and understanding if and why it still works.

4 Discussion

Due to the physical consequences of accepting non-local causality, we should prefer to accept that quantum mechanics provides a fundamental challenge to the counterfactual approach to causal inference and the theory that underlies it. If this is the case, we should examine what precise aspects of causal inference fail, and what we can do to revise them.

One key assumption underlying causal inference is the assumption of the faithfulness condition. This assumption holds that any two variables in a causal model which are dependent are either causally related or have a common cause. This is the assumption that clearly fails in the GHZ state — the outcomes of the measurements are fully dependent, but there is no common cause, and we want to assume that there is no causal relationship between the measurements.

This violation of faithfulness is concerning. Despite the fact that faithfulness holds in the majority of cases, the fact that it fails for fundamental physics shows that the universe may be inherently non-faithful. If this is the case, then it is not clear how we can justify our assumption of faithfulness when we perform causal analysis. It is probable that we can still assume faithfulness on certain types of variables and certain circumstances, but we may then need an account of when we can and cannot assume faithfulness, and how our fundamental physics can predict the faithfulness of a system.

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 fundamental challenge to our understanding of causality and requires further research in the philosophy of physics and causal inference.

References

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