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## Do the Causal Principles of Modern Physics Contradict Causal Anti-Fundamentalism?

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Elsewhere, I have outlined a form of skepticism about causation called “causal anti-fundamentalism” (Norton 2003). Its central idea is that the structure of the world is to be discovered empirically; it is not to be legislated in advance by metaphysical principles, such as a law of causation or a principle of causality. If the world conforms at a fundamental level to some robust principle of causality, we should expect our best science to tell us so. However, I have argued, it has failed to do so. This last claim may well be doubted by the casual observer of modern physics, for the field is replete with talk of causal relations and causal principles. In recounting recent work on “causal sets,” Jeremy Butterfield (2005) has drawn our attention once again to a new field of fundamental physics that appears to depend essentially on causal notions.

My purpose here is to demonstrate that causal anti-fundamentalism has nothing to fear from modern physics. I will argue that the causal notions and principles of modern physics do not express some universal causal principle brought to light by discoveries in physics. Rather, they merely prove to be a convenient way of describing the fact that, according to relativity theory, space-time happens to have an invariant velocity, that of light; and of expressing the demand that theories of matter in space-time must conform to it in that they admit no propagations faster than light. We are certainly free to choose to name this feature of modern physical theories “causality.” However we should not allow the natural associations of a familiar word to mislead us into

thinking that modern physics has found the proper expression of the ancient demands of a causal metaphysics. For to assume that is to assume that any theory not complying with the causal principles of modern physics is causally deficient. The immediate consequence is that older theories, notably Newton's mechanics, were causally defective in not admitting a finite upper bound to speeds of propagation. And that has the odd consequence that we were mistaken for hundreds of years in extolling the causal perfections of Newtonian mechanics.

### Causal Anti-Fundamentalism

Causal fundamentalism and the argument against it are summarized as follows (Norton, 2003, sec. 2):

*Causal fundamentalism*: 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.

*Causal fundamentalist's dilemma*: EITHER conforming a science to cause and effect places a restriction on the factual content of a science; OR it does not. In either case, we face problems that defeat the notion of cause as fundamental to science. In the first horn, we must find some restriction on factual content that can be properly applied to all sciences; but no appropriate restriction is forthcoming. In the second horn, since the imposition of the causal framework makes no difference to the factual content of the sciences, it is revealed as an empty honorific.

The first horn of the dilemma assumes that there is a factual principle of causality to which any causally adequate science must conform. It asks what that principle might assert. A survey (Norton 2003, sec. 2) of efforts over the centuries to articulate that principle reveals a history of such persistent failure that few could possibly expect a viable, factual principle still to emerge. Highlights of this survey include the reconfiguring of our notion of causation in the seventeenth century, with its move to discard Aristotle's final causes in favor of efficient causes. It also includes Newton's insistence (1692–93, third letter) that unmediated action at a distance is "so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it." Yet the continued success of Newton's own theory of gravitation, with its lack of any evident mediation or transmission time for gravitational action, eventually brought the grudging acceptance that this absurdity was not just possible but actual. In the nineteenth

century, what was required of a process to be causal was stripped of all properties but one, the antecedent cause must determine its effect: "For every event there exists some combination of objects or events, some given concurrence of circumstances, positive and negative, the occurrence of which is always followed by that phenomenon" (Mill 1872, bk. 3, chap. 5, sec. 2, p. 214). The advent of quantum mechanics in the early twentieth century established that the world was not factually causal in that sense and that, in generic circumstances, the present can at best determine probabilities for different futures. So we retreated to a probabilistic notion of causation. Yet the principles that we thought governed this probabilistic notion were soon empirically proved to be false. Reichenbach suggested that we could still identify the common cause of two events, in this probabilistic setting, by its ability to screen off correlations between the events. That, too, was contradicted by the EPR pairs of quantum theory.<sup>1</sup>

Time and again we have found that science eventually contradicts any factual, causal stereotype that we may try to impose upon it. If, however, we give up the search for factual, causal stereotypes and pursue the second horn of the dilemma, then we accept the idea that conforming a science to cause and effect makes no difference to its factual content. We may well continue to use the vocabulary of causation, identifying causes and effects by whatever system of rules we like. However it is no longer clear in what sense this exercise in naming is revealing some fundamental principle of causality whose expression the sciences are to seek in their individual domains. The assigning of causal labels now seems to be little more than the distribution of honorifics. Or perhaps it is some expression of how we like to think about the world, while not expressing any factual property of the world.

