inclusion of evidence for this. Instead of similarly requiring a causal connection, it actually requires the inclusion of one *special kind* of evidence for this. If it treated both requirements equitably, the model would be either trivial (causal explanations must be true and causally relevant) or deviously arbitrary (. . . must include *deductively* adequate grounds for the truth of any assertions and for the causal connection).

24. See Max Black's "Definition, Presupposition, and Assertion," in his *Problems of Analysis* (London: Routledge and Kegan Paul, 1954).

4

Statistical Explanation and Causality

Wesley C. Salmon

1. Statistical Explanation

The Nature of Statistical Explanation

Let me now, at long last, offer a general characterization of explanations of particular events. As I have suggested earlier, we may think of an explanation as an answer to a question of the form, "Why does this x which is a member of A have the property B?" The answer to such a question consists of a partition of the reference class A into a number of subclasses, all of which are homogeneous with respect to B, along with the probabilities of B within each of these subclasses. In addition, we must say which of the members of the partition contains our particular x. More formally, an explanation of the fact that x, a member of A, is a member of B would go as follows:

$$\begin{gathered} P(A.C_1,B) = p_1 \\ P(A.C_2,B) = p_2 \\ \vdots \\ P(A.C_n,B) = p_n \end{gathered}$$

where

$$\begin{gathered} A.C_1, A.C_2, \ldots, A.C_n \text{ is a homogeneous partition of } A \text{ with respect to } B, \\ p_i = p_j \text{ only if } i = j, \text{ and} \\ x \in A.C_k. \end{gathered}$$

With Hempel, I regard an explanation as a linguistic entity, namely, a set of statements, but unlike him, I do not regard it as an argument. On my view, an explanation is a set of probability statements, qualified by certain provisos, plus a statement specifying the compartment to which the explanandum event belongs.

The question of whether explanations should be regarded as arguments is, I believe, closely related to the question, raised by Carnap, of whether inductive logic should be thought to contain rules of acceptance (or detachment).[1] Carnap's problem can be seen most clearly in connection with the famous lottery paradox. If inductive logic contains rules of inference which enable us to draw conclusions from premises—much as in deductive logic—then there is presumably some number r which constitutes a lower bound for acceptance. Accordingly, any hypothesis h whose probability on the total available relevant evidence is greater than or equal to r can be accepted on the basis of that evidence. (Of course, h might subsequently have to be rejected on the basis of further evidence.) The problem is to select an appropriate value for r. It seems that no value is satisfactory, for no matter how large r is, provided it is less than one, we can construct a fair lottery with a sufficient number of tickets to be able to say for each ticket that [it] will not win, because the probability of its not winning is greater than r. From this we can conclude that no ticket will win, which contradicts the stipulation that this is a fair lottery—no lottery can be considered fair if there is *no* winning ticket.

It was an exceedingly profound insight on Carnap's part to realize that inductive logic can, to a large extent anyway, dispense entirely with rules of acceptance and inductive inferences in the ordinary sense. Instead, inductive logic attaches numbers to hypotheses, and these numbers are used to make practical decisions. In some circumstances such numbers, the degrees of confirmation, may serve as fair betting quotients to determine the odds for a fair bet on a given hypothesis. There is no rule that tells one when to accept an hypothesis or when to reject it; instead, there is a rule of practical behavior that prescribes that we so act as to maximize our expectation of utility.[2] Hence, inductive logic is simply not concerned with inductive arguments (regarded as entities composed of premises and conclusions).

Now, I do not completely agree with Carnap on the issue of acceptance rules in inductive logic; I believe that inductive logic does require some inductive inferences.[3] But when it comes to probabilities (weights) of single events, I believe that he is entirely correct. In my view, we must establish by inductive inference probability statements, which I regard as statements about limiting frequencies. But, when we come to apply this probability knowledge to single events, we procure a weight which functions just as Carnap has indicated—as a fair betting quotient or as a value to be used in computing an expectation of utility.[4] Consequently, I maintain, in the context of statistical explanation of individual events, we do not try to establish the explanandum as the conclusion of an inductive argument; instead, we need to establish the weights that would appropriately attach to such explanandum events for purposes of betting and other practical behavior. That is precisely what the partition of the reference class into homogeneous subclasses achieves: it establishes the correct weight to assign to *any* member of A with respect to its being a B. First, one determines to which compartment C_k it belongs, and then one adopts the value p_k as the weight. Since we adopted the *multiple homogeneity rule*, we can genuinely handle any member of A, not just those which happen to fall into one subclass of the original reference class.

One might ask on what grounds we can claim to have characterized explanation. The answer is this. When an explanation (as herein explicated) has been provided, we know exactly how to regard any A with respect to the property B. We know which ones to bet on, which to bet against, and at what odds. We know precisely what degree of expectation is rational. We know how to face uncertainty about an

A's being a B in the most reasonable, practical, and efficient way. We know every factor that is relevant to an A having property B. We know exactly the weight that should have been attached to the prediction that this A will be a B. We know all of the regularities (universal or statistical) that are relevant to our original question. What more could one ask of an explanation?

