

Causality and Explanation: A Reply to Two Critiques*

Wesley C. Salmon^{†‡}

Department of Philosophy, University of Pittsburgh and Universität Konstanz

This paper discusses several distinct process theories of causality offered in recent years by Phil Dowe and me. It addresses problems concerning the explication of *causal process*, *causal interaction*, and *causal transmission*, whether given in terms of transmission of marks, transmission of invariant or conserved quantities, or mere possession of conserved quantities. Renouncing the mark-transmission and invariant quantity criteria, I accept a conserved quantity theory similar to Dowe's—differing basically with respect to causal transmission. This paper also responds to several fundamental constructive criticisms contained in Christopher Hitchcock's discussion of both the mark-transmission and the conserved quantity theories.

1. Introduction. The June 1995 issue of *Philosophy of Science* contained two penetrating discussions of my views on causality and explanation. In "Causality and Conserved Quantities: A Reply to Salmon", Phil Dowe correctly states that we already agree on much, but that important differences remain. The first part of this reply (§2–7) explores further the similarities and differences between our two theories; it focuses entirely on our process theories of causality. In "Salmon on Explanatory Relevance", Christopher Read Hitchcock raises problems concerning the nature and role of causality in scientific explanation that

*Received February 1996.

†Send reprint requests to the author, Department of Philosophy, University of Pittsburgh, 1001 Cathedral of Learning, Pittsburgh, PA 15260.

‡I should like to express my gratitude to the Alexander von Humboldt Foundation for support of research embodied in this paper and to the University of Konstanz for providing a congenial environment in which to carry it out. My thanks also go to Paul Hoyningen-Huene and Johanna Seibt for helpful and clarifying comments on the issues here addressed. I am most especially grateful to Phil Dowe, Christopher Hitchcock, and Philip Kitcher for their insightful contributions to the discussion of causal explanation.

Philosophy of Science, 64 (September 1997) pp. 461–477. 0031-8248/97/6403-0004\$2.00
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apply just about equally to Dowe and me. These are addressed in the second part (§8–11). All three of us agree that, in one way or another, process theories of causality are important and viable. I hold, moreover, that such a theory provides an answer to Hume's famous question about the nature of causal connections.

2. Directionality: Temporal and/or Causal. In sketching a bit of background for the mark-transmission criterion for distinguishing causal processes from pseudo processes (Salmon 1994, 302–303), I pointed out that Reichenbach had maintained that the mark method was capable of establishing a time direction, but that Grünbaum had refuted that claim. I went on to state my earlier view that “the mark method provided a criterion for distinguishing between causal processes and pseudo processes, without any commitment to time direction” (ibid.). Unfortunately, although I intended to retain this neutrality with respect to direction in making the transition from the mark transmission criterion to the transmission of invariant (or conserved) quantities criterion, I failed to do so in the crucial DEFINITION 3:

A process transmits an invariant (or conserved) quantity from A to B ($A \neq B$) if it possesses [a fixed amount of] this quantity at A and at B and at every stage of the process between A and B without any interactions in the half-open interval $(A, B]$ that involve an exchange of that particular invariant (or conserved) quantity. (Ibid., 308)

As Dowe points out, the phrase “from A to B” obviously implies a direction. He also mentions the need for an *only if* condition in the definition. Both flaws can be repaired by slight reformulations (as indicated by emphasis). Moreover, for reasons that will become clear in §9—the corollary formulated in that section depends on conservation—I now wish to follow Dowe in formulating the criteria in terms of conserved, rather than invariant, quantities.

A process transmits a conserved quantity between A and B ($A \neq B$) if and only if it possesses [a fixed amount of] this quantity at A and at B and at every stage of the process between A and B without any interactions in the open interval (A, B) that involve an exchange of that particular conserved quantity.

This reformulation should be substituted for the previous DEFINITION 3.

Dowe distinguishes two types of asymmetry, causal and temporal. I agree that the two need not coincide. It is not a priori impossible for some causal processes to transpire in a direction contrary to the direction of time; for example, there is nothing logically absurd in Richard Feynman's interpretation of the positron as an electron moving back-

ward in time. Moreover, the “transactional” interpretation of quantum mechanics, cited by Dowe, cannot be ruled out a priori just because it appeals to “backward causation.” Like Dowe, I want to adhere to a causal theory of time, and this commitment precludes defining causal direction in terms of temporal direction. It does not, however, preclude “backwards in time causation” if a great preponderance of causal processes go in the same direction.

