Philosophy Compass (2016)11, 256–266, 10.1111/phc3.12319

Physics and Causation

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Abstract

More than a century ago, Russell launched a forceful attack on causation, arguing not only that modern physics has no need for causal notions but also that our belief in causation is a relic of a pre-scientific view of the world. He thereby initiated a debate about the relations between physics and causation that remains very much alive today. While virtually everybody nowadays rejects Russell's causal eliminativism, many philosophers (although by no means all) have been convinced by Russell that the fundamental physical structure of our world doesn't contain causal relations. This raises the question of how to reconcile the central role of causal concepts in the special sciences and in common sense with the putative absence of causation in fundamental physics.

1. Russell's Attack on Causation

Pre-theoretically, it seems obvious that the physical world is governed by cause and effect, and this view was prevalent in physics and in philosophy until the end of the 19th century, at which point skepticism about the usefulness of causal notions for physics became increasingly popular. The most forceful attack against causation came from Russell in 'On the Notion of Cause' (1913), which remains the point of departure for most contemporary discussions of physics and causation. Russell's discussion is intricate and addresses a large number of issues.[1] This section is not a historical exegesis of Russell but rather a summary of what contemporary philosophers see as the key points to be extracted from his discussion, with a special focus on the *metaphysical* issues raised by Russell's attack on causation.

Russell's main target was the Kantian and Millian law of causality, which he famously disparaged as 'a relic of a bygone era' (1913, 1). The law of causality says that every event has an earlier cause necessitating its occurrence. Russell regarded deterministic classical mechanics as the best physical theory of the world, and thus didn't object to the 'necessitation' aspect of the law of causality. Instead, he provocatively claimed that modern physics reveals that the world isn't governed by the relation of cause and effect: there is no law of causality because there is no causation.[2]

Using the tools of contemporary metaphysics, we can identify two claims that Russell appears to endorse (without explicitly distinguishing between them). First, there is *causal anti-fundamentalism*, the thesis that causation is not part of the fundamental physical ontology of the world. If true, this certainly entails that causation is not as central a feature of the world as ordinarily thought, but it is compatible with the existence of causal facts as non-fundamental features of the world 'grounded in' fundamental physical facts. Yet Russell also endorses *causal eliminativism*, insisting that fundamental physics properly understood simply leaves no place for the existence of causal facts *simpliciter*.

Russell defends causal anti-fundamentalism by arguing that the relations between states of the world described by the dynamical laws of physics cannot plausibly be regarded as causal relations. One of his arguments is that the word 'cause' doesn't appear in the fundamental equations

of classical physics such as $F = ma$. (Indeed, Russell contends that causal talk doesn't appear anywhere in physics, a claim to which I return in Section 4.) This argument isn't particularly convincing. After all, fundamental dynamical equations clearly describe *nomic* relations (they tell us how the state of the world at a time lawfully depends on its state at other times), even if the word 'law' doesn't appear in them. Likewise, these equations may very well describe how states of the world causally influence one another even if they do not use the word 'cause'. But Russell also has two additional, stronger arguments (Field 2003: 435–440). Each one identifies a feature of nomic relations that makes them very unlike causation as we ordinarily understand it.

First, there is the *globality* argument. Paradigmatic examples of causes are local events: the throwing of the rock causing the window to break, the lighting of the match causing the forest to burn, etc. But fundamental physical laws involve global states of the universe. If Suzy throws a rock at a window at t_0, the laws do not say anything about whether the window will break at t_1 unless we also specify what happens in other regions of space at t_0, e.g., whether Billy is standing ready to intercept the rock before it reaches its target. Generally, any local process can be disrupted by external influences, so that the laws determine what happens in region r at t_1 (or a probability for what happens there, if they are indeterministic) only when everything that goes on in an enormous spatial region at t_0 has been specified. Indeed, in classical mechanics, nothing less than the *complete* state of the world at t_0 is needed to determine what happens at t_0. Even assuming relativistic prohibitions on superluminal signaling, we need information about the entire cross-section of r's past light-cone at t_0 to fix what happens in r at t_1. If the two times are more than a few nanoseconds apart, this cross-section will be extremely large. Thus, there is a mismatch between the sort of states involved in nomic relations and the kinds of entities that we regard as prototypical causes.

