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Physics' Contribution to Causation

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Abstract: Most philosophers of physics are eliminativists about causation. Following Bertrand Russell's lead, they think that causation is a folk concept that cannot be rationally reconstructed within a worldview informed by contemporary physics. Against this thesis, I argue that physics contributes to shaping the concept of causation, in two ways. (1) Special Relativity is a physical theory that expresses causal constraints. (2) The physical concept of a conserved quantity can be used in the functional reduction of the notion of causation. The empirical part of this reduction makes the hypothesis that the transference of an amount of a conserved quantity is a necessary and sufficient condition for causation. This hypothesis is defended against several objections from physics: that amounts of energy do not possess the appropriate identity conditions required for being able to be transmitted, that there is no universal principle of the conservation of energy in General Relativity, and that there are at least two types of physical systems in which causation does not involve any transference: entangled systems in quantum mechanics and the Aharonov–Bohm effect. In order to show that physics provides means to elaborate the concept of causation it is important to avoid certain misunderstandings. In particular, the claim that there is causation in a physical world does not mean that causation is an additional ingredient of the "furniture" of the world, over and above the ingredients identified by physics.

Keywords: causation, eliminativism, relativity, functional reduction, transference

1 Introduction

It can hardly be denied that the concept of causation plays a central role in many domains of knowledge, both folk and scientific. Causation structures many notions and conceptual analyses in morals and the law. It is, e.g., constitutive of the framework of the consequentialist theory of moral evaluation according to which the consequences of an action are the basis of the moral evaluation of the action:

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consequences are effects. In criminal law, a culprit is a person who caused harm. According to the theory of massive modularity in cognitive psychology, the concept of causation structures innate theories such as folk physics or folk biology. Folk biology conceives of living beings as objects for which the cause of their motion is located within their body. Causal reasoning also seems to be omnipresent in science, following algorithms that are the object of much recent research (Pearl 2000; Spirtes, Glymour, and Scheines 2000).

On this background it may come as a surprise that many philosophers of physics, past and present, are eliminativists about causation. They hold that contemporary physics leaves no room for the concept of causation. How can causation play a central role not only in the common sense conception of the world but also in science if it doesn't play any role in physics, at least in its more fundamental parts, although physics is the most fundamental science?

At the end of the nineteenth century, Ernst Mach expressed hope "that the science of the future will discard the idea of cause and effect, as being formally obscure" (Mach 2012, p. 254), and in 1912, Bertrand Russell famously argued that "the word 'cause' is so inextricably bound up with misleading associations as to make its complete extrusion from the philosophical vocabulary desirable", and that "the reason why physics has ceased to look for causes is that, in fact, there are no such things" (Russell 1919, p. 180).

Eliminativists about causation in physics have come up with various proposals for explaining why there is no paradox in holding both that there is no causation in physics and that causation structures non-fundamental parts of science and common sense. For Russell, causation plays a role in common sense and "in the infancy of a science" (Russell 1919, p. 188), so that the range of the application of the concept of causation can be expected to shrink as other sciences approach the maturity of physics. Norton (2003) has recently argued that correct applications of the concept of cause in common sense and non-fundamental science "reduce" to applications of non-causal physical concepts.[1]

In this paper, I argue, against eliminativism about causation, that it is possible to integrate causation into a worldview compatible with contemporary physics. Indeed, physics contributes in at least two complementary ways to giving content and precision to the concept of causation, as it is used in science, including physics itself, in philosophical theories and in common sense.

1. In the first part, I argue that the special theory of relativity is a fundamental physical theory that contributes to making precise the content of the concept of

1 See Frisch (2014) and Blanchard (2016) for reviews of attempts to resolve the tension between eliminativism about causation in fundamental physics and the indispensability of the concept of causation in science in general.

causation. Causal relations between events must comply with a constraint the theory imposes on possible physical processes. Two events can only be causally related if their relation is time-like (or light-like), i.e., if the geodesic connecting them corresponds to speeds smaller than (or equal to) the speed of light. The reason for which eliminativist philosophers of physics do not acknowledge this causal constraint may be that they conflate several conditions that are misleadingly called "causal" in the contexts of the special and general theories of relativity.[2]

2. In the second part, I show that the physical concept of a conserved quantity can be used in the functional reduction of the notion of causation as it is used in non-fundamental science and common sense. According to the framework of functional reduction, science helps us understand what common sense concepts stand for, and fundamental physics helps us understand what the concepts of less fundamental theories stand for. In this framework, it is possible to draw a clear distinction, in a way that is compatible with contemporary physics, between causal and non-causal relations and processes among localized events.[3]
3. In the third part, I will briefly distinguish the conception of causation shaped in part by physics in these two ways from two concepts which are sometimes confused with causation. One can acknowledge that physics contributes to giving content to the distinction between causal and non-causal relations without accepting (i) "causal hyper-realism" (Field 2003, p. 443), or (ii) "causal fundamentalism" (Norton 2003, p. 3). Authors who deny that physics contributes to giving content to the concept of causation or hold that there cannot be any causation in a world conceived according to contemporary physics, often speak of one of these two concepts rather than of causation itself.

2 Relativistic Constraints on Causality

It is a consequence of the structure of space-time entailed by the theory of special relativity that no processes carrying matter-energy can propagate faster than the

2 Causality plays also other roles in physics, such as these: Causal structures must be used to obtain dynamical models of physical systems (Frisch 2014), and causality plays a role in the interpretation of different versions of quantum mechanics (Esfeld 2010).
3 This distinction can then be used to explain the further distinction between causal and non-causal explanations (Lange 2016; Reutlinger and Saatsi 2018).

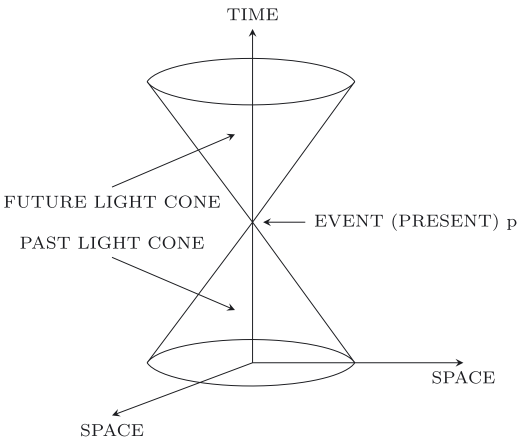

Figure 1: Minkowski diagram representing two light-cones around point *p*.

speed of light.[4] Physics textbooks call "causal theories" those theories that are compatible with this framework. The relativistic constraint on causal theories corresponds to the impossibility of the propagation of fields carrying matter-energy along curves containing space-like segments. This constraint can be represented in a Minkowski diagram that contains a hypersurface dividing space-time into two regions structured around a point p, sketched in Figure 1. The hypersurface appears in the diagram in the form of a double cone, with the summits of both cones situated at p. Points situated in the regions within the cones represent events that are time-like related to p; points outside the cones represent events that are space-like related to p.