It was not my intention in Salmon 1994 to introduce either temporal direction or causal direction; such asymmetries require separate treatment in terms of conjunctive forks, increase of entropy, or neural K-meson decay (see, for example, Dowe 1992b). I do not believe there is any residual difference of opinion between us on this issue.

3. The Conservation of Conserved Quantities. In formulating DEFINITION 3, I intended to convey the condition that any conserved quantity that characterizes a causal process retains a constant value as long as there is no causal interaction with another process involving an exchange of that quantity. (The bracketed insertion makes this supposition explicit.) The fundamental idea is that a fixed amount of the conserved quantity is transmitted by the process in question; it doesn’t have to be replenished from another source such as the spotlight that illuminates a spot on a wall. I assumed that Dowe intended a similar stipulation about conserved quantities in causal processes. It seemed reasonable to suppose that on his view conserved quantities are conserved overall in interactions involving exchanges of such quantities, and that their values remain constant in the absence of such interactions. Commenting on this point, Dowe says,

Of course, if we are talking about conserved quantities this obviously must be true. However, there are pragmatic difficulties: actual causal processes do not operate in the absence of interactions. A body moving under the action of a field, for example, is really a string of interactions. In reality most causal processes attenuate, as there is loss of energy to the environment. It seems that if we wish to accommodate the standard types of causal processes (e.g., Salmon’s example of the moving baseball) then we will have difficulties with this requirement. In theory, causal processes do possess a fixed amount of energy, say, in the absence of interactions, but in practice such a requirement renders useless the notion of a causal process, as opposed to an interaction. For this reason the CQ [conserved quantity] theory does not require that a causal process possess a constant amount of the relevant quantity over the entire history of the process. (1992b, 331)

Appearances to the contrary notwithstanding, there is little, if any, disagreement here. In presenting my theory of causal processes and interactions, I am talking *in theory*. I want to understand what is fundamentally involved in causal transmission and interaction. The pragmatic problems are not at issue. In the vast majority of cases I would analyze what Dowe considers a single causal process into a large number of distinct but connected processes. The difference is mainly terminological.

When it comes to practical investigation of actual processes pragmatic considerations determine the level of analysis. For some purposes the motion of a molecule of a gas between collisions with other objects (other molecules, Brownian particles, or walls of containers) may be considered a single causal process; for other purposes the motion of a baseball from a bat to a window (in spite of innumerable collisions with molecules in the atmosphere) may be regarded as a single causal process. I think we gain greater philosophical insight into causality by operating at a rather rarified theoretical level, recognizing, of course, that we must often descend from such abstract heights when it comes to practical investigations. There are many empirical methods for discovering and identifying causal processes.

Lest anyone believe that I have completely lost contact with physical reality in discussing extended causal processes without causal interactions, it should be noted that the mean free path of photons in intergalactic space is estimated in terms of very large numbers of light years. Such photons are causal processes, and the mean free path is the average distance between causal interactions with other processes. This fact may actually aid us in understanding why the night sky is dark (Olbers' paradox).

4. Causality and Fields. As we know, flying baseballs and other projectiles fall toward Earth with the same acceleration as Newton's apple. Ignoring for now the issue of action-at-a-distance, we should note that classically speaking there is a continuous interaction between two mutually gravitating bodies. In my past discussions of causal interactions, thinking in terms of causal interactions connected by causal processes, I have treated interactions as discrete occurrences. This approach has neglected the causal significance of fields—gravitational, electromagnetic, or whatever—a point Dowe raises in the preceding quotation. The issue need not detain us, however, for there is no need to deny the existence of a continuous series of interactions. In this context, we may go back to air resistance and wind, regarding them for practical purposes as results of a continuous series of interactions with a homogeneous medium, neglecting the particulate character of the atmosphere.

Where atmospheric effects are concerned we are making an idealizing simplification; with classical gravitation we are not.

Does an object like a baseball or a bullet then fail to qualify as a causal process? Suppose it is moving in a vacuum and is subject to no external forces—i.e., Newton's first law applies. It is often said that in Newtonian mechanics (in contrast to Aristotelian physics) such uniform motion needs no explanation; only changes of states of motion require explanation. I would say that such an object constitutes a causal process not subject to any interaction. This *is* the explanation—it is a particular type of causal process that is just doing its own thing without external interference.