Second, there is the *symmetry* argument. Causation as ordinarily understood is asymmetric: causes 'bring about' their effects but not *vice versa*. Moreover, the arrow of causation has a temporal orientation: causes precede their effects. But Russell points out that we find no such asymmetry in the laws. In classical mechanics, the state of the universe at a time determines its state at any later time, but it also determines its state at any earlier time. Thus, relations of nomic determination do not display the asymmetry characteristic of causation. One question here is whether the argument still works once one abandons classical mechanics. Contemporary deterministic theories such as Bohmian mechanics display the same sort of bi-directionality as classical mechanics, and some indeterministic theories do as well (in the sense that on those theories, the state of the world at a time determines a probability distribution over both later and earlier states). But not all do.[3] This is one instance where future developments in fundamental physics may have a bearing on the questions discussed here.

For Russell, the upshot of these considerations is that the physical world is not governed by any fundamental relation of cause and effect. More, according to him, they show that causation as ordinarily understood simply doesn't exist. His implicit assumption here is that on our ordinary concept of cause, causation requires nomic determination: c causes e only if c and the laws entail e's occurrence. (This is essentially Hume's 'constant conjunction' view of causation.) Moreover, for Russell, this condition and the principle that causation is local and asymmetric exhaust the content of our causal concept. So for him, the hypothesis that causes exist is simply a specific hypothesis about the content of the physical laws, viz. that those laws describe asymmetric local relations of determination. And if this way to analyze our ordinary causal concept is correct, the globality and symmetry arguments decisively establish the falsity of this hypothesis. Our view of the world as populated with causal relations is a primitive image of the world to be replaced by the more sophisticated picture painted by modern physics.

2. The Indispensability of Causation

Whatever the merits of Russell's case for causal anti-fundamentalism, today, there is a consensus against his causal eliminativism.[4] First, Russell's case for eliminativism is far from airtight. Although causation is tied to the idea of determination, the relationship between them is less direct and more complex than Russell makes it to be. Nor is an asymmetry in the laws the only possible source for a causal asymmetry (some alternative candidates will be discussed later). Second, one decisive argument against eliminativism is that causation is indispensable. Causation plays a crucial role in modern philosophical accounts of knowledge, reference, moral responsibility, and many other central concepts. Moreover, the special sciences (which Russell simply ignored in his discussion) are suffused with causal representations and explanations. Rejecting causation would lead to philosophical and scientific disaster.

The most influential indispensability argument for causation is due to Cartwright (1979), who points out that causal knowledge is indispensable to identify effective strategies. For instance, getting vaccinated against the flu is an effective strategy to avoid sore throat. This isn't simply because having the flu and having a sore throat are correlated, since to avoid the flu, taking medication against sore throat is useless. Rather, the obvious reason is that the flu *causes* sore throats. So causation and not mere correlation underlies the distinction between effective and ineffective ways to achieve goals, and plausibly, our repertoire of causal concepts exists in large part to track this distinction. Arguably, the connection between causation and effective strategies partially explains why causal concepts play such an important role in the special sciences, since the main role of at least some special sciences such as medicine or economics is to discover effective strategies to achieve socially useful aims.

Many philosophers regard the connection between causation and effective strategies as the central feature of our causal concepts – what 'causation is all about' (Hitchcock 2007, 52). It is worth noting that while this pragmatic stance on causation is associated with a rejection of causal eliminativism, it nevertheless fits naturally with causal anti-fundamentalism. If the point of causal notions is to capture aspects of the world that are important for practically and epistemically limited agents like us, arguably we shouldn't expect causation to show up into an objective description of the fundamental nature of the world. (Accordingly, philosophers who emphasize the pragmatic aspects of causal notions also tend to be causal anti-fundamentalists, while those who reject causal anti-fundamentalism often put the focus on less (or less obviously) pragmatic aspects of causation such as its connection with explanation.)