A theory is called "causal" in the sense of being compatible with special relativity if it integrates the constraint that it is impossible that processes carrying

4 There are systems in which processes with superluminous speeds are possible (Butterfield 2007; Earman 2014; Weinstein 2006). Thus, as Earman points out, it would be false to say that "relativistic theories cannot accommodate superluminal processes" (Earman 2014, p. 107). In some models of such theories, there are processes with superluminal speed, such as the propagation of sound in a perfect fluid (under certain conditions). However, "whether the field, and any energy-momentum it carries, propagates non-superluminally is (…) an intrinsic, observer independent matter" (Earman 2014, p. 105) and "the field itself does not propagate superluminally and, a fortiori, (…) the mass-energy, stress-energy, or anything else carried by the field does not propagate superluminally" (Earman 2014, p. 105). I avoid putting the restriction on physical processes in terms of signals because this raises difficulties independent of the aims of this paper. Weinstein (2006) proposes a definition of signaling according to which there can be superluminous signals.

mass-energy propagate along curves with space-like segments.[5] Points lying on the surfaces of the cones represent events that are limiting cases: being light-like related to *p*, they can be related to *p* by processes propagating with the speed of light. It is standard usage to describe this limitation on possible physical processes in causal terms. A major textbook on relativity describes the "causal structure of spacetime in special relativity" (Wald 1984, p. 188) in these terms: "The events lying in the interior of the future light cone represent events which can be reached by a material particle starting at *p*; these comprise the 'chronological future' of *p*. The chronological future of *p* together with the events lying on the cone itself comprise the 'causal future' of *p*, which physically represents events which, in principle, can be influenced by a signal emitted from *p*" (Wald 1984, p. 188).[6]

Physics textbooks explicitly label this restriction of possibility as "causal", contradicting Norton's claim that "the demand that matter in the spacetime admit no propagations outside the light cone (…) is not explicitly given the label of a causal principle until we venture beyond special relativity" (Norton 2007, p. 227). Qualifying a theory as "causal" corresponds to a limitation of possibilities; in other words, it has non-empty informational content. So why do many philosophers of physics deny that physical theories give precise content (corresponding to the limitation of possibilities) to the concept of causation, considering that it is just an "empty honorific" (Norton 2003, p. 4)? This thesis might stem from insufficient attention to the difference between special and general relativity and a conflation of different principles that are misleadingly all called "causal".

In general relativity, the structure of space-time is defined locally. "In general relativity, the causal structure of spacetime is locally of the same qualitative nature as in the flat spacetime of special relativity" (Wald 1984, p. 188). The limitation of physical possibility imposed on causal theories by special relativity still holds in the framework of general relativity, though only locally. The restriction on possible processes therefore takes the form of a local condition, called "local causality" (Hawking and Ellis 1973, p. 60).[7] It is important to distinguish the condition of

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5 In Reichenbach's words, "the combined space-time order reveals itself as the ordering schema governing causal chains and thus as the expression of the causal structure of the universe" (Reichenbach 1958, p. 268). In Torretti's words, "spacetime (…) lays out the permissible avenues of physical action" (Torretti 1966, p. 123). Reichenbach (1958) and Salmon (1984) have tried to define causality by the criterion of the capacity of transmitting a mark or signal. I will not rely on such a definition, which has later been abandoned (including by Salmon himself (Salmon 1994)) for being circular. See Kistler (2006).

6 I do not endorse the "signal" language, for the reason indicated in footnote 4 above.

7 This condition says that "the matter fields must be such that if U is a convex normal neighbourhood and p and q are points in U then a signal can be sent in U between p and q if and only if p and q can be joined by a C^1 curve lying entirely in U, whose tangent vector is everywhere non-zero and is either timelike or null", i.e. "*non-spacelike*" (Hawking and Ellis 1973, p. 60; italics in the text). A C^1 curve is (1) continuous and (2) has a continuous first derivative.

"local causality" from another condition, confusingly sometimes also called the "causality condition" (Hawking and Ellis 1973, p. 190), "strong principle of causality", or simply "strong causality". It holds of a space-time if it contains no closed non-space-like (light-like or time-like) curves, and no curves that come close to being closed. "If a spacetime violates strong causality at p, then near p there exist causal curves which come arbitrarily close to intersecting themselves" (Wald 1984, p. 196). To sum up the distinction between local and strong causality: according to the principle of local causality, no physical processes (carrying matter-energy[8]) can propagate along space-like curves, or more precisely, along any curve containing points at which the tangent vector is space-like. "Strong causality" imposes a further restriction on curves satisfying the principle of local causality.

The status of these two principles is importantly different. The former, weaker principle, is grounded in the theory of special relativity. It restricts physical possibility. By contrast, the stronger principle cannot be derived from the equations of general relativity itself. Indeed, the Einstein field equations allow solutions that contain closed causal curves as, e.g., in the "Gödel universe".[9] The different variants[10] of the stronger principle are not grounded in the theory of general relativity itself (nor in any other physical theory) and therefore do not restrict possibility.[11] General relativity does not exclude the possibility of universes that contain fields propagating along curves that violate one of the variants of the strong causality condition.

This suggests an explanation of why many philosophers hold that the restriction on possible physical processes imposed by special relativity is not causal. They conflate the condition that physical theories must be causal (so as to comply with special relativity) with "strong causality". Saying of a condition that it is only a tool of classification that does not restrict physical possibilities is wrong of the

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8 It is worth repeating here that relativity theory is not incompatible with the existence of superluminal processes in general (Butterfield 2007; Earman 2014; Weinstein 2006), only with the superluminal propagation of fields carrying matter-energy.

9 No contradictions or paradoxes arise from the existence of closed causal curves (see Arntzenius and Maudlin 2005).

10 Hawking and Ellis distinguish the "causality condition" which "holds if there are no closed non-spacelike curves" (Hawking and Ellis 1973, p. 190) from two stronger conditions, the "strong causality condition" (Hawking and Ellis 1973, p. 192) and the "stable causality condition" (Hawking and Ellis 1973, p. 198), which hold if there are not even curves that are *almost* closed, where "almost" is defined in two different ways in the two conditions.