The version of causal skepticism just sketched has proven easy to misinterpret because of the dominant trends in the literature. It is a thesis about the character of the world; it is not merely a thesis about the way we use causal language. It is the denial that the world has a universal, causal character such as would be expressed by a principle of causality that must be implemented in the individual sciences. It is not a denial that we can find a single meaning for the term "cause" that we agree upon universally. While this latter endeavor is sometimes described as the search for a theory of causation, it can only produce results about our habits of speech and language—a useful dictionary

entry, for example. Investigations into our language preferences will not tell us how the world is structured.<sup>2</sup>

This form of causal skepticism is also not Humean or positivistic. These other forms of skepticism depend upon a very austere epistemology that denies inference to unobserved entities. Causal anti-fundamentalism, as developed here, depends upon acceptance of a much more fertile epistemology that allows us to infer to much of the content of our best sciences. It is that content that refuses to deliver a factual, universal causal principle. The intuition behind causal anti-fundamentalism is that our best sciences are the proper means of developing a factual account of the world and not prior postulation of the causal stereotypes those sciences must implement.

One may be tempted to accept this form of causal skepticism since its target seems quite narrow, the prior positing of causal strictures on science. Yet a causal theorist, especially in philosophy of science, should not accept it lightly. For once the notion that science seeks to implement a principle of causality is lost, some other justification must be given for the attention lavished on developing theories of causation. Presumably a philosopher of science will not be satisfied with the justification that such a theory really only explores how we choose to use particular words, for that forgoes any pretense that the theory deepens our factual understanding of the world. So the challenge is to devise a positive theory that relates causal notions to factual matters in the world without at the same time reintroducing a priori strictures as objectionable as the principle of causality. (I include Kantian approaches in this last group, for they are still trying to stipulate in advance a quite profound restriction on how we humans and our cognitive apparatus must interact with the world.)

My own efforts in this direction form the positive thesis of Norton (2003, sec. 4–5). Very briefly, that thesis states that restricted domains of the world can manifest a causal character not present universally, although the form of causation manifested can vary from domain to domain. Moreover that causal character is not legislated a priori. It is derived from the natural laws that prevail in those domains. It arises through the generative power of reduction relations already familiar to us in well-known examples of theory reduction. So thermodynamics licenses the result that heat will behave like the conserved fluid caloric in domains in which heat is not converted to and from work. In that

domain, we might say the reduction relations generate the representation of heat as a conserved fluid. Similarly, general relativity has discarded the idea that gravity is a force. Nonetheless it licenses the result that gravitational actions will be well approximated by a force obeying an inverse square law in domains with weak gravitation. In both cases, this generative power is activated by the restriction of laws to particular domains. The positive thesis seeks to use this generative power as a means of introducing causal notions. Through it, a restriction on the domain under consideration may also activate one or another sort of causal behavior that has failed to be manifested universally. So causes are real in the same sense as caloric and gravitational forces are real, and all derive their license from natural laws through reduction relations.

### Causal Notions and Causal Principles in Modern Physics

At first glance, there may appear to be many distinct causal principles invoked in modern physics. It becomes apparent rather quickly, however, that they are very largely expressions of just two assertions:

- (1) There is a finite, invariant velocity in space-time (and that velocity happens to be the velocity of light).

This is a thesis about the structure of space-time essentially related to relativity theory and is often expressed in the slogan that space-time has a light-cone structure. The second assertion is:

- (2) There are no propagations in matter faster than light.

This is the thesis that material processes must conform to the light-cone structure of space-time. It is sometimes expressed in the slogan "No propagation outside the light cone."

Obviously it would be rash to claim that these two assertions exhaust all the meanings of the sentences in modern physics writing in which terms like cause and causation appear. However even the hasty survey below rapidly gives the sense that any other use of causal language in the foundational principles of modern physics is idiosyncratic. The two assertions above seem to capture the mainstream.