Indeed, the interventionist theory of Spirtes *et al.* (2000), Pearl (2009), and Woodward (2003) – by far the most popular and systematic way to articulate in detail this pragmatic or 'agentive' view of causation – is often taken to provide further support for causal anti-fundamentalism on top of Russell's original arguments. For interventionists, causal claims describe what would happen if a variable were subjected to an external manipulation or 'intervention' that places the variable under its control while leaving other aspects of the causal structure intact. Many authors have argued that on this picture, it is difficult and perhaps even incoherent to apply causal concepts in the context of fundamental physical theories that purport to represent the whole universe. One reason is that the universe is a close system, whereas claims about interventions apply most naturally to 'open systems' embedded in a larger environment that can serve as the source of external manipulations (Hausman 1998, Pearl 2009, Eagle 2007, Woodward 2007). Another reason is that interventionism arguably entails that the maximally fine-grained variables of fundamental physics cannot be causal relata, in part because dependence relations between such variables fail to display certain important statistical asymmetries that interventionists regard as intimately tied with causation (Arntzenius 1993, Field 2003, Woodward 2007).[5] However, Frisch (2014) argues that the interventionist framework can in

fact be understood in a way that makes causal notions applicable to fundamental physics. In particular, Frisch argues that interventions need not be regarded as external manipulations and so can be applied to closed systems. (See also Reutlinger 2014.) Given the popularity of interventionism, the debate on its implications for causation in fundamental physics is likely to continue in the years to come.

3. Neo-Russellianism

Neo-Russellians agree with Russell that causation is nowhere to be found in fundamental physics, and with Cartwright that causation is practically indispensable. Thus, the main issue for them is to find a place for (non-fundamental) local, asymmetric causation in a world whose fundamental laws are global and symmetric.

While neo-Russellians disagree on many important points, there is a broad consensus among them on the general form that a solution to the problem should have. Regarding the problem of meshing local causation with global laws, there is an agreement that the solution is to explicate causation in terms of counterfactual dependence or difference-making (following Lewis 1973) rather than nomic determination. This solves the problem insofar as a cause can make a difference to its effect without being nomically sufficient for the effect.[6] Thus, Suzy throwing a rock makes a difference to the window breaking in so far as the breaking (probably) wouldn't have happened without the throw, even if the throw by itself isn't sufficient to guarantee that the window will break. This also meshes well with a pragmatic view of our causal concept, since when making decisions, we care about actions that makes a difference to the occurrence of desired outcomes. (Of course the task here is to explain what difference-making consists in exactly.) As for the problem of the causal asymmetry, neo-Russellians tend to agree that the right way to go about solving the problem is to try to account for the asymmetry of difference-making in terms of some other asymmetry whose origins and fit with time-symmetric physics are better understood. All neo-Russellians also agree that *pace* Hume the causal asymmetry doesn't merely consist in the fact that earlier events 'causes' and later ones 'effects', as this view is unable to explain why backward causation appears at least conceptually possible, and why the causal asymmetry is intimately tied to asymmetries of action and explanation.[7] So the asymmetry which grounds the causal arrow, must be a more substantive one than the mere temporal asymmetry.

There are currently two main proposals for making this set of ideas more precise. The first is the statistical-mechanical account of Albert (2000) and Loewer (2007).[8] Their point of departure is the question of how to explain the thermodynamic asymmetry (the fact that entropy increases towards the future but not towards the past) and its compatibility with time-symmetric laws. Albert (2000) argues that the thermodynamic asymmetry should be explained in terms of three elements: time-symmetric fundamental laws, a postulate to the effect the universe began in a state of very low entropy (the 'Past Hypothesis'), and an objective equiprobability distribution over all microstates compatible with the initial low-entropy macrostate. Together, these three elements generate a statistical-mechanical probability distribution over possible lawful evolutions of the world. Albert and Loewer use this objective probability distribution to explain the existence of local, asymmetric relations of counterfactual dependence and their compatibility with acausal fundamental physics.