11 Some authors advocate the adoption of a fundamental principle, in the form of an energy condition, which excludes such possibilities. Cf. Curiel (2017). Another hypothesis that excludes possibilities is the cosmic censor conjecture (Wald 1984, pp. 302–5).

former condition although it is true of the latter condition. It is correct to say of the strong causality conditions in general relativity, but not of the special relativistic principle of "local causation" that they "are best understood as devices for cataloging the different ways that the light-cone structure may be spread globally over space-time. (…) They are not principles that are to be demanded universally, (…) for it is routine to consider solutions of the Einstein equations that do not conform to them" (Norton 2007, p. 228). Frisch, who argues that causality plays a role in physics for other reasons, also accepts the thesis that the relativistic condition that fields carrying matter-energy cannot propagate with speeds greater than the speed of light is no restriction of possibilities: "The relativistic concept of causation corresponds only to a classification of the structures that are defined by the fundamental dynamic equations of a theory but not to any limitation of what is physically possible" (Frisch 2012, p. 414).[12] This is correct with respect to the various concepts of "strong causality" in general relativity, but incorrect with respect to the special relativistic condition of "local causation" according to which fields carrying matter-energy cannot propagate with superluminal speed, nor connect points that are space-like related. As a restriction of physical possibility, the latter principle can play the role of a physical condition that gives precise content to the concept of causation.

According to Field, "the notion of causal signal is needed in physics only on an operational construal" whereas, "on a less operational view, notions like flow of energy-momentum and various temporal notions such as the light cone structure suffice for the purposes that talk of causal signals have been standardly put" (Field 2003, p. 436). Field does not justify his judgment that the light-cone structure of relativistic physics can replace the concept of a causal process. It would seem more correct to say that the light-cone structure provides a framework for representing the causal constraint imposed on all processes carrying matter-energy, to propagate with infraluminal speed.

3 Functional Reduction of Causation

There is a second way in which physics can contribute to give content to the concept of causation. This contribution is more indirect than the first. Physics

12 Elsewhere, Frisch (2014, p. 18) explains that the fact that physicists explore space-time structures that violate some version of the strong causality principle only shows that such structures are conceptually possible but not that they are physically possible.

provides part of the conditions of an analysis of the concept of causation, as it is used both in common sense and science.

The physical concept of a conserved quantity can be used in an analysis of the difference between causal and non-causal determination relations between spatio-temporally localized, particular events, or between facts bearing on such events. Consider the macroscopic magnetization $\vec{M}(t)$ of a macroscopic sample of nickel at a given time t. Two independent answers can be given to the question of what determines $\vec{M}(t)$. According to the first, $\vec{M}(t)$ is determined by the magnetic dipoles (spins) of the electrons contained in the sample at t. $\vec{M}(t) \neq 0$ if and only if (a majority of) those dipoles are aligned in the same direction. According to the second, $\vec{M}(t)$ is determined by a dynamic process due to the influence of a magnetic field $\vec{B}$ acting from outside the sample. That process starts at some earlier time $t - \Delta t$, at which the dipoles are not aligned so that $\vec{M}(t - \Delta t) = 0$, continues with the propagation of $\vec{B}$ that, when it reaches the sample, triggers a process of progressive alignment of the electronic spins with the direction of $\vec{B}$.

These determination relations differ in that the latter is causal whereas the former is not. Here is a way of making explicit the distinction between causal determination relations (such as the relation between the external field $\vec{B}(t - \Delta t)$ and $\vec{M}(t)$) and non-causal determination relations (such as the relation between the dipoles of the electrons in the sample at t and the sample's macroscopic $\vec{M}(t)$). Following a suggestion of Menzies' (1996) I will sketch a *functional reduction* of the concept of a causal relation. Such a functional reduction proceeds in two steps. The first step consists in a list of conditions for events of types F and G to be causally related. The second step consists in making the hypothesis of a physical condition that is satisfied, as a matter of fact in the actual world as it is known according to science, by all pairs of events F and G that fulfill most of the conditions listed in the first step. The following conditions seem to be the main constituents of the concept of causation, as it is used both in common sense and science. The list is not meant to be complete. After many failed attempts, it seems safe to say that these conditions cannot be integrated into a complete conceptual analysis that yields necessary and conditions for causation. Rather, causation seems to be a cluster concept the application of which is based on the following criteria.

1. Events F and G are localized in distant spatio-temporal regions (no spatio-temporal overlap).
2. The regions in which F and G are localized are time-like (or light-like) related.[13]
3. The probability of G, given F, is, under certain conditions, higher than the unconditional probability of G.
4. G depends, under certain conditions, counterfactually on F.
5. If F and G are represented by variables F* and G*, it is possible to intervene on F* and interventions on F* (obeying the appropriate constraints) are means of modifying G*.

Each of these conditions plays a role in determining whether the relation between F and G is causal. Each of (3), (4), and (5) has been developed into theories that were meant to account for causation by themselves. Here is not the place to review the efforts that have been put into developing each of conditions (3), (4), and (5) into necessary and sufficient conditions for causality (Kistler 2002, 2018). It is difficult to consider them together for several reasons. These conditions play quite different theoretical roles. (3) Is, e.g., suited for indeterministic or incomplete models, whereas (4) and (5) can also be applied to deterministic models. The conditions are usually put in different formats: condition (3) relates (types of) events, condition (4) (particular) events or facts, and condition (5), variables. Furthermore, conditions (1) to (5) do not all have the same epistemic status.

