Causal Inference in EPR

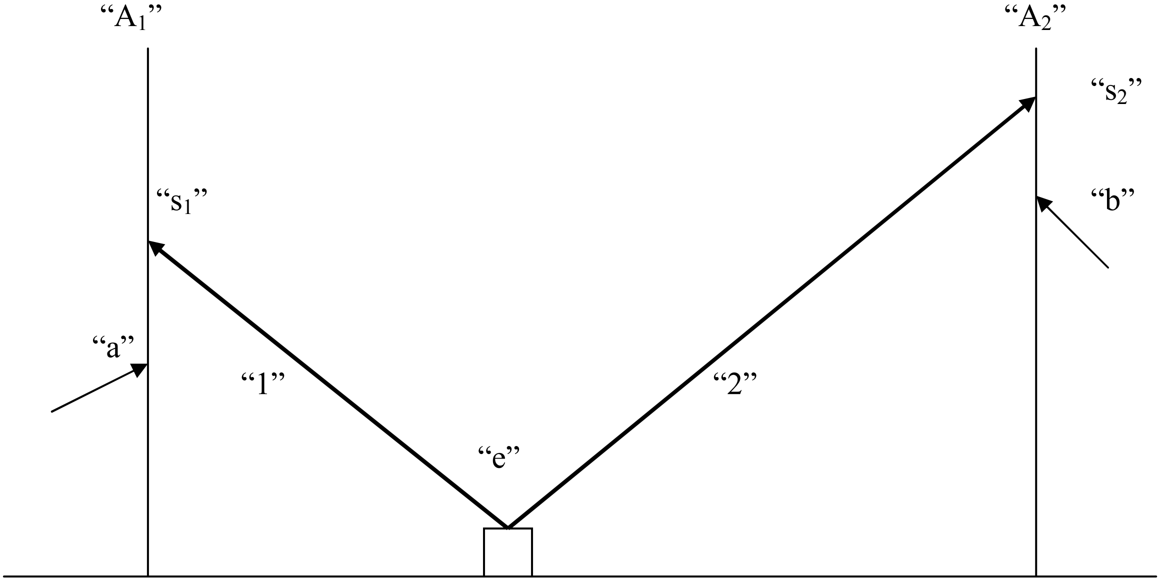
Mauricio Suárez, Universidad Complutense de Madrid

Appeared in: D. Greenberger, K. Hentschel and F. Weinert (eds.), *Compendium of Quantum Physics: Concepts, Experiments, History and Philosophy*, Berlin: Springer, 2009, pp. 93-96.

The status of causality in the EPR experiment has always been a source of controversy. A condition of local *causality* is implicit in the original EPR criterion of reality: "If, without in any way disturbing the system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." In the EPR set-up both systems have separated and are no longer interacting so it is assumed that "no real change can take place in the second system in consequence of anything that may be done to the first system" (EPR, p. 779). The non-disturbance clause in the antecedent is hence satisfied, and we may predict with certainty the values of properties in the distant wing. In other words: although the theory does not represent causal influences, there seems *prima facie* to be physical determination of values across a spatial gap. This notoriously led EPR to draw the conclusion that the theory is incomplete; but in the aftermath of Bell's theorem it is customary to draw the alternative conclusion – that there is non-local causation in nature. Indeed Bell's theorem has been the driving force of scepticism regarding local causality in the literature. In the last two decades the scepticism has linked up to a more general worry concerning the inference of causal hypotheses from statistical correlations in quantum mechanics. For physicists these issues matter to the evaluation of the compatibility of quantum mechanics with special relativity theory, and the prospects of a unified quantum gravitational theory. For philosophers these issues are key to a thorough assessment of the philosophical implications of quantum mechanics; and in addition EPR has become one benchmark against which all methodologies of causal inference are routinely tested.

The EPR experiment briefly reviewed

Recall that in Bohm's version of the EPR experiment two particles ("1" and "2") are simultaneously created at some event "e" in the singlet state Ψ and move in opposite directions. In a Minkowski space-time diagram, both particles describe symmetric paths along the time axis (see figure 1). The Stern-Gerlach apparati that measure these particles' spin at each wing of the experiment are at rest in the laboratory frame so their world lines are represented by vertical lines "A_1" and "A_2" in that frame. Each time the experiment is repeated, laboratory technicians can freely select a particular orientation of the measurement apparatus in each wing, and we denote such events as "a" and "b". Each particle's spin is measured on interaction with the associated measuring device on the corresponding wing. The outcomes that are produced are denoted by “s_1” and “s_2” respectively, and are known as the “outcome-events”:



The argument against causality in EPR

An essay by Bas Van Fraassen (1982) has been particularly influential in setting a default view against causality in EPR among philosophers of physics and foundational physicists alike. Van Fraassen’s argument tracks Bell’s own reasoning, with the notorious factorizability condition playing a key role. But there is a significant difference: whereas Bell was concerned with factorizability as a condition of physical locality, Van Fraassen takes it to be a condition of causality, in the tradition of Reichenbach’s *Principle of the Common Cause*. The putative conclusion of this influential argument is that the principle of the common cause fails in quantum mechanics: there are quantum phenomena that have no causal explanation.