First, Albert and Loewer propose a procedure for evaluating counterfactuals about local, macroscopic events (the kind of counterfactuals of interest to agents like us) that connects them to global laws via statistical-mechanical probabilities. On their view, to evaluate a counterfactual such as 'if Suzy were to throw the rock at t_0, the window would break at t_1', one takes the actual state of the world at t_0 and modifies it so that Suzy throws the rock instead of doing nothing

(everything else that happens at t_0 stays the same). This gives us a counterfactual t_0-state of the world that is large enough for the laws to yield a verdict about what happens at t_1. One complication here is that Suzy throwing the rock is a coarse-grained event realizable by various micro-physical states, some of which may not lead to the window breaking. For instance, for some possible velocities of the throw, the window will not break, so that the laws do not yield a *unique* verdict as to what will happen to the window. This is where Albert and Loewer appeal to the statistical-mechanical distribution, here applied to the possible microstates compatible with Suzy's throw and other features of the world at t_0. Evolving this distribution forward yields a high probability that the window will break, so that the counterfactual under consideration (or at least a probabilified version of it) comes out true.[9]

Albert and Loewer also argue that the statistical-mechanical distribution also explains the causal asymmetry, in the following way. First, the Past Hypothesis and the associated equiprobability distribution over possible initial microstates of the world underlie an asymmetry of *records*: for any actual macroscopic event *c*, there are many local events in *c*'s future that make it objectively likely that *c* occurred, but few if any such events in *c*'s past. Thus, Suzy's throwing of the rock has few traces in its past but many in its future such as Suzy's memory of the throw, passersby observing the rock flying, and so on.[10] Second, this asymmetry of records generates an asymmetry of counterfactual dependence. Had some current local event *e* not happened, the present state of the world would still contain many traces of the past, so that given *e*'s non-occurrence, the statistical-mechanical distribution entails that any actual past event *c* would still very likely have occurred. Since by contrast there are few traces of the future, current events can make a substantial probabilistic difference to the future evolution of the world. This explains why there are many 'causal handles' that allow us to influence the future but few (if any) that allow us to influence the past. Thus, the presence of causally asymmetric phenomena in a world whose fundamental laws are symmetric is explained in terms of a statistical-mechanical asymmetry that is itself a product of the initial conditions of the universe.

There is a lively discussion surrounding Albert and Loewer's account of causation and their more general program in the foundations of statistical mechanics.[11] In particular, Frisch (2007, 2010, 2014) has argued that their account of causal direction faces difficulties. One of his criticisms is that the asymmetry of records isn't as pervasive as Albert and Loewer make it to be, so that their account cannot explain why the causal time-asymmetry is as sharp as we intuitively think it is.[12] The question whether the Past Hypothesis and related statistical-mechanical asymmetries can ground the causal asymmetry remains a matter of debate.[13]

The other main neo-Russellian account is the 'perspectival' view defended by Price (1996, 2007), Weslake (Price and Weslake 2009) and Ismael (2007, 2011, 2016), as well as Eagle (2007) and Menzies (2007). Whereas Albert and Loewer regard causation as an objective if derivative feature of the world, perspectivalists hold that causation (and especially its directionality) is a less than fully objective phenomenon: a feature of the world as viewed from the perspective of creatures like us.[14] Like Albert and Loewer, perspectivalists regard causation as a matter of counterfactual dependence, although they tend to construe it in a way that gives a more explicit role to agency. Thus, many of them endorse an interventionist view on which a counterfactual of the form 'if *c* were to happen *e* would happen' describes the consequence of a hypothetical external intervention producing *c*. While interventions need not involve agency, our interest in such counterfactuals is explained by the fact that our own actions or decisions are interventions.

In addition, a key claim of perspectivalism is that the asymmetry of those counterfactuals is in some sense a product of the distinct perspective that agents like us have on the world. Thus, Price and Weslake (2009) argue that the causal arrow is a projection of an agentive asymmetry of deliberation: the fact that the immediate objects of our deliberations lie in our immediate

