CAUSALITY WITHOUT COUNTERFACTUALS*

WESLEY C. SALMON†‡

Philosophy Department
University of Pittsburgh

This paper presents a drastically revised version of the theory of causality, based on analyses of causal processes and causal interactions, advocated in Salmon (1984). Relying heavily on modified versions of proposals by P. Dowe, this article answers penetrating objections by Dowe and P. Kitcher to the earlier theory. It shows how the new theory circumvents a host of difficulties that have been raised in the literature. The result is, I hope, a more satisfactory analysis of physical causality.

1. Introduction. Ten years ago, I offered an account of causality involving *causal processes*, as the means by which causal influence is transmitted (Salmon 1984, chap. 5), and *causal forks*, as the means by which causal structure is generated and modified (chap. 6). Causal forks come in two main varieties, interactive forks and conjunctive forks. (Perfect forks are a limiting case of both of these types.) Interactive forks are used to define *causal interactions*. Causal processes and causal interactions are the basic causal mechanisms according to this approach. Although causal interactions are more fundamental than causal processes on this view, for various heuristic reasons I introduced causal processes before causal interactions. (I fear that the heuristic strategy was counterproductive.) The idea was to present a "process theory" of causality that could resolve the fundamental problem raised by Hume regarding causal connections. The main point is that causal processes, as characterized by this theory, constitute precisely the objective physical causal connections which Hume sought in vain. The so-called *at-at theory* of causal propagation enables us to account for the transmission of causal influence in a manner that does not conflict with (what I take to be) Humean empirical strictures.

To implement this program it is necessary to distinguish genuine causal processes from pseudo processes. The notion of a process (causal or pseudo) can reasonably be regarded as a primitive concept that can be made sufficiently clear in terms of examples and informal descriptions, such as what B. Russell (1948) called "causal lines"; however, even though Russell

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‡Send reprint requests to the author, Philosophy Department, University of Pittsburgh, Pittsburgh, PA 15260, USA.

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used the word "causal", he did not make a careful distinction between causal processes and pseudo processes. Prior to this distinction, the concept of process carries no causal involvements. If one thinks in terms of relativity theory and Minkowski spacetime diagrams, processes can be identified as spacetime paths that exhibit continuity and some degree of constancy of character. These spacetime paths and their parts may be timelike, lightlike, or spacelike.

Processes, whether causal or pseudo, often intersect one another in spacetime; in and of itself spacetime intersection is *not* a causal concept. Looking at intersections, we need criteria to distinguish genuine causal interactions from mere spacetime intersections. The basic theses are (1) that causal processes could be distinguished from pseudo processes in terms of their capacity to transmit marks, and (2) that causal interactions could be distinguished from mere spacetime intersections in terms of mutual modifications—changes that originate at the locus of the intersecting processes and persist beyond that place. In order to explain what is meant by transmitting a mark it is necessary to explain what is involved in introducing a mark. Introducing a mark *is* a causal concept, so it needs to be explicated; this is done in terms of the notion of a causal interaction. Causal interactions are explicated without recourse to other causal concepts. Contrary to the heuristic order, causal interactions are logically more basic than causal processes.

This account of causality has certain strong points and certain defects, and it has been subjected to severe criticism by a number of philosophers. Some of the criticisms are well founded; some are based on misinterpretations. In this paper I address these difficulties. First, I will try to clear away the misinterpretations. Second, I will attempt to show how the account can be modified so as to remove the genuine shortcomings. In this latter endeavor I rely heavily on work of P. Dowe (1992a,b,c). The result is, I believe, a tenable—more tenable?—theory of physical causation.

2. The Circularity Charge. Dowe (1992c) claims that the foregoing account is circular and discusses similar criticisms made by several authors. As a basis for his discussion of this and other criticisms he advances, Dowe formulates six propositions to characterize my position:

D-I. A process is something which displays consistency of characteristics.

D-II. A causal process is a process which can transmit a mark.

D-III. A mark is transmitted over an interval when it appears at each spacetime point of that interval, in the absence of interactions.