To begin the survey, we need just to call to mind the way causal terms are used in special relativity. In the Minkowski space-time of special relativity, events may be timelike related, if a point moving at

less than the speed of light can joint them; lightlike or null related, if points moving at the speed of light, but not slower, may join them; and spacelike related otherwise. The adjective “causal” is associated in very many ways with timelike or lightlike relatedness (that is, equivalently, with non-spacelike relatedness). Two events that are timelike or lightlike related are “causally connectible” with the earlier one “causally preceding” the later. The set of all events that causally precede some nominated event is its “causal past,” and the set of all events it causally precedes is its “causal future.” These definitions are extended naturally to timelike or lightlike four vectors, which are “causal vectors,” and the curves to which they are tangent “causal curves”; they represent points moving at less than or equal to the speed of light. The totality of all lightlike curves in the space-time is called the space-time’s “light-cone structure” and sometimes its “causal structure.” (For examples of many of these usages, see Torretti 1983, sec. 4.6, 192.)

So far, these notions simply implement assertion 1 above. They all pertain to the existence of the invariant velocity in space-time without really expressing its significance, beyond the vague connotations of the word “causal.” The articulation of its significance comes through the implementation of 2. It is the demand that matter in the space-time admit no propagations outside the light cone, so the invariant velocity is identified as the upper limit to the velocity of these propagations.

This demand, I believe, is not explicitly given the label of a causal principle until we venture beyond special relativity. In the context of general relativity, this demand on classical fields in space-time is called “local causality” (Hawking and Ellis 1973, 60). It amounts to requiring that the field equations of the theory enable the fields at an event to be fixed by the fields in that event’s causal past, that is, its past light cone and the events contained within it. Indeed it is required that the fields on any spacelike slice of that causal past fix the fields at the event. Thus the specification is local in the sense that the fields at the event are fully fixed by any spacelike slice of the causal past that may be chosen arbitrarily close to the event.

In special relativity, the light-cone structure is fixed. It is not fixed in general relativity and varies from model to model. Indeed the possibility of unusual topologies in general relativity means that the theory must deal rather more carefully with the light-cone structure, for it is now possible for causal curves to become closed, so that the future of a causal curve will meet its past. Restrictions on these possibilities are

encoded in a series of conditions of varying strictness. A “causality condition” is said to hold if there are no closed causal curves (Hawking and Ellis 1973, 190). The “strong causality condition” precludes not just closure of causal curves in space-time, but arbitrarily close near misses.<sup>3</sup> Finally the “stable causality condition” requires that the overall light-cone structure not be arbitrarily close to admitting closed causal curves, in the sense that it is always possible to expand the light cones slightly at every event without introducing such curves (Hawking and Ellis 1973, 198).

It may seem that these three causality conditions are implementing a prior demand on reasonable causal behavior. For they may be justified informally by noting that closed causal curves correspond to a type of time travel and that, through them, a system may influence its own past. That is sometimes taken as a primal offense against causation, for it triggers familiar paradoxes such as the “kill your grandfather” paradox.<sup>4</sup> In my view, this interpretation of the causality conditions is mistaken. As more careful analyses have shown (see, for example, Arntzenius and Maudlin 2005), there is no contradiction in closed causal curves. Rather they merely restrict the possibilities in space-time in less familiar, global ways. Without closed, causal curves, the evolution of fields into the future in space-time is constrained only by the fields locally around them. If there are closed, causal curves, those fields must evolve in a way that will lead to agreement with their own past states, which will be met eventually when the evolution proceeds far enough into the future. This is not contradictory or paradoxical; it is just unfamiliar.

As a result, these three causality conditions are best understood as devices for cataloging the different ways that the light-cone structure may be spread globally over space-time. They are elaborations of the basic assertion that space-time has a light-cone structure and amount to categorization of the different types of that structure. They are not principles that are to be demanded universally, like the Einstein field equations, for it is routine to consider solutions of the Einstein equations that do not conform to them, such as a Gödel universe. Their utility is that they enable us to divide the models of general relativity into classes with different properties.