Let us briefly review the argument. Van Fraassen rules out a direct causal link between the wings by appeal to special relativity theory. I will not discuss this assumption here, although it is controversial (see e.g. Maudlin (1995) for an extended critique). The main statistical condition at the heart of Bell’s theorem (the notorious “factorizability” condition) is:

$$prob(s_1 \,\&\, s_2 / a \,\&\, b \,\&\, \Psi) = prob(s_1 / a \,\&\, \Psi)\, prob(s_2 / b \,\&\, \Psi) \qquad \text{(FACT)}$$

The condition can be further analysed into three Reichenbachian screening-off conditions, which in different versions have received the names “causality” or “outcome independence”; “hidden locality” or “parameter independence”; and “hidden autonomy”:

$$prob(s_1/s_2 \,\&\, a \,\&\, b \,\&\, \Psi) = prob(s_1/a \,\&\, b \,\&\, \Psi)$$
$$prob(s_2/s_1 \,\&\, a \,\&\, b \,\&\, \Psi) = prob(s_2/a \,\&\, b \,\&\, \Psi) \qquad \text{(Causality)}$$

$$prob(s_1/a \,\&\, b \,\&\, \Psi) = prob(s_1/a \,\&\, \Psi)$$
$$prob(s_2/a \,\&\, b \,\&\, \Psi) = prob(s_2/b \,\&\, \Psi) \qquad \text{(Hidden Locality)}$$

$$prob(\Psi/a \,\&\, b) = prob(\Psi) \qquad \text{(Hidden Autonomy)}$$

However, in the Aspect experiments a violation of (Hidden Locality) would be as much in conflict with relativity as a direct causal link; while a violation of (Hidden Autonomy) would entail backwards-in-time causation. Hence (Causality) must bear the blame for the violation of factorizability, and indeed it is easy to show that in an EPR experiment with parallel settings an perfect anticorrelation, (Causality) is false. This seems to imply that no causal model is viable for the EPR correlations, and that Reichenbach's principle of the common cause is false as a matter of fact: not all well established correlations admit of a screening-off causal model.

Arguments in favour of causality in EPR

However influential, the above argument is not conclusive, and several authors explicit or implicitly take issue with it. Maudlin (1995) argues that direct causation between the wings remains compatible with relativity, and objects to the analysis of factorisability in terms of the three conditions above. Healey (1992) and Cartwright and Jones (1991) object to the screening-off condition on common causes more generally. Fine (1987) accepts the argument but claims that no causal explanation was required in the first place. Bohmian mechanics is widely believed to reject "hidden locality". Price (1997) rejects "hidden autonomy", and builds "backwards in time" models following Costa de Beauregard (1977). Höfer-Szabo, Redei and Szabo (1999) argue that Van Fraassen's proof assumes not just common causes, but what they term *common common causes*; without this assumption, they claim, Reichenbach's Principle may be rescued (their claim has also been recently contested – see Butterfield, forthcoming, for an overview). Some of the various options are mapped out in detail in Suárez (2007).

Primary References:

Einstein, A., Podolski, B. and N. Rosen, (1935) "Can Quantum-Mechanical Description of the World Be Considered Complete?" *Physical Review*, **47**, pp. 777-780.

Van Fraassen, B. (1982) “The Charybdis of Realism: Epistemological implications of Bell’s inequality”, *Synthese*, **52**, pp. 25-38.

Secondary References:

Butterfield, J. (forthcoming), “Stochastic Einstein Locality Revisited”, *Brit. J. Phil. Science*.

Cartwright, N. and M. Jones, “How to Hunt Quantum Causes”, *Erkenntnis*, **35**, pp. 205-231.

Costa de Beauregard, O. (1977), “Time Symmetry and the Einstein Paradox”, *Nuovo Cimento*, **42B**, pp. 41-64.

Fine, A. (1989), “Do Correlations Need to Be Explained?”, in Cushing and McMullin (eds.), *Philosophical Consequences of Quantum Theory*, Notre Dame University Press, pp. 175-194.

Grasshoff et al. (2005), “Minimal Assumption Derivation of a Bell-type Inequality”, *Brit. J. Phil. Science*, **56**, pp. 663-680.

Healey, R. (1992), “Chasing Quantum Causes: How Wild is the Goose”, *Philosophical Topics*, **20**, pp. 181-204.

Höfer-Szabo G., M. Redei and L. Szabo (1999), “On Reichenbach’s Common Cause Principle and Reichenbach’s Notion of Common Cause”, *Brit. J. Phil. Science*, **50**, pp. 569-589.

Maudlin, T. (1995), *Quantum Non-Locality and Relativity*, Oxford Blackwells.

Price, H. (1997), *Time’s Arrow and Archimedes’ Point*, Oxford University Press.

Suárez, M. (2007), “Causal Inference in Quantum Mechanics: A Reassessment”, in F. Russo and J. Williamson (eds.), *Causality and Probability in the Sciences*, London College Texts, pp. 65-106.