D-IV. A mark is an alteration to a characteristic, introduced by a single local interaction.

D-V. An interaction is an intersection of two processes.

D-VI. A causal interaction is an interaction where both processes are marked. (Ibid., 200; "D" stands for Dowe)

In order to evaluate various criticisms we must examine the foregoing propositions. Dowe's concern with circularity focuses on D-IV and D-VI; taken together, he argues, they contain a circularity. Statements D-I through D-IV are acceptable just about as they stand; only D-IV requires a bit of modification, namely, the substitution of "intersection" for "interaction". Propositions D-V and D-VI require more serious revision; in fact, D-V should be deleted, while D-VI should be modified to read, "A causal interaction is an *intersection* in which both processes are marked *and the mark in each process is transmitted beyond the locus of the intersection*". There are two crucial points. First, in my terminology "causal interaction" and "interaction" are synonymous; there are no such things as noncausal interactions. There are, of course, noncausal intersections. Second, for an intersection to qualify as a causal interaction, the modifications that originate in the intersection must persist beyond the place at which the intersection occurs.

Let us rewrite the foregoing propositions, taking the required modifications into account and rearranging the order. For the sake of further clarity I substitute a different proposition for D-V. Let "S" stand for Salmon; in each case Dowe's counterpart is indicated parenthetically:

S-I. A process is something that displays consistency of characteristics (D-I).

S-II. A mark is an alteration to a characteristic that occurs in a single local intersection (D-IV).

S-III. A mark is transmitted over an interval when it appears at each spacetime point of that interval, in the absence of interactions (D-III).

S-IV. A causal interaction is an intersection in which both processes are marked (altered) and the mark in each process is transmitted beyond the locus of the intersection (D-VI).

S-V. In a causal interaction a mark is introduced into each of the intersecting processes. (This substitute for D-V can be construed as a definition of "introduction of a mark".)

S-VI. A causal process is a process that can transmit a mark (D-II).

This revised list of propositions involves certain problems to which I will

return, but it does not suffer from circularity. We assume that such spatiotemporal concepts as intersection and duration are clear. We assume (for the moment, but see section 3) that we know what it means to say that a property of a process changes, or that two characteristics of processes differ from one another. Proposition S-I indicates what counts as a *process*. Material particles in motion, light pulses, and sound waves are paradigm examples. Proposition S-II introduces the concept of a *mark*. Notice that a mark is simply a modification of some kind; it need not persist. When the shadow of an automobile traveling along a road with a smooth berm encounters a signpost, its shape is altered, but it regains its former shape as soon as it passes beyond the post. It was marked at the point of intersection, but the mark vanishes immediately. Notice also that a pair of *causal processes* can intersect without constituting a causal interaction; for example, light waves that intersect are said to interfere in the region of intersection, but they proceed beyond as if nothing had happened.

Statement S-III is a key proposition; it characterizes the notion of transmission. Even if we give up the capacity for mark transmission as a fundamental explication of causal process—as I will do—the concept of transmission remains crucial (see sec. 7, def. 3 below). Statement S-IV is also a key proposition because it introduces the most basic notion—causal interaction. It says that a causal interaction is an intersection of processes in which mutual modifications occur that persist beyond the locus of intersection.

Proposition S-V, in contrast, is trivial; it defines "introduction of a mark", a concept we will not need. Proposition S-VI is one of the central theses of my 1984 theory; it is one I am prepared to abandon in the light of Dowe's alternative proposal. I return to this issue in section 7.

