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Comparing causality principles

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Abstract

The principle of common cause is discussed as a possible fundamental principle of physics. Some revisions of Reichenbach's formulation of the principle are given, which lead to a version given by Bell. Various similar forms are compared and some equivalence results proved. The further problems of causality in a quantal system, and indeterministic causal structure, are addressed, with a view to defining a causality principle applicable to quantum gravity.

Keywords: Causality; Locality; Quantum mechanics; Bell's theorem; Causal sets

1. Introduction

In the search for new and more general theories of nature, it is of interest to ask which physical principles will survive in the next fundamental theory, and which will be only approximately true. Candidate answers have been of use in the formulation of theories in the past, and one might hope that they may be again, for instance in quantum gravity. Most directly, given a kinematical framework, physical principles can be used to constrain the dynamics until only a small class of theories remain (e.g. the derivation of general relativity from the principle of equivalence, general covariance, *etc*.). In the causal set quantum gravity program, which is based on a simple kinematical structure, this approach is particularly natural, and has already been used to formulate a stochastic dynamics for causal sets (Rideout & Sorkin, 2000).

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As superluminal signalling (or more objectively, superluminal influence) is widely held to be impossible in current theories, and moreover seemingly impossible to square with relativity, a condition based on this would be a strong candidate for a fundamental principle (Dowker, Henson & Sorkin). What form would such a principle take? It would be desirable to avoid two things: subjective statements involving observers, and controversies in the philosophy of causation. Therefore, so far, the causal principles of most interest to physics have been those that give conditions, in terms of probabilities, that are meant to be physically reasonable without the need for one agreed definition of causes, effects and so on. These conditions, and their names, are many and various; screening off, the Reichenbach principle of common cause (PCC) (Reichenbach, 1956), local causality (Bell, 1987, pp. 52–66), and stochastic Einstein locality (SEL) (Hellman, 1982) are most widely used. Uffink (1999) provides a good introduction to the PCC, raises some of the questions that I attempt to deal with below, and criticises other forms of the principle.

The seeming variety of formulations might be taken as speaking against causality as a fundamental principle. However, as the conditions are clarified, generalised and otherwise revised, they tend either to fall victim to paradox or to converge to equivalence. An example of this is given in the first section of this article, where Reichenbach's PCC becomes a statement resembling Bell's version of screening off after a few well-motivated revisions (Butterfield (1994) includes a related discussion of SEL). In the same section, screening off is seen to be immune to certain paradoxes that afflict other PCC-like principles. Various other forms of the principle are compared and some claims of equivalence proved. An argument by Dowker, Henson, and Sorkin (n.d.) is also touched on below: that even "weak relativistic causality", a very weak "common cause" condition, is equivalent to screening off, if taken to be true when probabilities are conditioned on past events.

All this would not be surprising if quantum mechanics did not violate screening off. As it is, all of the stochastic definitions of causality fall down here. But still, quantum mechanics does not allow superluminal signalling, leading many to think that there really is no superluminal influence, i.e. that some principle of relativistic causality should still hold here. If this attitude is taken, then there is some assumption that has been used so far which needs to be dropped. One such assumption is this: that the framework of stochastic processes is a sufficiently general one to describe our physical theories, containing all relevant information about the system in question, in particular everything that could possibly be relevant to causality. Recent developments in quantum mechanics cast doubt on this. Quantum mechanics can be described as *quantum measure theory* (Sorkin, 1994, 1995; Martin, O'Connor, & Sorkin, 2004), a generalisation of probability measure theory, giving rise to the idea of a *quantal process* as a more fundamental framework than the stochastic process. In Dowker et al. (n.d.) a candidate principle called *quantum screening off* is derived using this line of thought, and shown to be obeyed by local relativistic QFT. In Section 3, quantum screening off is reviewed and two forms compared, in close analogy to the previous section's discussion of stochastic screening off.