According to the conception of functional reduction developed by Jackson (1998), Kim (1998) and others, the set of conditions making explicit the criteria of application of the reduced concept are purely *a priori*. In other words, functional reduction is meant to apply to concepts that are part of common sense and mastered by every competent speaker of the linguistic community. This means that the criterion of correctness for those conditions is the compatibility of their application with the intuitions of arbitrary members of the linguistic community. Science and a posteriori knowledge enter functional reduction only in the second step, which we will consider shortly. Menzies' (1996) proposal for a functional reduction of the concept of causation also accepts the idea that the first step of the reduction is conceptual and a priori whereas the second step is scientific and a posteriori. However, the very distinction between purely conceptual and purely empirical hypotheses seems to be a remnant of

13 Many true causal statements bear on overlapping spatio-temporal regions, such as "fire causes smoke". However, what makes them true is a set of physical processes each of which satisfies requirement (2). For each of the particles constitutive of a given cloud of smoke at each moment, the localization of the smoke particle at that moment does not overlap the localization of the combustion event from which it results. I thank an anonymous referee for *Kriterion* for challenging me on this point.

the dogma of logical empiricism according to which there is a strict distinction between analytical (conceptual) and synthetic (empirical) truths. It seems more plausible to situate the criteria on a continuous scale, from the most a priori (in the sense of being constitutive of the concept) to the most a posteriori. This allows for the possibility that the position of a criterion on that scale may change. Criterion (2) is of scientific origin. It is a consequence of the theory of special relativity, which is an a posteriori empirical theory, that processes carrying mass-energy cannot propagate with superluminal speed. As scientific knowledge spreads it gets progressively integrated into common sense, and thus moves towards the a priori end of the spectrum of the epistemic status of the criteria for causation, where "a priori" is meant to express the fact that it becomes constitutive of the concept of causation. Criterion (1) is purely conceptual. The distinction between dependencies between events that are situated at some spatio-temporal distance from each other and dependencies between events happening in the same spatio-temporal region precedes scientific knowledge about the specificities of dependencies of both sorts. Criteria (3), (4), and (5) are best seen as the result of both; in other words, they belong to common sense refined by science. It is common sense that causes raise the probability of their effects, but it is the result of science and philosophical reflection on science that this is true only under certain conditions, using models that are either incomplete (so that the probabilities can be interpreted epistemically) or indeterministic. (4) and (5) suffer exceptions: if F is causally related to G but accompanied by a second cause H (which would alone be sufficient for G), so that F is redundant, G is not counterfactually dependent on F; similarly, if there is an event H that is preempted from causing G but would have caused G in the absence of F, G is also not counterfactually dependent on F.

In a similar way, it is common sense that causes can be used as "handles" to manipulate their effects, but it is the result of philosophical reflection on science to note that this is true only if, among other conditions, the cause is not correlated with other causes of the effect. (5) is not a necessary condition because there are situations in which F causes G although it is impossible to intervene on F* in accordance with the conditions required for an intervention. One such case is where F* is a variable representing the state of the universe as a whole (Woodward 2009, p. 256/7), on which it is conceptually impossible to intervene.[14] Here is another situation where it is impossible, for scientific reasons, to intervene on F*

14 This problem does not arise with the concept of intervention used by Pearl (2000, p. 69f.). Pearl's "do" operator represents the intervention on a variable *X* by the replacement, in the model of the system, of the structural equation for *X* with an equation setting *X*'s value to be x_i. This concept of an intervention does not presuppose the existence of variables not included within the model of F, where such variables cannot exist if *F* is taken to be a model of the actual universe as a whole. Cf. Frisch (2014, p. 93ff.).

without at the same time intervening on G*, as is required for an intervention. The position and mass of the moon has a causal influence on the tides but it is physically impossible to intervene on the position or mass of the moon without thereby also directly modifying the tides.

The list of conditions (1)–(5) is the result of the first step of a functional reduction of the concept of F having a causal influence on G. Here is an empirical hypothesis concerning the condition corresponding to the second, empirical step of the reduction (Kistler 1998, 2006, 2014). According to this hypothesis, there is a unique physical condition that is satisfied, in the actual world, by all pairs of events (F, G) that satisfy conditions (1) and (2) and that satisfy (3) to (5) in the appropriate circumstances. For each of these pairs of events (F, G), there is a process of transference of an amount of a conserved quantity (energy, linear momentum, charge etc.) from the space-time region in which F is localized to the space-time region in which G is localized. If we take conditions (1)–(5) as characterizing together the functional role of causation, the transference of an amount of a conserved quantity is what plays that role in our world, according to what we know from contemporary physics. Transference is a necessary and sufficient condition for causation.[15]

4 Physical Objections Against the Transference Hypothesis

This hypothesis is often rejected for physical reasons.[16] In what follows, I will examine four physical objections against the transference hypothesis.

O1 Amounts of energy (and other conserved quantities) cannot be transmitted because this would require amounts of energy to be substances, or to have identity conditions that would make it conceptually possible for them to remain identical through time, in the manner of substances.

15 I will not try to show here that the condition of transference accounts for situations in which other analyses of causation face difficulties. Many versions of the counterfactual analysis of causation fail, e.g., to account for situations in which an effect is caused by two processes, one of which turns out to be redundant. Such an effect is not counterfactually dependent on either of the two processes. What makes the difference between the cause and the redundant backup process in such a situation is the fact that the cause reaches the effect by means of a process, which is, according to our hypothesis, always a process of transference. Cf. Kistler (2014, p. 85).

16 The hypothesis that causation is always based on a process of transference is also often rejected for purely conceptual reasons, and in particular for the reason that events of omission, triggering or interruption seem to be cases of causation but are not based on any transference (Schaffer 2000). I have dealt with some of these objections elsewhere (Kistler 2002, 2006, 2014, 2018).

O2 There is no general principle of the conservation of energy in the theory of general relativity.

O3 In entangled quantum systems of the sort first described by Einstein et al. (1935), there are relations of dependence between events that are space-like related, which is incompatible with transference of mass-energy according to special relativity.

O4 The Aharonov–Bohm effect is a case of causal influence (from the magnetic flux within a solenoid to an interference pattern on a screen) without any transference.

Let us look at these challenges to the transference hypothesis in turn.

O1 A first challenge against the hypothesis that transference fills the role of causation from a physical point of view has been put forward by Dieks (1986). In classical physical theories, "energy and momentum are introduced as quantities which obey global conservation laws" so that "there is no need to regard energy and momentum as a kind of substance which is transferred, while retaining its identity, from the particles and fields before the interaction to those after the interaction" (Dieks 1986, p. 88). Conservation laws being global, not only is it not necessary to conceive quantities such as energy as substances, but physics provides no grounds for conceiving them in this way. As Maxwell has put it, "we cannot identify a particular portion of energy, or trace it through its transformations. It has no individual existence, such as that which we attribute to particular portions of matter" (Clerk Maxwell 1925, p. 90).[17]

Here is my reply to the objection that energy and other conserved quantities cannot be transmitted because they do not satisfy the conditions for being a substance. The application of the notion of transference to localized amounts of conserved quantities does not require that such amounts persist through time like substances, where a substance is something that can exist independently of everything else and persists through time, whether or not some of its intrinsic properties change. The statement that an amount Q of mass-energy (or some other conserved quantity) is transferred between the space-time regions A and B can be justified without requiring that Q is a substance. A necessary and sufficient condition for the transference of mass-energy (or another conserved quantity) between

17 Phil Dowe, who is often mistakenly quoted as an advocate of a version of the transference theory, rejects it for this reason (Dowe 2000, pp. 55–58) and replaces transference with the requirement of the regular appearance of amounts of conserved quantities. According to Dowe, "it is not possible to identify a quantity of energy as being the same as an earlier quantity" (Dowe 1992, p. 214). Dowe's analysis of causation does not require such an identification "because there is no notion of transference or transmission in the definitions" (Dowe 1992, p. 214) of his account, only the notion of the "manifestation" of conserved quantities. See also Dowe (2000, p. 111).