3. The Problem of Vagueness. Dowe (1992c, 201–204) justifiably complains that in my discussions of marking and mark transmission (Salmon 1984, chap. 5) I used such terms as "characteristic" and "structure" without specifying their meanings. He suggests that introduction of the concept of a *nonrelational property* might have clarified the situation. He is right. Somewhat ironically, in an earlier chapter of the same book (ibid., 60–72), I worked hard to precisely characterize the concept of objective homogeneity of reference classes, and dealt with the kind of problem that comes up in the discussion of marks. Unfortunately, I neglected to carry the same type of consideration explicitly into the context of marking. The key concept is that of an *objectively codefined class* (ibid., 82, def. 2), which is explicated in terms of physically possible detectors attached to appropriate kinds of computers that receive carefully specified types of information. It is possible to ascertain, on the basis of local observa-

tions—detections—whether an entity possesses a given property at a particular time. Since, in scientific contexts, we often detect one property by observing another, it must be possible in principle to construct a computer to make the determination. For example, when we measure temperature by using a thermocouple, we actually read a galvanometer to detect an electrical current. The computer to which the explication refers must be able to translate the galvanometer reading into a temperature determination, on the basis of laws concerning the electrical outputs of thermocouples, but without receiving information from other physical detectors. Notice that this explication is physical, not epistemic. This kind of definition would easily suffice to rule out such properties as *being the shadow of a scratched car* (Kitcher 1989, 463) or *being a shadow that is closer to the Harbour Bridge than to the Sydney Opera House* (Dowe 1992c, 201), as well as properties such as grue (Goodman 1955).

No basic problems concerning the nature of marks arise in connection with the distinction between causal processes and pseudo processes that cannot be handled through the use of the techniques involved in explicating objectively codefined classes. As Dowe (1992c, 203) notes, I made a remark to this effect in Salmon (1985), but regrettably (due to severe space limitations) I neglected to give details. However, since I am about to abandon the mark criterion altogether, there is no need to pursue the question here.

4. Statistical Characterization of Causal Concepts. In an illuminating discussion of the possibility of characterizing causal concepts in statistical terms, Dowe (1992c, 204–207) voices the opinion that this enterprise is hopeless. He quotes my remark, "I now think that the statistical characterization is inadvisable" (Salmon 1984, 174, n. 12), correctly noting that it expresses agreement with his thesis. Citing the paucity of reasons given in my note, he offers reasons of his own. In a brief paper (Salmon 1990), I attempt to spell out reasons of my own. As nearly as I can tell, Dowe and I have no basic disagreement on this issue.

5. Counterfactuals. I have frequently used the example of a rotating spotlight in the center of a circular building to illustrate the difference between causal processes and pseudo processes. A brief pulse of light traveling from the beacon to the wall is a causal process. If you place a red filter in its path the light pulse becomes red and remains red from the point of insertion to the wall without any further intervention. The spot of light that travels around the wall is a pseudo process. You can make the white spot red by intervening at the wall where the light strikes it, but without further local intervention it will not remain red as it passes

beyond the point of intervention. Thus, causal processes transmit marks but pseudo processes do not.

The untenability of this characterization was shown forcefully by N. Cartwright (in conversation) by means of a simple example. Suppose that a few nanoseconds before a red filter at the wall turns the moving spot red someone places a red lens on the rotating beacon so that, as the spot moves, it remains red because of the new lens on the beacon. In such a case, the spot *turns* red due to a local interaction and *remains* red *without any additional local interactions*. With or without the intervention at the wall, the spot of light moving around the wall would have been red from that point on. Consideration of such cases required a counterfactual formulation of the principle of mark transmission. I had to stipulate, in effect, that the spot would have remained white from that point on if there had been no local marking (Salmon 1984, 148). In Cartwright's example, the spot would have turned red anyhow, regardless of whether any marking had occurred at the wall.

In an extended and detailed discussion of scientific explanation, Kitcher articulates a penetrating critique of my causal theory (1989, sec. 6), making heavy weather over the appeal to counterfactuals. He summarizes this aspect of his critique as follows:

> I suggest that we can have causation without linking causal processes. . . . What is critical to the causal claims seems to be the truth of the counterfactuals, not the existence of the processes and interactions. If this is correct then it is not just that Salmon's account of the causal structure of the world needs supplementing through the introduction of more counterfactuals. The counterfactuals are the heart of the theory, while the claims about the existence of processes and interactions are, in principle, dispensable. Perhaps these notions may prove useful in protecting a basically counterfactual theory of causation against certain familiar forms of difficulty (problems of preemption, overdetermination, epiphenomena, and so forth).* But, instead of viewing Salmon's account as based on his explications of process and interaction, it might be more revealing to see him as developing a particular kind of counterfactual theory of causation, one that has some extra machinery for avoiding the usual difficulties that beset such proposals. [*Kitcher's note: See Lewis (1973), both for an elegant statement of a counterfactual theory of causation and for a survey of difficult cases. Loeb (1974) endeavors to cope with the problem of overdetermination.] (1989, 472)

When H. Reichenbach proposed his mark method, he thought it could be used to determine a time direction ([1928] 1957, 136–137). This was a mistake, as A. Grünbaum (1963, 180–186) has shown. However, draw-

ing upon suggestions offered in Reichenbach (1956, sec. 23) concerning the mark method and causal relevance, I concluded that the mark method provided a criterion for distinguishing between causal processes and pseudo processes, without any commitment to time direction (earlier-later). That is a separate problem (see Dowe 1992b). It has always been clear that a process is causal if it is *capable* of transmitting a mark, whether or not it is *actually* transmitting one. The fact that it has the capacity to transmit a mark is merely a *symptom* of the fact that it is actually transmitting something else. That other something I described as information, structure, and causal influence (1984, 154–157).

When the mark criterion was clearly in trouble because of counterfactual involvement, it should have been obvious that the mark method ought to be regarded only as a useful experimental method for tracing or identifying causal processes (e.g., the use of radioactive tracers) but that it should not be used to explicate the very concept of a causal process. Dowe took the crucial step. He pointed out that causal processes transmit conserved quantities; and by virtue of this fact, they are causal. I had come close to this point by mentioning the applicability of conservation laws to causal interactions, but did not take the crucial additional step (ibid., 169–170). Dowe's theory is not counterfactual.

6. Dowe's Conserved Quantity Theory. Dowe's proposed *conserved quantity* theory is beautiful for its simplicity. It is based on just two definitions (1992c, 210):

DEFINITION 1. *A causal interaction is an intersection of world-lines which involves exchange of a conserved quantity.*

This definition is a substitute for my much more complex and contorted principle CI (for causal interaction) which was heavily laden with counterfactuals (Salmon 1984, 171).

In discussing interactions it is essential to keep in mind the fact that we are dealing with conserved quantities. In an interaction involving an exchange of momentum, for example, the total momentum of the outgoing processes must be equal to that of the incoming processes. This point is important in dealing with certain kinds of interactions in which three or more processes intersect in virtually the same spacetime region. For example, a solidly hit baseball and an atmospheric molecule, say nitrogen, strike a glass window almost simultaneously. It may be tempting to say that the baseball caused the window to shatter, not the nitrogen molecule, because the window would not have shattered if it had not been struck by the baseball. But this analysis is unacceptable if we want to avoid counterfactuals.

We should say instead that, in the interaction constituted by the nitro-

gen molecule and the shattering window, momentum is not conserved. Take the window to be at rest; its linear momentum is zero. The linear momentum of the nitrogen molecule when it strikes the window is not zero, but fairly small. The total linear momentum of the pieces of the shattered window after the collision is enormously greater than that of the incoming molecule. In contrast, the total linear momentum of the baseball as it strikes the window is about equal to the momentum of the pieces of glass and the baseball after the collision. So if we talk about causes and effects, we are justified in saying that the window was broken by the collision with the baseball, not by the collision with the nitrogen molecule. With these considerations in mind, I think we can say that Dowe's definition 1 is free of counterfactuals, and is acceptable as it stands.

DEFINITION 2_a. *A causal process is a world-line of an object which manifests a conserved quantity.*

As we will see, definition 2 requires some further work—hence the designation 2_a.