future, not in our past. They suggest that this asymmetry of deliberation can be explained in terms of the Past Hypothesis and the statistical-mechanical asymmetries to which it gives rise. (In that respect, the viability of their account depends on the outcome of the debates about the Past Hypothesis.) According to them, the fact that the only events we can directly bring about are in our future explains also why we can never influence the past, even indirectly: their idea is that our decision to perform an action 'screens off' any relations of probabilistic dependence between the action and earlier states of the world. Crucially, this asymmetry of deliberation also explains why we regard causation as time-asymmetric in cases that do not involve human agency. When assessing the causal consequences of an event c that we cannot manipulate, we bring our own temporal perspective to bear by considering what would happen were c to be brought about directly by an intervention that originates from c's past and thereby screens off ordinary relations of dependence between c and its normal causes. Thus, our own deliberative asymmetry explains why we care so much about the specific kinds of interventions in terms of which Woodward and others define causation.[15] The upshot is that the causal direction is a matter of perspective (Price 2007). Hypothetical creatures living in spacetime regions where statistical-mechanical asymmetries are reversed would have a deliberative arrow running in the opposite direction from ours and would therefore regard causation as running towards the past, and their perspective would be no less correct than ours.

The statistical-mechanical and the perspectival accounts have more in common than it may appear at first glance, and in fact, where and to what extent they really differ is a matter of debate. For one thing, on both views, statistical-mechanical asymmetries play an important role (although not the same one). Moreover, Albert and Loewer would presumably agree that creatures living in regions where statistical-mechanical asymmetries run in reverse would have a causation-like concept (call it 'causation*') on which causes* precede their effects*. Now, perspectivalists often appear to endorse the view that causal statements contain a hidden contextual parameter for a perspective; so they would regard causation* as the very same concept as our causal notion, but with a different perspective plugged into that parameter. Albert and Loewer, on the other hand, would presumably say that causation* is very similar but not identical to our concept of causation. However, it isn't clear whether anything of significance hangs on this semantic matter. Ismael (forthcoming) argues that perspectivalism shouldn't be interpreted as a view about the semantics of causal concepts. On her view, one key claim of perspectivalism is that causation is ontologically on a par with many other non-fundamental relations, and it is facts about us that explain why we are so interested in that notion. But it isn't clear that Albert and Loewer would disagree with this claim, since on their view, our interest in counterfactuals about small macroscopic events is explained by the fact that our own actions themselves are small macroscopic events. Perhaps, the clearest difference between the statistical-mechanical view and accounts such as Price and Weslake's is that on the latter's view, any plausible account of the causal direction and our interest in it must appeal to *time-asymmetric* facts about agents like us (such as the arrow of deliberation), whereas for Albert and Loewer, our interest in causation can be explained without appealing to an antecedent asymmetry of agency.

Note that one may side with Price and Weslake on this last issue without regarding causation as being in an interesting sense a matter of perspective. One may also hold that an asymmetry of agency is needed to explain (our interest in) the causal directionality but doesn't constitute the whole story. A case in point is the recent account of the causal direction offered by Kutach (2013, chs. 6–7). Like Price and Weslake, Kutach holds that appealing to an asymmetry of agency is needed to explain why we cannot influence the past. (Like them, he thinks that this asymmetry is a byproduct of the fact that we are embedded in a thermodynamically asymmetric environment.) But Kutach rejects perspectivalism, in part on the ground that scenarios in which the arrow of agency runs in the opposite direction are too far-fetched to be of much

significance. Moreover, for Kutach, the asymmetry of agency is necessary but not sufficient to explain why we cannot influence the past, as it doesn't rule out the possibility of zigzagging influence that goes towards the future and then reverses towards the past. On his account, we need an objective asymmetry to explain not only the temporal orientation of agents but why this kind of 'future-then-past-directed' influence is impossible. (For Kutach, the relevant asymmetry is a statistical-mechanical asymmetry of typicality that precludes the kind of bizarre coincidences that, he argues, would be required for zigzagging influence to occur.)

4. Challenges to Neo-Russellianism

While neo-Russellianism is the dominant view among naturalistically minded philosophers of causation, one also finds authors who defend modernized versions of causal fundamentalism, challenge certain key aspects of (neo-)Russellianism, or otherwise insist that its picture of the relations between physics and causation needs to be nuanced in certain important respects.