Now consider an object falling freely toward Earth in a vacuum. According to classical physics it is changing its state of motion, and the gravitational force explains this change; in my terms we would refer to a continuous series of interactions between this object and Earth's gravitational field. Considered from the standpoint of general relativity, however, the worldline of this object is a geodesic in spacetime. This is the relativistic analogue of Newton's first law. It has been rightly said that, while Newton's theory requires an explanation of the apple's falling, relativity requires instead only an explanation of its stopping when it hits the ground. On my view any such falling object is a single causal process that is free from interactions. This point applies to photons as well as to material particles. As far as explanation of such motion is concerned, it suffices to specify the spacetime metric. Action-at-a-distance is not involved; the moving particle responds to the local spacetime structure.

Electromagnetic phenomena are different. According to our best contemporary theory, quantum electrodynamics, the electromagnetic force is mediated by exchanges of photons. This means, in my terms, that whenever a photon is emitted or absorbed by a charged particle we have a causal interaction. Thus a charged particle undergoing acceleration in an electromagnetic field consists of a series of causal processes standing between frequent causal interactions. It is analogous to a baseball moving through air. For most practical purposes we can, of course, idealize the situation and treat the electromagnetic field as continuous, much in the same manner as we treated the air as a continuous medium above. Action-at-a-distance is excluded from the account of the motions of charged particles.

It may be that the gravitational force is mediated by spin-two uncharged particles known as gravitons, in somewhat the same way as the electromagnetic force is mediated by photons, but it is too soon to say whether this is a correct account. We do not yet have a unified theory of gravitation and electrodynamics.

5. Transmission. The fundamental point on which Dowe and I do actually disagree also concerns DEFINITION 3. Dowe says that it is unnecessary; I claim that it is indispensable. The issue concerns the concept of transmission, and it is centered on the final clause of the definition, “without any interactions . . . that involve an exchange of that particular conserved quantity.” In support of my view I invited consideration of a paradigmatic case of a pseudo process, namely, a spot of light moving across a wall. In earlier writings (e.g., Salmon 1984, 145–146) I had argued that the spot possesses energy, but the energy is not transmitted; therefore, mere possession of (a fixed quantity) of energy is not a sufficient condition for the status of causal process. Dowe replied (1992a, 127) that the bright spot does not possess energy; instead the illuminated patch of wall has it. Taking Dowe’s point, I then suggested that the patches of the surface layer of the wall that absorb the energy would qualify collectively as a causal process with respect to Dowe’s criterion. Dowe responds that such a “gerrymandered aggregate” does not really qualify as a thing that can possess conserved quantities. So, we are left with the problem of determining what kinds of “things” can possess conserved quantities and what kinds of “things” cannot. I address this question in §6.

Before discussing that issue, I must comment on Dowe’s assertion that “Salmon’s account in terms of the transmission of an invariant quantity is itself vulnerable to this objection. For according to that account, transmission amounts just to regular appearance . . . if counterexamples such as the rotating spotlight [spot] count as cases of regular possession then they count also as cases of transmission” (Dowe 1995, 327). This criticism is untenable precisely because it overlooks the clause in DEFINITION 3 that precludes outside interactions. The spot of light traveling around the wall exists by virtue of constant illumination from the central spotlight. The energy that appears in the successive patches of the surface of the wall is present only because it is constantly being supplied by an outside source. These are cases in which something is present in all of the intermediate stages of a (pseudo) process, but it is not “present without any interactions . . . that involve an exchange of that particular conserved quantity” (DEF. 3). From my point of view the crucial question regarding causal processes is what they do on their own without outside intervention. My answer is that they transmit something—e.g., conserved quantities, information, or causal influence—and it is by virtue of such transmission that events at *A* and *B* (DEF. 3) are causally related. Dowe gives a different answer.