A and B is the existence of a time-like or light-like curve connecting these regions along which a field carrying mass-energy (or another conserved quantity) is propagated.

O2 The second objection against the hypothesis that transference underlies all cases of causal influence between spatio-temporally localized events is based on a fact about the theory of general relativity. "There are in general no integral conservation laws, and correspondingly there are in general no well-defined scalar energetic quantities of physical significance" (Curiel 2000, p. 50; see also Lam 2005) in this theory. Indeed, general relativity contains only a differential form of the conservation of energy-momentum:

$$\bigtriangledown T^{ab} = 0\,,$$

where T^{ab} represents the energy-momentum tensor field of matter, and $\bigtriangledown$ represents the covariant derivative.

In general relativity there is no generally valid integral version of that conservation law. The reason is that, in general relativity, integrals over a macroscopic surface, as would be required for an integral form of the conservation law, are not in general well defined. Such integrals are well defined only for flat space-times or for space-times with special symmetries. The justification we have given above that it makes sense to speak of the transference of an amount Q of energy between space-time regions A and B, requires an integral form of the conservation law: its application to regions A and B guarantees that some amount Q that is lost by A is gained by B. However, *in space-time regions that can locally be approximated to be flat*, the conservation law $\bigtriangledown T^{ab} = 0$ can locally be given a well-defined integral form.[18] The transference condition can play the role of the realizer of causal relations only between events that are localized in approximately flat regions of space-time. In other words, Curiel (2000) and Lam (2005) are right in noting that the transference condition is neither applicable to large scale causal judgments, such as the statement that the big bang is the distant cause of some event happening on Earth in 2020, nor in regions with non-negligible space-time curvature. It remains to be seen whether physics can

18 This restricts the domain of application of the suggested account of causation. Dowe (2000, p. 97) acknowledges the fact that an analysis of causation in terms of conserved quantities (whether in terms of transmission, as proposed here, or without transmission, as in Dowe's account) requires the integral form of the conservation laws, in particular for mass-energy, but claims that the conditions for expressing the conservation laws in their integral form are satisfied in the actual world. However, this does not seem to be correct for the universe at large. Our hypothesis is weaker: Transmission realizes causation only in spacetime regions that are approximately flat or contain special symmetries.

contribute to make sense of causal statements bearing on such events in some other way.

O3 A third argument against the transference hypothesis relies on the existence of non-local dependencies between events happening in entangled systems in quantum mechanics. In a variation of the experiment first conceived by Einstein et al. (1935), two electrons are prepared in an entangled singlet state of spin 1/2, and then move in opposite directions. According to quantum mechanics, measurements of a given component of the spins of such entangled pairs of particles are strictly correlated. When the two particles are at some distance, say at the left and right wings of a measurement apparatus, let an experimenter at the left wing choose to set the measurement apparatus to measure one determinate component of the spin of the left particle, and let the experimenter at the right wing choose to measure one determinate component of spin, where her choice is independent of the choice of the left experimenter. The results of both measurements are correlated; however, given that the measurement events can be space-like related, this correlation cannot be due to the propagation of a causal influence from one measurement to the other. Bell's theorem proves that quantum mechanics (and every theory that is in agreement with well-established experimental results) violates a "principle of local causality", according to which the result of the outcome of the measurement on the left side of the experiment depends only on the past history of the left part of the system together with the setting of the measurement apparatus on the left hand side, but is causally independent of the setting and the result of the apparatus on the right hand side (Maudlin 2011). Whether or not the results of the measurements are determined before the measurements (as hidden-variable theories assume) or not (as the orthodox version of quantum mechanics assumes), the result of one measurement seems to have an instantaneous causal influence at a distance on the other measurement. This seems to be incompatible with the transference hypothesis.

However, according to the analysis of the concept of causation sketched above, the dependence of one measurement on the other in an EPR-style experiment does not satisfy the necessary conditions on causal dependence. The two measurement events in such an experiment can be space-like related, whereas special relativity requires that only pairs of events that are time-like (or light-like) related can be causally related. The non-causal character of the dependence of one result of measurement on the other can also be brought out (using the interventionist condition (5)) by the fact that it is impossible to manipulate one result by intervening on the other (Hausman and Woodward 1999, p. 565). The correlations between measurement events on entangled pairs of particles that are space-like related are cases of non-local but non-causal determination.[19]

The correlation between the measurement results in an EPR-style apparatus appears to be causal because it satisfies conditions (3) and (4): The measurement results on the left and right arms are both probabilistically and counterfactually related.[20] However, conditions (2) and (5) yield the result that the EPR correlation is non-causal. Thus, there is a clash between the different criteria for causality. Why should (2) and (5) overrule (3) and (4), yielding the result that the correlation is non-causal? This is a consequence of the hypothesis that (3), (4) and (5) are fallible criteria, i.e., have exceptions, and that what is crucial is what fills the conceptual role of causation, i.e. transference of mass-energy (or other conserved quantities). Transference of mass-energy (and other conserved quantities) is constrained by condition (2). Therefore a dependence relation between events that does not respect condition (2) is not causal. This reasoning shows that the plausibility of the hypothesis according to which transference of mass-energy (or other conserved quantities) is what realizes causal influence in our world depends on the respective importance of Special Relativity and quantum mechanics in physics. The analysis of EPR-type experiments shows that any empirically adequate quantum theory violates either parameter independence (the probability of a distant measurement outcome in an EPR-type experiment is independent of the setting of the nearby measurement apparatus) or outcome independence (the probability of a distant measurement outcome in an EPR-type experiment is independent of the nearby measurement outcome) (Shimony 1984). The violation of parameter independence seems to imply that an EPR-type apparatus could at least in principle be used as a signaling device between space-like separate events, in contradiction with special relativity (Berkovitz 2016; Shimony 1984). This means that, if it turns out that Special Relativity is not after all a universally valid theory, our hypothesis would have to be modified, so as to allow causal influence to be realized either by

19 Dowe suggests an interpretation according to which the measurements are causally related after all, by introducing the hypothesis of backwards causation. "The act of measurement on particle A brings about causal influence which propagates backwards in time to the source of the two particles, whereupon it is partially causally responsible for some hidden characteristics of the state S of that pair of particles" (Dowe 1996, p. 228/9). Ardourel and Guay (2018, p. 14) suggest that the EPR correlation between the two measurements is no case of causation because that would require that the measurements are *two* events or bear on *two* systems. If the particles are entangled at the time of measurement, they are one system, not two.