In his elaboration of the foregoing definitions Dowe mentions mass-energy, linear momentum, angular momentum, and electric charge as examples of conserved quantities. He explains the meanings of other terms:

> An *exchange* means at least one incoming and at least one outgoing process manifest a change in the value of the conserved quantity. "Outgoing" and "incoming" are delineated on the spacetime diagram by the forward and backward light cones, but are essentially interchangeable. The exchange is governed by the conservation law. The intersection can therefore be of the form X, Y, λ or of a more complicated form. An *object* can be anything found in the ontology of science (such as particles, waves or fields), or common sense. (1992c, 210)

Dowe offers several concrete examples of causal interactions and causal processes involving electric charge and kinetic energy, and a pseudo process not involving any conserved quantity (ibid., 211–212). I made passing mention of two sorts of interaction which, to my great frustration, I did not know how to handle (1984, 181–182). A *Y*-type interaction occurs when a single process splits in two, such as radioactive decay of a nucleus or a hen laying an egg. A *λ*-type interaction occurs when two separate processes merge, such as the absorption of a photon by an atom or the consumption of a mouse by a snake. Dowe points out that his conserved quantity theory handles interactions of these two kinds.

7. Conserved Quantities and Invariants. A curious ambiguity arises near the conclusion of Dowe (1992c). D. Fair (1979) had proposed a theory of causality in terms of transmission of energy which Dowe criticizes on the basis of several considerations, "Another advantage [of Dowe's theory] concerns Fair's admission that energy is not an invariant and therefore will vary according to the frame of reference. . . . On our account, however, cause is related to conserved quantities and these *are* invariant, for example, energy-mass, energy-momentum, and charge" (Dowe 1992c, 214). Up to this point Dowe has formulated and discussed his theory entirely in terms of conserved quantities, and the concept of an *invariant* has not entered. The terms "conserved quantity" and "invariant" are not synonymous. To say that a quantity is *conserved* (within a given physical system) means that its value does not change over time; it is constant with respect to time translation. To say that a quantity is *invariant* (within a given physical system) means that it remains constant with respect to change of frame of reference.

Consider linear momentum, which Dowe identifies as a conserved quantity (ibid., 210). We have a law of conservation of linear momentum; it applies to any interaction described with respect to any particular frame of reference, for instance, the "lab frame" in which an experiment is conducted. Within any closed system the total quantity of linear momentum is constant over time. If you switch to a different frame of reference to describe the same physical system, the quantity of linear momentum will again be constant over time, but not necessarily the *same* constant as in the lab frame. On Einstein's famous train, for instance, the linear momentum of the train is zero, but in the frame of the ground observer it has a great deal of linear momentum. Linear momentum is a conserved quantity, but *not* an invariant. Its value differs from one frame to another. Electric charge *is* an invariant; the electric charge of the electron has the same value in any frame of reference. It is also a conserved quantity. Kinetic energy—which Dowe mentions in one of his examples (ibid., 212, example 3)—is neither a conserved quantity nor an invariant. In inelastic collisions it is not conserved, and its value changes with changes of reference frame. This example is easily repaired, however, by referring to linear momentum instead of kinetic energy.

The question arises as to whether we should require causal processes to possess invariant quantities, or whether conserved quantities will suffice. At first blush it would seem that conserved quantities will do. We should note, however, that causality is an invariant notion. In special relativity the spacetime interval is invariant; if two events are causally connectable in one frame of reference they are causally connectable in every frame. Spacelike, lightlike, and timelike separations are invariants. If two events are causally connected in one frame of reference they are

causally connected in all frames. Since we are attempting to explicate frame-independent causal concepts it seems reasonable to insist that the explicans be formulated in frame-independent terms (see Mühlhölzer, forthcoming).

If, however, we rewrite Dowe's definition 2_a as follows, substituting "invariant" for "conserved",

DEFINITION 2_b. *A causal process is a world-line of an object that manifests an invariant quantity*,

we find ourselves in immediate trouble. Consider, for example, a shadow cast by a moving cat in an otherwise darkened room when a light is turned on for a limited period. This shadow is represented by a world-line with an initial point and a final point. The spacetime interval between these two endpoints is an invariant quantity that is manifested by a pseudo process. Any pseudo process of finite duration manifests such an invariant quantity. Definition 2_b is patently unacceptable.