6. Gerrymandered Aggregates vs. Objects. Dowe lays his cards on the table when he says, “there is implicit in the CQ [conserved quantity]

theory a restriction on what counts as an object. This now needs to be made explicit. I take it that *an object must be wholly present at a time in order to exist at that time*" (Dowe 1995, 329; Dowe's italics). According to Dowe, "time-wise gerrymanders" do not fulfill this requirement. He invites consideration of the following putative object x (ibid., 328):

- for $t_1 \leq t < t_2$; x is the coin in Dowe's pocket
- for $t_2 \leq t < t_3$; x is the red pen on Dowe's desk
- for $t_3 \leq t < t_4$; x is Dowe's watch

It is intuitively clear, for example, that at time T ($t_2 < T < t_3$) the pen part of x is present but the coin part and the watch part are absent. One reason for this intuitive clarity is the obvious spatiotemporal discontinuity of x . Since I take causal processes to be spatiotemporally continuous, I am not tempted to regard x as a causal process (though each of the three pieces is).

Dowe allows that the spot of light is an object (1995, 329), but it is not the kind of object that possesses conserved quantities. It has size, shape, and speed; it does not have energy, momentum, or electric charge (ibid., 327). I agree. Thus, the spot is not a causal process according to the conserved quantity theory. Moreover, he argues, neither is the portion of the surface of the wall that is illuminated by the moving spot of light a causal object; it is a time-wise gerrymander—in Philip Kitcher's term, a piece of "spatiotemporal junk." It fails the criterion of being wholly present at any given moment in its 'history'. I disagree. Given that this four-dimensional 'object' has a continuous worldline, of which we may take a slice at any moment, I would ask why that time-slice is not wholly present in Dowe's sense.

Dowe responds by distinguishing two different ways of viewing objects, namely, (1) as three-dimensional entities having temporal histories or (2) as four-dimensional entities whose totalities include a temporal dimension as well as three spatial dimensions. An object of the former type can be wholly present at any given moment of its history; an object of the latter type has temporal parts that are wholly present at various moments, but (given that it has nonzero duration) it is not wholly present at any particular moment. Dowe opts for the first approach, which is certainly legitimate; I do not have a strong preference as long as we are clear about which of them is being adopted. For purposes of this discussion it does not really matter, because, as Dowe explicitly states, in either manner of speaking the key point is the same. Regarding the first alternative, one needs a way of determining whether a given putative object is wholly present at a given time; this requires

a relation of identity over time, as one easily sees in connection with time-wise gerrymanders. Dowe says, “the CQ theory identifies genuine causal objects according to the possession of certain properties at a time, and identifies genuine processes over time via the additional presumption of a relation of identity over time” (1995, 330). Regarding the second alternative, he says, “the CQ theory takes identity over time as primitive” (ibid.). On either approach he is using the concept traditionally called *genidentity* without offering an analysis of it.

The concept of genidentity is not intuitively easy. Consider the spacetime portion of wall surface that is illuminated by the moving spotlight, each part of the surface belonging to it only during the time that it is actually illuminated. One might say that this is not a genidentical object because it does not consist of the same molecules at different times in its history. But consider also my body. It has been said—whether truly or not I do not know—that the human body undergoes a complete change of cells in any seven year period. If this is true I have undergone about ten complete replacement cycles in my three score and ten years of life; yet, although my body has undergone many changes from birth to its present stage, I consider myself to have possessed the same body. A similar consideration applies to a boat that has been repaired so many times that no original piece remains in it.

Things are even worse in the quantum domain. As Feynman (1965, Sec. 3–4) explains, when two identical particles collide and recoil from each other, it is impossible in principle to determine which outgoing particle is genidentical with which entering particle. The concept of genidentity breaks down. This fact has empirical consequences in the probabilities for scattering at various angles.

7. Transmission vs. Genidentity. The upshot of the foregoing discussion is that I have offered a concept of causal transmission, analyzed in terms of the “at-at” theory, for which Dowe has traded an unanalyzed concept of genidentity. This is not, I think, an advantageous exchange. To be sure, as I acknowledged above, the analysis that I gave in Salmon 1994 was faulty. I believe, however, that DEFINITION 3 as given above is correct. Taken in conjunction with DEFINITION 1:

A causal interaction is an intersection of world-lines that involves exchange of a conserved quantity,

and DEFINITION 2:

A causal process is the world-line of an object that transmits a non-zero amount of a conserved quantity at each moment of its history (each spacetime point of its trajectory),

it yields a criterion that is impeccably empirical, and thus it provides an acceptable answer to the fundamental problem Hume raised about causality. (In §9 a corollary of these definitions will be spelled out explicitly to deal with a putative counterexample given by Hitchcock). The aim, which I hope to have achieved, is to make clear the fashion in which causal influence is propagated throughout our world.