Let us now turn to quantum theory. Causal conditions are used routinely to require that quantum theory conform to the light-cone structure of space-time. In the case of ordinary quantum theory, this

was one of the major loci of concern in the protracted discussions of the Einstein-Podolsky-Rosen thought experiment and the Bell inequalities. Ordinary quantum theory appeared to license the conclusion that a measurement performed on one particle of a spread-out singlet state may trigger collapse of the other instantaneously. The demand that this not happen is described as a “locality principle.” One version (Redhead 1987, 75) asserts:

Locality Principle (L): Elements of reality pertaining to one system cannot be affected by measurements performed “at a distance” on another system.

The principle turns out to be a schema yielding different principles according to how the locution “at a distance” is understood. One rather vague understanding, labeled “Bell locality,” construes the locution to mean the “absence of causal influences recognized by current physical theories,” a condition that is empty until “current physical theories” is properly specified. The other understanding, “Einstein locality,” seems to identify one candidate for these theories as special relativity. It identifies “at a distance” with “at a spacelike separation” and seems to be the standard interpretation of the locality principle. In effect, it precludes propagations faster than light, emanating from quantum measurement events.

This class of causality requirements is mentioned here for completeness because it is so often discussed. However, these locality principles are not postulates of ordinary quantum theory. Rather that theory is fully formed prior to invocation of locality principles. The theory is used to predict the consequences of measurement on various systems. Then a locality condition is introduced as a condition external to the theory to check whether quantum theory licenses behavior that we may deem causally respectable. Were such behavior not to be found, we would most likely end up dismissing the locality principle in this quantum context as another casualty of quantum oddness, as has already happened with the principle of the common cause. In any case, a locality principle, as routinely invoked, still amounts to the demand that there be no propagations outside the light cone, since it ends up demanding suitable independence of processes at spacelike separated events.

In quantum field theory, the presence of causality conditions in the axiomatic foundations is clearer. There are two causality requirements



that demand conformity of material processes to the light-cone structure. They are expressed precisely in the Wightman axioms of Axiomatic Quantum Field Theory. The axiom labeled “Causality” (Axiom E in Haag’s development, 1996, 57) requires that spacelike separated field operators commute or anticommute according to whether the fields are bosonic or fermionic. Since commutation is a form of independence, this requirement is routinely glossed with the explanation that it prohibits measurements on a field at one event affecting fields at a spacelike separated event. The axiom labeled “Time-slice axiom” or “Primitive causality” (Axiom G in Haag’s development, 1996, 57) eventually requires that the laws of the theory be such that quantum field operators propagate in timelike classical fields; that is, the field operator at one event is fixed by the field operators in its causal past analogously to the demand above of “local causality” for classical fields.

For completeness I mention that Reichenbach’s principle of the common cause (Salmon 1984, chap. 6) is sometimes discussed in the context of ordinary quantum mechanics (van Fraassen 1980, 28–31) and in the context of quantum field theory (Redei and Summers 2002). For my purposes in this little survey, all that matters is that the common cause principle is called upon as a familiar device used outside quantum theory to identify which events stand in causal relations. The common cause principle is not introduced as a fundamental principle of quantum mechanics. Rather, the goal is to understand how well our everyday expectations about causation cohere with the dynamics found in quantum theory. The principle is generated externally and is compared to the dynamics licensed by quantum theory. When that dynamics contradicts the common cause principle, the appropriate response, in my view, is to conclude that quantum theory does not admit the same causal behavior as other contexts and not to demand that quantum theory change to fit our prior causal stereotypes.

### Conclusion: Peace

It is now apparent that the use of causal notions and causal principles in modern physics does not contradict causal anti-fundamentalism. That use does not arise from the application of a universal, factual principle of causality, as demanded by the first horn of the causal fundamentalist’s dilemma above. In this regard, the causal principles of

modern physics are unlike the principle of conservation of energy, which is one factual principle of purportedly universal scope to which all physical theories must conform, be they classical, quantum, or special relativistic. Since the causal strictures we found in modern physics all make essential reference to the light-cone structure of relativity theory, if it did supply this universal factual principle, we would have to conclude that all nonrelativistic theories are causally defective. Most prominent among these causal failures would be Newtonian theory — a theory that reigned for several centuries as a paradigm of causal order.<sup>5</sup>

Should we be tempted to escape this problem by maintaining that the causal principles of modern physics are merely one expression of a deeper causal principle that, in other expressions, is also compatible with Newtonian theory? That deeper and as yet unknown principle must have quite remarkable content. For somehow it has to be expressed in modern physics essentially by the idea of a finite upper limit for the velocity of propagations. At the same time, it must also be expressed in another form in the Newtonian context, in which there is no such upper limit. Since these two requirements border on contradicting each other, we are unlikely to find a principle meeting them, if it is to have nontrivial, factual content.