The main trouble with definition 2_b may lie with the term "manifests", for with its use we seem to have abandoned one of the most fundamental ideas about causal processes, namely, that they *transmit* something (e.g., marks, information, causal influence, energy, electric charge, momentum). A process, causal or pseudo, cannot be said to transmit its invariant spacetime length. A necessary condition for a quantity to be transmitted in a process is that it can meaningfully be said to characterize or be possessed by that process at any given moment in its history. A proton, for example, has a fixed positive electric charge—which, as already noted, is both conserved and invariant—and it has this charge at every moment in its history. Thus, it makes sense to say that the charge of a particular proton changes or stays the same over a period of time. Perhaps, then, we could reformulate definition 2_b as follows:

DEFINITION 2_c. *A causal process is a world-line of an object that manifests an invariant quantity at each moment of its history (each spacetime point of its trajectory).*

We should also note that "manifests" contains a possibly serious ambiguity. A photon, for example, has an electric charge equal to zero. Do we want to say that it manifests that particular quantity of electric charge?

Consider first the claim that a neutral hydrogen atom manifests an electric charge of zero. This seems unproblematic because the atom is composed of two parts, a proton and an electron, each of which has a nonzero charge. Since the atom can be ionized we can separate the two charged particles from one another. The neutron is also unproblematic for two reasons. First, it is thought to be composed of three quarks, each of which has a nonzero charge, but separating them is extremely difficult if not

impossible. Second, a free neutron has a half-life of a few minutes, and when it decays it yields two charged particles, a proton and an electron (plus an uncharged antinutrino); unlike the hydrogen atom, however, the neutron is not composed of a proton and an electron. The photon is more difficult. Under suitable circumstances (e.g., near a heavy atom) a high-energy photon will vanish, yielding an electron-positron pair, each member of which has a nonzero charge. Thus energetic photons may be said to have zero electric charge, an attribution which can be extended to less energetic photons. Any entity that can yield products with nonzero electric charge can be said to *manifest* an electric charge of zero. However, this kind of principle might not hold for all invariants that a process might manifest. The important point is that we must block the assertion that a shadow is an entity that manifests an electric charge (whose value is zero) and similar claims. Let us make an additional modification:

DEFINITION 2_d. *A causal process is a world-line of an object that manifests a nonzero amount of an invariant quantity at each moment of its history (each spacetime point of its trajectory).*

We need not fear for the causal status of photons on this definition; they manifest the invariant speed c.

When we speak in definition 2_d of a nonzero amount of a given quantity, it must be understood that this refers to a "natural zero" if the quantity has one. Although temperature is neither a conserved quantity nor an invariant, it furnishes the easiest exemplification of what is meant by a "natural zero". The choice of the zero point in the Fahrenheit and Celsius scales is arbitrary. The fact that water freezes at 0° C and boils at 100° C does not remove the arbitrariness, since the scale is referred to a particular substance as a matter of convenience. In contrast 0° K on the absolute scale is a natural zero, because it is the greatest lower bound for temperatures of any substance under any physical conditions. Applying similar considerations, we can argue that electric charge has a "natural zero" even though it can assume negative values. An entity that has a charge of zero esu (electrostatic units) is not attracted or repelled electrostatically by any object that has any amount of electric charge. When it is brought into contact with an electroscope the leaves do not separate. It would be possible (as an anonymous referee pointed out) to define a quantity electric-charge-plus-seventeen, which is possessed by photons, shadows, neutrons, and so on in a nonzero amount. This would be an invariant quantity, but it lacks a "natural zero". Given the "natural zero" from which it departs, it should be considered inadmissible in the foregoing definition. I believe that all of the quantities we customarily take as conserved or invariant have "natural zeroes", but I do not have a general proof of this conjecture.