20 According to theories that try to reduce causation either in probabilistic terms or in counterfactual terms, the results of measurements in the EPR-type apparatus are causally related even though they are space-like separate. According to those accounts, there are superluminous causal relations (Berkovitz 2016).

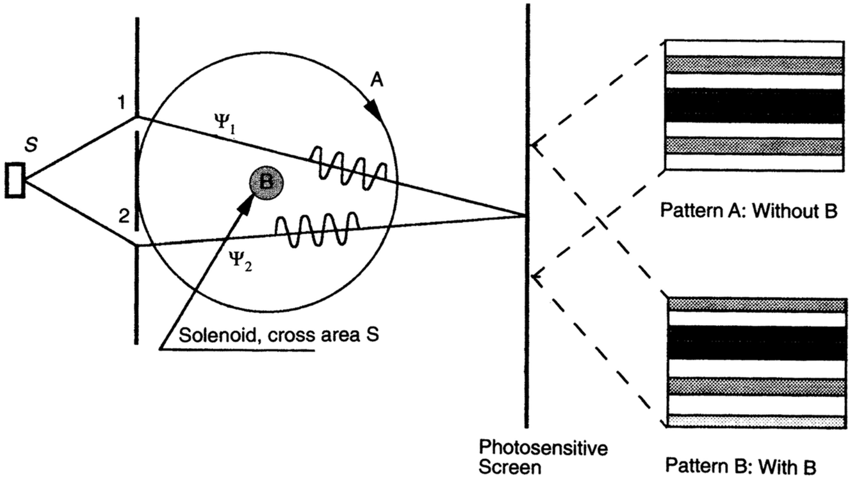

Figure 2: (From Liu 1994, p. 990). Ψ_1 and Ψ_2 represent the paths of electrons from the source S on the left to the screen on the right, and B represents the magnetic field within the solenoid. When field B is present, the interference pattern on the screen shifts from pattern A (above) to pattern B (below).

transference of mass-energy or by some other mechanism, one of which might be at work in superluminous signaling between space-like separate parts of the EPR-type apparatus.

O4 The Aharonov–Bohm (AB) effect provides yet another challenge for the transference hypothesis. The AB effect consists in the modification of the interference pattern appearing on a screen created by the convergence of a stream of charged particles emitted from a source and then divided in two paths (Figure 2). If a non-zero magnetic flux is enclosed between the two paths then this flux produces a shift of the interference fringes. This is surprising in situations in which the electro-magnetic field strength is zero everywhere along the paths of the particles.

The AB effect, i.e., the shift in the position of the interference fringes, can be explained by a change of the phase of the electrons due to the presence of a non-zero magnetic flux within the solenoid. However, the complete physical explanation of the AB effect is still controversial (Earman 2019). The currently accepted hypothesis attributes a role to the vector potential A, over and above the electromagnetic field (Liu 1994; Olariu and Iovitzu Popescu 1985). A does not itself have any physical reality because it is not gauge invariant. Only the fields E and B, whose strengths are determined by a derivative with respect to A, are physically real and causally powerful. However, the phase shift of the electrons can be calculated by means of the path integral of the vector potential A, corresponding to the magnetic flux, along the paths of the electrons from the source S to the screen. More precisely, the quantity that is used to explain and predict the phase shift of the electrons is the holonomy or Dirac phase factor calculated on the basis of that path integral.[21] The modification of the phase of the electrons then manifests as a shift of the interference pattern on the screen.

Boyer (2000) has proposed an alternative explanation of the effect in terms of electromagnetic forces, which does not use the holonomy.[22] The explanations in terms of the holonomy and in terms of electromagnetic forces have experimentally distinguishable consequences; however, no crucial experiment has yet been performed. If Boyer's explanation of the AB effect is correct, the effect is compatible with the transference hypothesis, because it is due to forces resulting from electromagnetic fields, which propagate the conserved quantities energy and momentum.

So let us consider the mainstream physical explanation of the AB effect in terms of the holonomy, calculated by means of a path integral over the vector potential A. According to that explanation, the AB effect does indeed challenge the transference hypothesis because it seems to contain a causal process without transference of any conserved quantities. The magnetic flux (and the vector potential A due to this flux) do not modify any of the conserved quantities associated with the electrons, such as their momentum or spin (Liu 1994, p. 994); they only modify the electrons' phase, which is not a conserved quantity. Ardourel and Guay conclude that "the AB effect is a counter-example for the transference theory in its current form" (Ardourel and Guay 2018, p. 12) because "this phenomenon does not involve the transmission of any physical quantity" (Ardourel and Guay 2018, p. 15) although it is a sort of causal influence. It seems indeed plausible that the magnetic flux in the solenoid causes a shift in the pattern of interference fringes on the screen. From an interventionist perspective, the relation looks causal because an experimenter can modify the pattern of fringes by intervening on the flux, for example by plugging in the solenoid. Another reason for taking the AB effect to be causal is that it "allows signaling" (Ardourel and Guay 2018, p. 17). If one state of the interference pattern in Figure 2 is interpreted as "0" and the other as "1", an experimenter can send signals from the solenoid to the screen.

However, the case against the correctness of the transference hypothesis in the situation of the AB effect is not straightforward. Take the cause to be the beginning of a positive magnetic flux within the solenoid at t, and take the effect to be the shift of the interference pattern at $t + \Delta t$. The electrons move to the screen with finite

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21 The holonomy is gauge-invariant, and can thus be interpreted as being a real and powerful property of the system.