8. The Mechanical Philosophy. In his penetrating discussion, “Salmon on Explanatory Relevance”, Christopher Read Hitchcock concludes, “In the new mechanical philosophy [Salmon’s], as in the old, the explanatory store contains nought but geometric properties” (1995, 319). This, he says, is not enough to capture the concept of explanatory relevance. In support of his claim about the early mechanical philosophers he cites Eduard Dijksterhuis’s statement, “The only properties recognized as explanatory principles were the size, the shape, and the state of motion of corpuscles, supplemented by characteristics of their aggregates that could also be defined geometrically” (*ibid.*, 318). Although this remark applies correctly to Descartes, it does not properly apply to all other early mechanical philosophers, some of whom included mass (or weight) among the primary properties of objects. Given mass, we can substitute “quantity of motion” for “state of motion,” thereby adding momentum, “a concept acceptable to mechanical philosophers” (Westfall 1971, 134). This line of development culminated in the work of Newton—who first clarified the concept of mass, carefully distinguishing it from weight—in whose hands the old mechanical philosophy became a powerful explanatory engine (*ibid.*, 143).

Hitchcock’s claim about my theory of *causal* explanation is more fully justified, for I have appealed, thus far, only to a complex network of causal processes and causal interactions. In Salmon 1984 I employed a mark-transmission criterion to distinguish causal processes from pseudo-processes, and a similar criterion to distinguish causal interactions from mere intersections of processes. The result was a geometrical structure. There is nothing wrong with this sort of geometrical approach as long as its limitations are recognized. It furnishes something like a model of a telephone network that exhibits the lines of communication and the connections. (As I shall explain in §10, even information about the bare network can be useful in eliminating faulty explanations.) With the “at-at” theory of causal propagation, which was included in that presentation, it also provides an account of transmission. It does not, however, reveal anything about the messages that are sent.

Having identified the skeleton, we now need to make a transition analogous to the introduction of mass in the old mechanical philoso-

phy. As Hitchcock observes, “The intuitive relation of explanatory relevance does not hold between regions of space-time; it holds between the *properties* instantiated in certain regions of space-time (or perhaps between the *propositions* that certain properties are instantiated in certain regions of space-time)” (1995, 310, Hitchcock’s emphasis). In Salmon 1994 I adopted a version of Phil Dowe’s (1992) conserved quantity theory, in which I tentatively opted for invariant quantities, but the result was, as before, a geometrical network. It was just that different criteria were offered as the defining characteristics of causal processes and causal interactions. A major part of the motivation for this change was an aversion to counterfactuals. I was seeking completely objective causal concepts; counterfactuals are notoriously context dependent. However, the conserved quantity theory has an additional benefit; it does tell us something crucial about what is transmitted by causal processes and what is modified in causal interactions, namely, conserved quantities.

The conserved quantity theory does not tell us what quantities are conserved; for that information we must appeal to empirical science. However, given conservation of linear momentum, we can easily see why a baseball traveling from a bat to a window can (for many practical purposes) be regarded as a single causal process, ignoring collisions with molecules in the atmosphere. We can see why the collision of the baseball, rather than collisions with molecules in the air, explains the breaking of a window. In some situations wind and air resistance do make a practical difference; in such cases collisions of a ball with molecules in the air are a significant factor. We can go further. Appealing to the Bernoulli effect—a consequence of the conservation of energy—we can show why spinning balls follow various curved trajectories. In such cases we treat collisions with atmospheric molecules statistically; it is not necessary to detail the trajectories and collisions of individual molecules.

9. Some Counterexamples. Hitchcock offers the following counterexample to the conserved or invariant quantity view of causality I gave in Salmon 1994:

Suppose that a shadow is cast on a metal plate that has a uniform nonzero charge density on its surface. The shadow then moves across the plate in such a way that the area of the plate in shadow remains constant. The shadow then possesses a constant quantity of electric charge (a quantity that is both conserved and invariant) as it moves across the plate. The shadow is not participating in any causal interactions as it moves; in particular it is not being bom-

barded with photons as is the spot of light in a similar example discussed by Salmon (1984, 308). By definition 3, the shadow transmits the charge, and by definition 2, it is a causal process. (Hitchcock 1995, 314–315)