A claim that has received a significant amount of critical discussion is Russell's contention that causal talk and reasoning play no useful role in physics. Many have taken issue with this claim, arguing that it embodies an inadequate and impoverished picture of scientific practice in physics. As has been repeatedly observed,[16] physicists routinely use the word 'cause' in their work. Lange (2009) argues that like the special sciences, physics is also concerned with explaining why certain local events occur, and given the tight connection between causation and explanation this requires positing causal relations in physics. More recently, Frisch (2014) makes a detailed case for the importance of causal representations and assumptions in physics. Frisch shows that many physical models are on a par with representations found in the special sciences in that they posit relations of causal dependence among small sets of coarse-grained variables. He also points out that many ordinary physical inferences are straightforward instances of common cause reasoning (e.g., inferring the presence of a star from repeated observations of points of sky in the light).

As has often been noted, the presence of causal representations and reasoning in physical practice is in itself compatible with causal anti-fundamentalism, which is a physical claim about the *fundamental* physical ontology of our world. The need for causal representations in physics may simply be a byproduct by the fact that epistemically limited beings like us cannot build complete representations of states of the universe in all its physical details, nor compute how such states evolve through the laws. But some of the causal assumptions and principles that appear in physics appear at least at first glance to be in tension with causal anti-fundamentalism. Here one issue that has received a lot of attention is the fact that in some areas of physics such as linear response theory and electromagnetism, some equation solutions are routinely rejected by physicists on the ground that they are incompatible with the principle that causes precede their effects. There is an ongoing debate on whether this principle can be recovered on the basis of other non-causal assumptions already present in these theories. If not, this would be at least *prima facie* case for the presence of irreducible asymmetric causal relations in the fundamental ontology. Frisch (2005, 2009, 2014) argues that the principle may be a *sui generis* constraint not recoverable from non-causal assumptions, while Norton (2009) and Smith (2013) argue that the principle doesn't put constraints on the behavior of physical systems that are not already present in the relevant theory.[17] Norton (2007b) argues that similar causal principles that appear in relativity theory raise no particular problem for causal anti-fundamentalism.[18]

In addition to this potential challenge from scientific practice in physics, one also finds views and arguments that challenge neo-Russellianism on broadly metaphysical grounds. Ney (2009) argues that the right lesson to draw from Russell's arguments is not that causation is absent from the fundamental fabric of the world, but that we should revise our concept of causation. The

globality argument simply tells us that there is much more causation at the fundamental level than we may naively think: everything in the backward light-cone of an event is causally relevant to it. And the symmetry argument simply shows that fundamental causation isn't asymmetric. As Ney recognizes, however, eliminativism about our ordinary concept of causation is out of the question, so that there is still the issue of explaining the asymmetry of folk causation. Thus, it is not clear whether there is more than a verbal dispute with neo-Russellians here (Farr and Reutlinger 2013).

Frisch (2014) takes issue with the key neo-Russellian claim that the causal direction is to be explained in terms of a more fundamental probabilistic asymmetry. Drawing on his criticism of Albert and Loewer's account, Frisch argues that the probabilistic asymmetry most tightly connected with the causal asymmetry is not the asymmetry of records but an asymmetry of randomness. (Roughly, this is the fact that spatiotemporally distant processes are uncorrelated before but not after they interact.) Frisch argues that while the asymmetry of randomness may be seen as grounding the causal asymmetry, it can also be derived from certain causally asymmetric assumptions central to our causal modeling practices. Thus, he tentatively endorses the view that there may simply be no fact of the matter as to whether probabilistic asymmetries are more or less fundamental than the causal asymmetry.

Finally, the debate about neo-Russellianism and the place of causation in physics is connected to larger issues in the metaphysics of science. One of them is the debate between categorical and dispositionalist or structuralist views of fundamental properties, on which scientific properties are individuated by their causal profiles. On this view, causal relations are built into the nature of physical properties themselves, even if they do not appear overtly in the laws. See Esfeld (2010) for a defense of dispositionalism that emphasizes its anti-Russellian implications, and Saatsi (forthcoming) for a rejoinder. Another relevant issue is the question of the nature of laws and time. The view of time presupposed in Russell's arguments and in the neo-Russellian literature is a four-dimensionalist view on which there is no intrinsic, substantive temporal asymmetry. In addition, neo-Russellians tend to endorse a Humean view of laws of nature. Maudlin (2007) proposes for an alternative package view of laws and time, on which the dynamical laws of fundamental physics describe primitive relations of 'production' by which earlier states of the world generate later states. Thus, if the laws allow us to predict both past and future states of the world, one of these directions is metaphysically privileged. His main argument is that such a view is required to make sense of our deep intuition that time is passing. On this view, lawful relations are very much like asymmetric causal relations after all, and there is no special problem of understanding how the arrow of causation fits with fundamental physics. See Loewer (2012) for a comparison of the Humean and Maudlinian views of laws and time and a defense of the former.