Rather, the causal principles of modern physics express no deeper principle of causality. They are the sorts of usages of causal language that arose in the second horn of the dilemma, in which we presumed that conforming to a causal principle placed no factual restriction on the content of a theory. In effect, we go to a physical theory and assign the label of causality to one or another property of the theory because we perceive some sort of commonality with a broader, if vague, notion of causality. In the case of modern physics, we label as causal principles the requirements that space-time have a particular light-cone structure and that the dynamics of matter in space-time conform to that light-cone structure. While these requirements are factual, they do not arise through the application of some universal factual restriction applicable to all metaphysically respectable, physical theories. In another theoretical context, we might identify the causal character of the theory in some quite different property. For example, in the context of Newtonian theory in the tradition of Laplace's calculator, the theory's causal character was associated with its supposed determinism.<sup>6</sup> Success seems assured. Every theory, even one as peculiar as modern quan-

tum theory, seems to have properties that we are willing to designate as causal.

In sum, the causal principles of modern physics are really just a convenient way of naming a requirement peculiar to relativistic theories. They are not the implementation of some overarching metaphysical principle that could properly carry the name “principle of causality,” with the full import that term carries in the philosophical literature. They are just a compact way of describing one facet of the space-time structure in which relativistic theories are set and of expressing the demand that processes licensed by relativistic theories conform to that structure. Their violation leads not to metaphysical incoherence, just to a different physical theory.

## NOTES

These remarks were prepared as a reaction to Jeremy Butterfield’s “Spacetime as a Causal Set: A Philosopher’s Introduction,” presented at the Seventh Meeting of the Pittsburgh-Konstanz Colloquium in the Philosophy of Science, Causation: Historical and Contemporary Perspectives, May 26–29, 2005, Konstanz. I thank Jeremy for his stimulating talk and comments; Miklos Redei and the participants in the conference for their helpful reactions and discussion; and Deutsche Bahn, Schweizerische Bundesbahnen, and Trenitalia for providing the rail service between Konstanz, Zurich, Milan, Florence, and Turin on which this note was drafted.

1. Redei (2002) cautions that, from a mathematical point of view, nothing precludes the expansion of the algebra of operators to include common causes for the correlations, although it remains unclear how the new content of the expansion is to be justified physically.

2. To illustrate the difference, assume we all decide tomorrow that “causation” means “determinism.” That universal linguistic agreement would not compromise causal anti-fundamentalism. For it to fail in this example, the world itself would also have to be deterministic; that determinism would then be the world’s fundamental causal character.

3. “The strong causality condition is said to hold at  $p$  if every neighborhood of  $p$  contains a neighborhood of  $p$  which no non-spacelike curve intersects more than once” (Hawking and Ellis 1973, 192).

4. Hawking and Ellis (1973, 189) write in justification of a prohibition on closed, timelike curves: “However the existence of such [closed, timelike] curves would seem to lead to the possibility of logical paradoxes: for, one could imagine that with a suitable rocketship one could travel round such a curve and, arriving back before one’s departure, one could prevent oneself from setting out in the first place. Of course there is a contradiction only if one assumes a simple notion of free will; but this is not something which can be dropped lightly since the whole of our

philosophy of science is based on the assumption that one is free to perform any experiment.”

5. I set aside here qualms over action at a distance. Newtonian theory, restricted to the collisions of bodies like billiard balls, was long the paradigm of good causal order, even though it did not conform its motions to a light-cone structure (with a finite invariant velocity).

6. The oddness of this tradition is that it overlooks the awkward fact that Newtonian theory never was deterministic. The violation of determinism is generic in Newtonian systems with infinitely many degrees of freedom, such a system of infinitely many interacting masses. (See Alper et al. 2000.) Determinism can also fail in very simple Newtonian systems, such as a mass sliding on a dome, as described in Norton (2003, sec. 3).

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# Thinking about Causes

From Greek Philosophy to Modern Physics

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