Definition 2_d brings us back, regrettably, to Fair's (1979) account of causation in terms of energy transfer, which is open to the objection that it gives us no basis for distinguishing cases in which there is genuine *transmission* of energy from those in which the energy just happens to show up at the appropriate place and time. Making reference to the rotating beacon in the astrodome, I argued that uniform amounts of radiant energy show up along the pathway of the spot moving along the wall, and that therefore the fact that the world-line of this spot manifests energy in an appropriately regular way cannot be taken to show that the moving spot is a causal process (Salmon 1984, 145–146). Dowe (1992c, 214) complains that it is the wall rather than the spot that possesses the energy; however, we can take the world-line of the part of the wall surface that is absorbing energy as a result of being illuminated. This world-line manifests energy throughout the period during which the spot travels around the wall, but it is not the world-line of a causal process because the energy is not being transmitted; it is being received from an exterior source. (If Dowe's objection to this example is not overcome by the foregoing considerations, other examples could be supplied.) For this reason, I would propose a further emendation of Dowe's definition:

DEFINITION 2_e. *A causal process is a world-line of an object that transmits a nonzero amount of an invariant quantity at each moment of its history (each spacetime point of its trajectory).*

This definition introduces the term "transmits", which is clearly a causal notion, and which requires explication in this context. I offer the following modification of my mark transmission principle (MT) (Salmon 1984, 148):

DEFINITION 3. *A process transmits an invariant (or conserved) quantity from A to B ($A \neq B$) if it possesses 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.*

The interval is specified as half-open to allow for the possibility that there is an interaction at *A* that determines the amount of the quantity involved in the transmission. This definition embodies *the at-at theory of causal transmission* (ibid., 147–157), which still seems to be fundamental to our understanding of physical causality. Definition 3 does not involve counterfactuals.

Speaking literally, the foregoing definitions imply that a causal process does not enter into any causal interactions. For example, a gas molecule constitutes a causal process between its collisions with other molecules or the walls of its container. When it collides with another molecule, it

becomes another causal process which endures until the next collision. A typical value for the mean free path is 10^{-7} m, which, though small, is much greater than the size of the molecule. If we consider the life history of such a molecule during an hour, it consists of a very large number of causal processes each enduring between two successive collisions. Each collision is a causal interaction in which momentum is exchanged. When we understand this technical detail, there is no harm in referring to the history of a molecule over a considerable period of time as a single (composite) causal process that enters into many interactions. The history of a Brownian particle suspended in the gas is an even more extreme case, for it is undergoing virtually continuous bombardment by the molecules of a gas, but I think it should be conceived in essentially the same manner.

In many practical situations definition 3 should be considered an idealization. As an anonymous referee remarked, "You'd want to say that the speeding bullet transmits energy-momentum from the gun to the victim, but what about its incessant, negligible interactions with ambient air and radiation?" Of course. In this, and many similar sorts of situations, we would simply ignore such interactions because the energy-momentum exchanges are too small to matter. Pragmatic considerations determine whether a given "process" is to be regarded as a single process or a complex network of processes and interactions. In the case of the "speeding bullet" we are not usually concerned with the interactions among the atoms that make up the bullet. In dealing with television displays we may well be interested in the flight paths of individual electrons. In geophysics we might take the collision of a comet with the earth to be an interaction between just two separate processes. It all depends upon the domain of science and the nature of the question under investigation. Idealizations of the sort just exemplified are not unfamiliar in science.

There is, however, another source of concern. According to Dowe, "A *conserved quantity* is any quantity universally conserved according to current scientific theories" (1992c, 210). This formulation cannot be accepted. Parity, for example, was a conserved quantity according to the then-current theories prior to the early 1950s, but in 1956 it was shown by T. D. Lee and C. N. Yang that parity is not conserved in weak interactions. According to more recent theories parity is not a conserved quantity. What we should say is that we look to currently accepted theories to tell us what quantities we can reasonably regard as conserved. We had good reason to regard parity as a conserved quantity prior to 1956; subsequently, we have had good reason to exclude it from the class of conserved quantities. So our current theories tell us what quantities to think of as conserved; whether or not they are conserved is another question.