22 Hegerfeldt and Neumann (2008) and Wilhelm and Dwivedi (2016) offer other explanations.

speed and carry conserved quantities. The modification of the potential A by the modification of the flux also propagates with finite speed from the solenoid to the electrons' path. However, the only physically real quantity that mediates between the change in flux and the shift of the interference pattern is the holonomy, which is a quantity determined by a path integral over the entire path of the electrons. The propagation of A would be a process of propagation of causal influence without any transference of conserved quantities if it were a real physical process. However, given that A is not gauge invariant, it cannot be interpreted as a physically real quantity.

The crucial point is the interpretation of the modification of the holonomy by the change of flux. This modification appears to be causal in light of some of the criteria listed above: The flux and the holonomy concern spatio-temporally distinct events (condition 1 above); the modification of the flux raises the probability of the modification of the holonomy (condition 3 above); the modification of the holonomy depends counterfactually on the modification of the flux (condition 4) and interventions on the flux are means for modifying the holonomy (condition 5).

The only reason for doubting whether the relation is causal concerns criterion (2) according to which cause and effect cannot be space-like related. The effect being non-local, it is not clear whether the change of flux and the modification of the holonomy are time-like separated. If they are not, the dependence of the latter on the former is not causal by virtue of criterion (2).[23] Given that the physical determination of the phase shift is mediated by the non-local holonomy, it cannot be excluded that the modification of the flux in the solenoid modifies the phase of the electrons non-causally and non-locally, all along their path at the same time. The dependence of the holonomy on the magnetic flux may be a non-local and non-causal dependence relation, though of a different sort from the dependence between the measurements on the two parts of a system of entangled particles in an EPR experiment.

It might be objected that the holonomy is just a calculating device that cannot be interpreted ontologically as representing any real physical entity.[24] The project of functionally reducing the concept of causation requires that physical theories can be used to find out what realizes causation in the actual world. This

23 It is also possible to conclude that the AB effect belongs to a type of causal relation that does not satisfy criterion (2). According to the hypothesis examined in this paper, all pairs of events that are causally related and satisfy (1) and (2) are related by transference. This leaves open the possibility that there are causal processes that do not satisfy either (1) or (2). The AB effect might be such a process. It remains to be seen by what physical condition causation is realized in situations where cause and/or effect are not localized. At any rate, if there is causation relating non-local events, transference is only one among several physical realizations of causation.

24 I thank an anonymous referee for *Kriterion* for raising this objection.

presupposes that the relevant physical theories can be interpreted realistically. If the relevant physical theories cannot be so interpreted, the project of using physics for finding out what realizes causation is indeed doomed. So this is just a general presupposition of the whole project. Alternatively, one might argue that it is precisely the holonomy that cannot be interpreted realistically and that must be taken as a mere calculating device. There are two possibilities. Either there is an alternative account of the AB effect that makes use only of realistically interpretable theories. Then everything depends on that alternative account. Boyer's (2000) is one such account, which seems to be compatible with the transference hypothesis.[25] Or there is no realistically interpretable theory available. Then I would argue that we do not yet have sufficient scientific information to judge whether the AB effect is compatible with the transference hypothesis.

Here is a reason for interpreting the holonomy realistically. The criterion that is used for justifying the judgment that the vector potential A is only a mathematical tool that must not be given a realist interpretation is that A is not gauge-invariant. However, the holonomy is gauge-invariant; so this criterion yields the result that the holonomy can be realistically interpreted.[26]

In conclusion, the AB effect raises a serious challenge to the transference hypothesis from the point of view of contemporary physics. However, the interpretation of the AB effect is still controversial; there are interpretations according to which the AB effect is based on electromagnetic processes that are compatible with the transference hypothesis. According to the mainstream interpretation in terms of a holonomy, defined as a path integral over the path of the electrons of the vector potential A, the AB effect is mediated by a non-local modification of the electrons' phase. Being non-local, it is unclear whether it can be a term in a causal relation satisfying condition (2). If it cannot, the dependence of the phase shift on the flux may be non-local and non-causal. If it can or if further research reveals other reasons for thinking that this non-local modification is causal after all, the

25 Nounou (2003) has developed a topological and holistic account of the AB effect. With the mathematical formalism of fibre bundles, it is possible to consider that "the flux of the electromagnetic field inside [the solenoid] modifies the spacetime around it" (Nounou 2003, p. 192), so that "the shift in the phase of the electrons happens as a result of this modification" (Nounou 2003, p. 190). Rather than an entity with a causal influence, the non-vanishing holonomy is a mathematical consequence of the non-trivial topology of the space-time around the solenoid. However, Nounou expresses doubts about the possibility of interpreting her topological explanation of the AB effect in a realist way, because "a topological explanation like the one we employed for the A–B effect misrepresents reality" (Nounou 2003, p. 197).

26 Being gauge-invariant is only a necessary but not a sufficient condition for a realist interpretation. The non-locality of the holonomy is a reason for not interpreting it realistically although it is gauge-invariant. As Nounou points out, "it is hard to imagine what kind of a physical, causally interacting with the electrons, entity that integral might represent." (Nounou 2003, p. 194).

transference hypothesis must be modified. Transference would be only a sufficient but not a necessary condition on causation, because some causal interactions are grounded on something else than the transference of conserved quantities.

5 What Causation is Not

Why is it often denied that physics contributes to determining the concept of causation? Some arguments of causal eliminativists depend on the assumption that causation is a metaphysical constraint imposing restrictions on physical possibility that are not equivalent to any restrictions arising within physical theories. In other words, such eliminativists about causation start from the premise that causation, if there were such a thing, would be *a priori* science. Not surprisingly, there is no causation in that sense: what can be found are (1) constraints that arise within physical theory, such as the constraint of "relativistic causality", but those count as non-causal by the eliminativists' definition of causation. By definition, causation must be a metaphysical, as opposed to a physical constraint. And one can find (2) a notion of causation that corresponds to a difference between two kinds of determination relations: portions of physical reality (and facts bearing on them) can stand in two sorts of dependence relations, causal and non-causal. Eliminativists may point out that this distinction plays no role in physical theory itself. However, even if this were correct, it would be no reason to deny that it is an objective distinction based on empirical criteria.