As Hitchcock points out, however, the mark method would easily handle his example. If one were to change locally the amount of charge where the shadow falls at one moment, the change would not be transmitted as the shadow moves on. Should we, therefore, retreat from a conserved quantity criterion to the mark criterion? Before deciding this issue we must consider a counterexample to the mark criterion offered by Philip Kitcher:

Imagine that a vehicle equipped with skis is sliding on an ice rink and casting a shadow. A projectile is thrown in such a way that it lands at the edge of the shadow with a horizontal component of velocity equal to that of the shadow of the vehicle. Because the projectile lies across the edge there is an immediate distortion of the shadow shape. Moreover, the distortion persists because the projectile retains its position relative to the vehicle (and to its shadow). (Kitcher 1989, 464)

I confess that I too had been vaguely troubled for some time about cases of the following sort until Kitcher's example forced me to focus upon them directly.

Suppose a truck, traveling along a road on a sunny day, casts a shadow on the smooth berm. The truck collides with an overhanging tree branch, leaving a permanent dent in the roof of the truck and a permanent scar on the branch. This is a causal interaction; both causal processes, the truck and the branch, are modified in ways that persist beyond the locus of intersection. Both are marked and they transmit their respective marks. When the truck encounters the branch the truck's shadow does so as well. Given the deformation of the roof of the truck, the shape of its shadow is also modified—i.e., marked—and that modification persists beyond its intersection with the branch. Moreover, had the intersection with the branch not occurred, the shadow would have traveled along the berm with an unchanged shape. Thus, the shadow qualifies as a causal process by MT, the mark-transmission criterion, (Salmon 1984, 148)

Dowe would be untroubled by either of these examples, because they cut only against the mark criterion, not against Dowe's conserved

quantities theory. I take the same attitude, regarding the class of such examples as one more reason for abandoning the mark criterion.

Hitchcock was not making a case for a retreat to the mark criterion; instead, he says,

I suggest that the conserved quantity theory is best viewed as augmenting rather than replacing the mark-transmission theory. Neither theory provides a reductive analysis of the concepts of causal process and interaction, and neither provides infallible rules for detecting causal processes and interactions. Rather, each provides *guidelines* for recognizing causal processes and interactions, as well as reasons for thinking that these concepts are presupposed by physical science. (Hitchcock 1995, 316, his emphasis)

Hitchcock's view appears to reflect sound reason. He seems to have shown how, according to my 1994 conserved or invariant quantity criterion, a shadow can transmit a quantity—electric charge—that is both conserved and invariant. Kitcher seems to have shown how, according to my 1984 mark criterion, a shadow can transmit a mark.

I am not, however, prepared to abandon the conserved quantity theory. Dowe will readily reject Hitchcock's example on the ground that shadows do not have electric charges; in this case, the charge belongs to the metal plate. This response is, I believe, correct. Shadows have such properties as shape, size, velocity, and relative darkness/lightness, but none of these is a conserved quantity. This claim is as well supported by empirical evidence as is the assertion that flying baseballs have linear and angular momentum. In Salmon 1994 I block resort to the claim that shadows qualify as causal processes by virtue of having an electric charge equal to zero. I therefore maintain that the conserved quantity theory can cope adequately with Hitchcock's counterexample as he has formulated it.

Were Hitchcock to amend the example by attributing the charge in question to that portion of the surface of the plate that is in shadow, but only as long as it is in shadow, Dowe would reject the "object" in question as a time-wise gerrymander—a piece of "spatiotemporal junk." Failing to qualify as an object, it cannot be an object possessing an electric charge (see Dowe 1992, 1995). I cannot endorse this response because, as I have argued above, it invokes an unanalyzed notion of genidentity—a concept I consider highly problematic.

How can one then respond to the reformulated example? Informally we want to say that electric charges are carried by particles like electrons and protons; they are transmitted between different spatiotemporal regions by the movement of such particles. This involves the passage of electric charges from one locale to another, thereby aug-

menting the electric charges already there. The same consideration applies to the intermediate spacetime locations—that is, the electric charge in question must vacate its location at one stage of the process and appear at the other stages of the process at the appropriate times. Otherwise, the electric charge would not be a conserved quantity.