We might be tempted to say that conserved quantities are those quantities governed by conservation laws, where by "law" we mean either a true lawlike statement or a lawful regularity in nature. If we were to take this tack, however, we would free ourselves from the curse of counterfactuals only at the price of taking on the problem of laws. An approach of this sort is given by F. J. Clendinnen (1992), in which he proposes a "nomic dependence" account of causation as an alternative to D. Lewis's counterfactual theory. This may not take us out of the frying pan into the fire, but it does seem to offer another hot skillet in exchange for the frying pan. The hazard can be avoided, I think, by saying that a conserved quantity is a quantity that does not change. I am prepared to assert that the charge of the electron is 4.803×10^{-10} esu, and that the value is constant. Obviously I could be wrong about its value or about its constancy, but what I said in the foregoing sentence is true to the best of my knowledge. If the statement about the electron charge is true, then there is a true generalization about the charge of the electron. However, *it makes no difference whether or not that true generalization is lawful; only its truth is at stake.* The problem of laws is the problem of distinguishing true lawlike generalizations from other true generalizations. That is a problem we do *not* have to face.

In discussing the relationship between conserved quantities and laws, I deliberately chose as an example a quantity that is also an invariant. Thus, in fact, I want to stick to the formulation of definition 2_e in terms of invariants. I have a further reason for this choice. When we ask about the ontological implications of a theory, one reasonable response is to look for its invariants. Since these do not change with the selection of different frames of reference—different perspectives or points of view—they possess a kind of objective status that seems more fundamental than that of noninvariants.

Apparently, although Dowe's conserved quantity (CQ) theory of causality embodies important improvements over my mark transmission theory, it is not fully satisfactory as he has presented it. In definitions 1, 2_e and 3 I think we have made considerable progress toward an adequate theory of causality. This is a result, to a large extent, of Dowe's efforts in developing a process theory of causality that avoids the problems of counterfactuals with which my former theory was involved. We have, I believe, clean definitions of causal interaction, causal transmission, and causal processes on which to found a process theory of physical causality.

8. Kitcher's Objections. Among the many critiques of my account of causality, those of Dowe (1992c) and Kitcher (1989) seem the most penetrating and significant. Dowe's discussion is motivated by a desire to provide an account of process causality that is more satisfactory than mine.

As I have indicated, I think he has succeeded in very large measure, and in the preceding section I tried to improve on his version. Kitcher's motivation is essentially the opposite; he supports an altogether different account of causality. His thesis is that "the 'because' of causation is always derivative from the 'because' of explanation" (ibid., 477). My view is roughly the opposite, and I think Dowe would agree. Dowe (1992a) assesses the difficulties posed by Kitcher and offers his own defense against them.

Kitcher does not claim to have refuted the causal account of explanation, "The aim of this section has been to identify the problems that they will have to overcome, not to close the books on the causal approach" (1989, 476). While I do not think that the theory I advocated in Salmon (1984) contained adequate resources to overcome the difficulties he pointed out, I am inclined to believe that the version developed herein—leaning heavily on Dowe's work—does have the capacity to do so. For example, Kitcher considers the problem of counterfactual entanglement "the most serious trouble of Salmon's project and [one] which I take to threaten any program that tries to use causal concepts to ground the notion of explanation while remaining faithful to an empiricist theory of knowledge" (1989, 470). Dowe's primary contribution is to free the concept of causality from its dependence on counterfactuals. This I consider a major part of the answer to Kitcher's challenges.

Another cluster of problems involves the concept of a mark (ibid., 463–464). Inasmuch as I have now abandoned the mark transmission approach and substituted the invariant (or conserved) quantity transmission view, the difficulties concerning marks have been bypassed. In addition, Kitcher points to the problem of sorting out in complex situations which interactions are relevant and which are not pertinent (ibid., 463). Definition 3 goes some distance in responding to this problem inasmuch as it identifies a particular invariant (or conserved) quantity that is involved in the transmission. So Kitcher's misgivings—well taken regarding my (1984) treatment—have been circumvented.

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