5.1 Causation Versus Causal Hyper-Realism

It may help to distinguish the conception presented here of what causation is in our actual world, from two other accounts. One is "causal hyper-realism", a doctrine that Field (2003, p. 443) attributes to Nancy Cartwright. According to causal hyper-realism, causal facts do not supervene on the totality of non-causal facts. This means that even if all non-causal facts are fixed, it remains open whether there are causal facts. For example, Newton's law according to which an object accelerates in direct proportion to the force impressed on it and in inverse proportion to its mass ($\vec{a} = \vec{F}/m$) does not, according to causal hyper-realism, *make* it the case that a force on an object makes the object accelerate. Causal facts constitute an addition to physical reality, beyond the facts described by physics. According to Field's construal of this doctrine, "there is some sort of causal fluid that is not taken account of in the equations of physics" (Field 2003, p. 443). Nothing of this sort is implied by the analysis of the concept of causation sketched above.

5.2 Causation Versus Causal Fundamentalism

According to Norton (2003), "causal fundamentalism" is the thesis that causation imposes constraints on physical possibility without being itself physical. According to this construal of causation, it imposes a constraint on physical possibility *from outside the physical*, i.e. a constraint that does not have its source in physical theories. Norton (2003) argues that causality is a concept that exclusively belongs to folk physics (as opposed to the science of physics) because there exists no scientifically rigorously defined relation that (1) can be identified with causation and (2) exists over and above all relations identified within science. It is indeed no surprise that there cannot be anything that satisfies the contradictory constraints Norton imposes on causation: be found within science but also be additional to science.

Norton's model of causation as folk science uses a concept of reduction that has been analyzed (and distinguished from what philosophers usually call "reduction") by Nickles (1973). In this sense of "reduction", one can say that new physical theories replace their predecessor theories, in such a way that the new theory "reduces to" the older theory in particular circumstances. Relativistic mechanics is said in this sense to reduce to classical mechanics in situations where velocities are much smaller than the speed of light. In an analogous way, Norton takes causation to be a folk concept that does not refer to anything real, but reduces to something real. "We can have causes in the world of science in the same way as we can retain the caloric" (Norton 2003, p. 21). To say that causation is analogous to caloric in the sense that causal statements "reduce to" physical statements that are non-causal, just as statements about the flow of caloric reduce to statements about the flow of heat, implies that strictly speaking there is no causation, just as strictly speaking, there is no caloric.

Norton's reduction of the existence of causation in a strict sense presupposes the adoption of "hyper-realism" with respect to causation, in Field's sense of this term. Norton's demonstration that causation does not strictly speaking exist, starts from the premise that causation, if it existed, would be some particular sort of relation, in the same sense as caloric was supposed to be a particular sort of substance. According to this hypothesis – which is a form of hyper-realism – it might appear reasonable to expect that "the task of science is to find the particular expressions of some fundamental causal principle in the domain of each of the sciences" (Norton 2003, p. 1). The general concept of causation I have introduced above does not make any hypothesis of this sort. Nickles' concept of reduction is therefore not applicable to it.

Let us look more closely at how Norton refutes causal fundamentalism, which he defines as the doctrine according to which “nature is governed by cause and effect; and the burden of individual sciences is to find the particular expressions of the general notion in the realm of their specialized subject matter” (Norton 2003, p. 3). Norton refutes this doctrine with the help of the following dilemma: “EITHER conforming a science to cause and effect places a restriction on the factual content of a science; OR it does not” (Norton 2003, p. 3/4). Against the first horn, he points out that no-one has yet found any such “principle of causality” that restricts what is physically possible. Against the second horn, he argues that it is equivalent to admitting that the notion of causation is empty: “The imposition of the causal framework makes no difference to the factual content of the sciences” (Norton 2003, p. 4).

Norton’s refutation targets a strawman, i.e., a conception of causation in terms of causal fundamentalism held by no-one. In the light of the analysis of the role of causation in science proposed above, none of the horns is justified.

1. According to the first horn of Norton’s dilemma, no constraint imposed by physical theories on reality is causal. However, as we have seen, special relativity contains causal constraints.
2. According to the second horn of Norton’s dilemma, the use of the concept of causation is just an “exercise in naming” (Norton 2007, p. 224), which is “little more than the distribution of honorifics” (Norton 2007, p. 224). However, this is not true if causation is construed, as we have suggested above, as a category of dependence between events (or facts). The concept of causation marks a distinction among relations of dependence between events (or facts). According to this construal, the concept of causal dependence is characterized by a set of necessary conditions (constituting the functional role of causation): to be causally related, the regions in which F and G are localized must be time-like related, and it must be possible to manipulate G* by intervening on F*, etc. The transference of conserved quantities is then offered as a hypothesis about the physical nature of the processes that realize the functional role of causation in the actual world.

6 Conclusion

I have argued that physics contributes in two ways to determining the concept of causation. First, Special Relativity, a physical theory, contains a causal constraint. Second, the concept of causation makes a useful and clear distinction between two sorts of determination relations between localized events. In case two events occupy distant, non-overlapping space-time regions, the determination of one by the other may be causal; in case their locations overlap or are identical, one can only determine the other non-causally. The concept of causation marks an important distinction between two sorts of relations among events that is not made within physics itself. I have suggested a functional reduction of the concept of causation, as it is applied both in common sense and science, according to which transference of mass-energy or other conserved quantities plays the role of causation in the actual world.

The examination of various objections that have been raised against this hypothesis for physical reasons has shown that its scope must be limited in several ways: (1) The proposed reduction of the concept of causation does not apply to regions of space-time that are not approximately flat. (2) It may turn out that Special Relativity is not after all a universal theory even for such regions, in particular if some version of quantum theory turns out to be true according to which parameter independence is violated, so that causal influence among space-like separated events is in principle possible. In this case, the functional reduction of causation would have to be modified, because the role of causal influence would be filled by different mechanisms, one of which would be transference of amounts of conserved quantities and one of which would mediate causal influence among space-like separated events in entangled quantum systems. (3) The uncertainty about the universal validity of Special Relativity carries over to the interpretation of the AB effect. Our analysis of the AB effect suggests that the dependence of the position of the pattern on the screen on the value of the magnetic flux in the solenoid is non-causal. However, this result is hypothetical for three reasons. First, there is no universal consensus in physics about the correct interpretation of the AB effect. Second, if the mainstream explanation is accepted, our result depends on the universal validity of Special Relativity. Third, the conclusion that the AB effect is a case of non-causal dependence rests on the realist interpretation of the holonomy that plays a crucial role in the mainstream physical explanation of the AB effect. This interpretation may be incorrect. However, the fact that the holonomy is gauge-invariant is a reason to interpret it in a realist and not merely in an instrumentalist way.

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