Consider some other examples. Suppose that a bullet collides inelastically with the bob of a ballistic pendulum. When the intersection (an interaction) occurs, the linear momentum in the region of the intersection is the vector sum of the momenta of the two objects. When two billiard balls collide elastically the momentum of the combined system equals the sum of the momenta of the two subsystems in the region of interaction. When two light waves intersect, the energy in the region of intersection equals sum of the energies of the two waves. This is *not* an interaction; although there is a superposition—usually called “interference”—the waves continue beyond the intersection as before, just as if nothing had happened. There is no exchange of energy or any other conserved quantity.

Although the point of the preceding two paragraphs follows logically from the fact that the quantities in question are conserved, I shall formulate it explicitly as a COROLLARY:

When two or more processes possessing a given conserved quantity intersect (whether they interact or not), the amount of that quantity in the region of intersection must equal the sum of the separate quantities possessed by the processes thus intersecting.

In the reformulated version of Hitchcock’s example, this means that, *if the region of the surface in shadow were transmitting electric charge*, the charge density in the portion of the surface that is in shadow would have to be augmented as the shadow passes over it, and then reduced as the shadow goes beyond. This condition is not fulfilled, however, because the uniform charge on the surface of the plate is present regardless of the shadow and regardless of its presence in any particular area that happens to be in shadow at any other moment.

Looking at the surface of the plate relativistically from its own frame of reference, we can say that its vertical world-worm (not a worldline, because it is spatially extended) retains a uniform charge distribution. Smaller vertical world-worms, representing portions of the surface equal in extent to the area of the shadow, but at rest in this frame of reference, also exhibit constant uniform charge distributions. These constant uniform charge distributions are no different in the spacetime regions where the nonvertical world-worm of the moving shadow intersects them. This shows that the portion of the surface defined by the

motion of the shadow is not transmitting any electric charge; the electric charge is being transmitted by the plate.

10. Counterfactuals and Statistical Relevance. As Hitchcock points out, my earliest criticisms of Hempel's "covering law" models of explanation focused on their failure to capture the relation of explanatory relevance (Salmon 1965, 1971). Many years later, Kitcher and I (1987) offered the same criticism of Bas van Fraassen's "pragmatics of explanation." Now, ironically, Hitchcock levels the same charge against my causal theory of explanation, whether formulated in terms of the mark criterion or in terms of the conserved quantity theory. The argument is, roughly, that this theory does not give an adequate basis for determining which properties possessed by causal processes and interactions are pertinent to a given outcome and which are not. This is the fundamental gap in the exclusively geometrical approach; as I acknowledged above, the criticism is sound. A map of causal processes and interactions can be useful, however, in weeding out irrelevant factors that are not present at the right place and time.

Consider an example first given by Ellis Crasnow. A certain businesswoman usually arrives at her office about 9:00 A.M., makes herself a cup of instant coffee, and settles down to read the morning paper before starting her daily work. From time to time, however, she arrives at her office promptly at 8:00 A.M., meets a colleague from another site, and both are served cups of freshly brewed coffee upon arrival. On the mornings when she arrives at 9:00 A.M. she takes the 8:00 bus from home, but when she arrives at 8:00 she takes the 7:00 bus. The taking of the 7:00 bus thus fulfills statistical conditions (Reichenbach's conjunctive fork) that partly characterize a common cause of the coincidence of the availability of the freshly brewed coffee and the arrival of her colleague. Catching the earlier bus is not the common cause, however, because appropriate causal connections do not exist. The 7:00 bus is a causal process connecting her boarding of it to her 8:00 arrival, but there is no similar connecting process relating her taking of the earlier bus to the brewing of the coffee prior to her arrival. The actual common cause is a telephone appointment made by her secretary the preceding day. This is one type of example that emphasizes the need to consider actual causal connections furnished by causal processes in addition to statistical relevance relations.

Many cases of causal preemption can be handled similarly. Consider again the baseball and the window. Suppose that a well-hit ball is traveling on a trajectory that would surely strike and break a certain window pane, if the glass were intact when the ball arrived. As it happens, however, a stray bullet shatters the window just prior to the arrival of

the ball. In this case, the ball never intersects with the window pane, and thus plays no part in the explanation of the breaking of the window. (The baseball players may, however, face a difficult problem in convincing the homeowner that they were not responsible.)