5. Conclusion

Many questions raised by Russell's discussion remain hotly debated. On the one hand, the neo-Russellian view that causation has no place in fundamental physics has received an increasing amount of critical attention lately. On the other hand, many issues internal to the neo-Russellian program are still to be settled, including questions about the origins of the causal arrow, the connection between causal and agentive asymmetries, and whether causation is a matter of perspective.

Short Biography

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Notes

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[1] See Hitchcock (2007) for an excellent overview.

[2] As Ross and Spurrett (2007) note, Russell's argument is a precursor of contemporary philosophical naturalism – the view that science is our best guide to metaphysics and may lead us to revise our view of the world in possibly radical ways.

[3] In particular, on the GRW interpretation of quantum mechanics, probabilities are well-defined in the future direction only. Albert (2000, ch. 7) argues that if GRW is true, the causal arrow (and other physical asymmetries) may be a direct product of the laws.

[4] Indeed, Russell himself abandoned eliminativism later on. In his (1948) he offers an early version of a process theory of causation.

[5] See Woodward (2007) for a general overview of the various points of tension between causation understood along interventionist lines and fundamental physics.

[6] See Eagle (2007) for a very clear statement of this idea.

[7] See, e.g., Price and Weslake (2009: 414-6).

[8] See also Kutach (2002, 2007).

[9] Elga (2007) complements this picture of difference-making by arguing that statistical-mechanical probabilities also explain why our practice of explaining events in terms of a sparse set of nearby difference-makers is successful: the statistical-mechanical probability distribution makes it highly unlikely that (e.g.) what happens on Mars will make any meaningful difference to local goings-on Earth. Kutach (2013) offers an account of counterfactual dependence along roughly the same lines as Albert and Loewer, although for him, the probability distribution needed to connect counterfactuals with fundamental laws need not be the statistical-mechanical probability distribution: him, any reasonable probability distribution will do.

[10] Here, Albert and Loewer are inspired by Lewis (1979), who argued that our world displays an asymmetry of overdetermination: for any event *c,* there are many local events in *c*'s future that nomically determine *c*'s occurrence, but few if any such events in *c*'s past. However, since nomic determination involves only global states, Lewis's thesis is false (Elga 2001, Frisch 2005). The asymmetry of records is not an asymmetry of determination but a statistical asymmetry, and thus escapes this objection.

[11] See Ernst and Hüttemann (2010), Wilson (2014), Loewer *et al.* (forthcoming) for recent anthologies addressing various aspects of this program.

[12] See Albert (2014, 2015) for a response to Frisch's criticisms.

[13] Here, it is worth mentioning that the asymmetry of records is not the only statistical asymmetry candidate to the role of explaining the causal arrow. There is a tradition originating in Reichenbach (1956) that seeks to ground the causal asymmetry in an asymmetry of screening-off. This is the fact that in our world, relations of probabilistic dependence between two simultaneous events often disappear conditional on earlier events, but they rarely if ever disappear conditional on later events. See Horwich (1987), Papineau (1993), Dowe (2000: ch. 8), Field (2003: 445–6) and Strevens (2007) for accounts of the causal arrow in terms of this asymmetry, and Price (1996) and Weslake (2006) for critical discussions. One problem here is that on the face of it, it isn't obvious how and why the screening-off asymmetry should have any bearing on the fact that we cannot influence the past.

[14] Ramsey (1978) is an early defender of this view.

[15] However, Frisch (2013) argues that Price and Weslake's account is in fact in tension with certain aspects of interventionism.

[16] See, e.g., Suppes (1970), Hitchcock (2007), Ross and Spurrett (2007).

[17] See also North (2003) and Earman (2011).

[18] See also his (2007a) for a more general argument that any putative causal principle is either false or too vague to be fundamental.

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