Another example, mentioned by Hitchcock (1995, 305, 316), is John Jones' explanation of his avoidance of pregnancy on the basis of his consumption of oral contraceptives. We can obviously rule out this explanation on grounds of statistical irrelevance, but what about causal processes and intersections? Normal pregnancy occurs when a sperm and an egg unite in a certain way (an instance of a λ -type interaction) in a human body. Since Jones does not possess ovaries he cannot produce eggs, and such an interaction cannot occur. He cannot become pregnant by implantation of a fertilized egg because he possesses no uterus. Again, the required interaction cannot occur. Sperm and eggs are complex causal processes, but they do transmit such classically conserved quantities as mass.

While Hitchcock does not advocate a counterfactual theory of causal or explanatory relevance, he does claim that counterfactual considerations are near at hand in explanatory contexts. When an explanation is offered it is pertinent to consider what would have happened if the explanans had not obtained. For example, when asserting that a window was shattered because it was struck by a baseball travelling at a considerable velocity, we presumably have in mind that the window would not have broken if the intersection with the baseball had not occurred. This is, I think, a relatively unproblematic counterfactual statement because it is supported by well-established assertions of statistical relevance. (We assume no stray bullets intrude.) At the time the window pane broke numerous atmospheric molecules were colliding with it, but window panes very seldom shatter under those circumstances (unless the wind velocity is extremely great, in which case there would be no ballgame in the vicinity). At the same time, sounds from the mouths of the players would be reaching the window, but again, windows seldom shatter when only shouts from ballplayers impinge. These are not speculations; they are reports of observed relative frequencies. We can give a more sophisticated answer in terms of momentum conservation, as sketched above, but the physical assertions here invoked have enormous empirical support.

My main motivations in working out a theory of causal explanation as a successor to my theory of statistical explanation were the convictions, first, that causality is an essential ingredient in scientific explanation, and second, that causal relations cannot be explicated wholly in terms of statistical relations. These points still seem sound. In Salmon 1984 I characterized scientific explanation as a two-tiered structure, con-

sisting of statistical relevance relations on one level and causal processes and interactions on the other. As a result of Hitchcock's analysis, I would now say (1) that statistical relevance relations, in the absence of connecting causal processes, lack explanatory import and (2) that connecting causal processes, in the absence of statistical relevance relations, also lack explanatory import. In various discussions I have focused on (1) to the virtual neglect of (2). As the preceding discussion of the baseball breaking the window shows, this was a mistake. Both are indispensable.

The relationship between counterfactuals and statistical relevance is quite close. If $P(B|A.C) \neq P(B|A.\neg C)$, then (given background conditions A), in the absence of C , we can say that *if C had been present* the probability of B would have been different. This is statistical relevance. The probabilities to which I am referring are objective; in this context I am not considering subjective or personal probabilities. Assertions of such objective probability relations must be based directly or indirectly on empirical evidence. Such probability statements are either true or false, without regard to contextual features. There is, of course, an epistemic question. If we appeal to relations of statistical relevance as above, we must consider whether $A.C$ constitutes a homogeneous reference class, or whether there are other factors D, E, F that are also relevant to the occurrence of B . In cases of statistical explanation the question of homogeneity of reference classes assumes great importance (see Salmon 1984, Ch. 3), but such questions are open to empirical investigation.

If B obtains, but $A.\neg C \rightarrow \neg B$, then we can say that B would not have occurred if C had not. The counterfactual is a limiting case of statistical relevance; if such a statement is true $A.\neg C$ is automatically a homogeneous reference class. Counterfactuals, like statistical relevance relations, are often effectively tested by controlled experiments. If, however, counterfactuals must be evaluated by comparing intuitions concerning the nearness of possible worlds, then I think they are unsuited for the explication of causality or scientific explanation.

11. Philosophical Methodology. In the course of his discussion, Hitchcock remarks, "in these post-positivistic times we do not expect there to be any specifiable set of observable conditions that is both necessary and sufficient for the presence of causal processes and interactions" (1995, 313–314). His skepticism regarding the possibility of reductive analyses of these concepts is expressed in a passage quoted above. He does not thereby condemn the search, because its pursuit may lead to a more accurate characterization of causal processes and interactions. Such a result is unquestionably desirable. My attempt to answer Hitch-

cock's counterexample is partly motivated, however, by the hope, perhaps vain, that reductive analyses within the framework of the logical empiricist (*not* logical positivist) program can be given. I take comfort in Hitchcock's view that even unanswerable counterexamples are not necessarily fatal to the philosophical enterprise of understanding causality and its role in scientific explanation.

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