There are several general remarks that should be added to the foregoing theory of explanation:

a. It is evident that explanations as herein characterized are nomological. For the frequency interpretation probability statements are statistical generations, and every explanation must contain at least one such generalization. Since an explanation essentially consists of a set of statistical generalizations, I shall call these explanations "statistical" without qualification, meaning thereby to distinguish them from what Hempel has recently called "inductive-statistical."[5] His inductive-statistical explanations contain statistical generalizations, but they are inductive inferences as well.

b. From the standpoint of the present theory, deductive-nomological explanations are just a special case of statistical explanation. If one takes the frequency theory of probability as literally dealing with infinite classes of events, there is a difference between the universal generalization, "All A are B," and the statistical generalization, "$P(A,B) = 1$," for the former admits no As that are not Bs, whereas the latter admits of infinitely many As that are not Bs. For this reason, if the universal generalization holds, the reference class A is homogeneous with respect to B, whereas the statistical generalization may be true even if A is not homogeneous. Once this important difference is noted, it does not seem necessary to offer a special account of deductive-nomological explanations.

c. The problem of symmetry of explanation and prediction, which is one of the most hotly debated issues in discussions of explanation, is easily answered in the present theory. To explain an event is to provide the best possible grounds we could have had for making predictions concerning it. An explanation does not show that the event was to be expected; it shows what sorts of expectations would have been reasonable and under what circumstances it was to be expected. To explain an event is to show to what degree it was to be expected, and this degree may be translated into practical predictive behavior such as wagering on it. In some cases the explanation will show that the explanandum event was not to be expected, but that does not destroy the symmetry of explanation and prediction. The symmetry consists in the fact that the explanatory facts constitute the fullest possible basis for making a prediction of whether or not the event would occur. To explain an event is not to predict it *ex post facto*, but a complete explanation does provide complete grounds for rational prediction concerning that event. Thus, the present account of explanation does sustain a thoroughgoing symmetry thesis, and this symmetry is not refuted by explanations having low weights.

d. In characterizing statistical explanation, I have required that the partition of the reference class yield subclasses that are, in fact, homogeneous. I have not settled for practical or epistemic homogeneity. The question of whether actual homogeneity or epistemic homogeneity is demanded is, for my view, analogous to the question of whether the premises of the explanation must be true or highly confirmed for Hempel's view.[6] I have always felt that truth was the appropriate requirement, for I believe Carnap has shown that the concept of truth is harmless enough.[7] However, for those who feel too uncomfortable with the stricter requirement, it would be possible to characterize statistical explanation in terms of epistemic homogeneity instead of actual homogeneity. No fundamental problem about the nature of explanation seems to be involved.

e. This paper has been concerned with the explanation of single events, but from the standpoint of probability theory, there is no significant distinction between a single event and any finite set of events. Thus, the kind of explanation appropriate to a single result of heads on a single toss of a coin would, in principle, be just like the kind of explanation that would be appropriate to a sequence of ten heads on ten consecutive tosses of a coin or to ten heads on ten different coins tossed simultaneously.

f. With Hempel, I believe that generalizations, both universal and statistical, are capable of being explained. Explanations invoke generalizations as parts of the explanans, but these generalizations themselves may need explanation. This does not mean that the explanation of the particular event that employed the generalization is incomplete; it only means that an additional explanation is possible and may be desirable. In some cases it may be possible to explain a statistical generalization by subsuming it under a higher level generalization; a probability may become an instance for a higher level probability. For example, Reichenbach offered an explanation for equiprobability in games of chance, by constructing, in effect, a sequence of probability sequences.[8] Each of the first level sequences is a single case with respect to the second level sequence. To explain generalizations in this manner is simply to repeat, at a higher level, the pattern of explanation we have been discussing. Whether this is or is not the only method of explaining generalizations is, of course, an entirely different question.

g. In the present account of statistical explanation, Hempel's problem of the "nonconjunctiveness of statistical systematization"[9] simply vanishes. This problem arises because in general, according to the multiplication theorem for probabilities, the probability of a conjunction is smaller than that of either conjunct taken alone. Thus, if we have chosen a value r, such that explanations are acceptable only if they confer upon the explanandum an inductive probability of at least r, it is quite possible that each of the two explananda will satisfy that condition, whereas their conjunction fails to do so. Since the characterization of explanation I am offering makes no demands whatever for high probabilities (weights), it has no problem of nonconjunctiveness.

Conclusion

Although I am hopeful that the foregoing analysis of statistical explanation of single events solely in terms of statistical relevance relations is of some help in understanding the nature of scientific explanation, I should like to cite, quite explicitly, several respects in which it seems to be incomplete.

First, and most obviously, whatever the merits of the present account, no reason has been offered for supposing the type of explanation under consideration to be the only legitimate kind of scientific explanation. If we make the usual distinction between empirical laws and scientific theories, we could say that the kind of explanation I have discussed is explanation by means of empirical laws. For all that has been said in this paper, theoretical explanation—explanation that makes use of scientific theories in the fullest sense of the term—may have a logical structure entirely different from that of statistical explanation. Although theoretical explanation is almost certainly the most important kind of scientific explanation, it does, nevertheless, seem useful to have a clear account of explanation by means of empirical laws, if only as a point of departure for a treatment of theoretical explanation.

Second, in remarking above that statistical explanation is nomological, I was tacitly admitting that the statistical or universal generalizations invoked in explanations should be lawlike. I have made no attempt to analyze lawlikeness, but it seems likely that an adequate analysis will involve a solution to Nelson Goodman's "grue-bleen" problem.[10]

Third, my account of statistical explanation obviously depends heavily upon the concept of *statistical relevance* and upon the *screening-off relation*, which is defined in terms of statistical relevance. In the course of the discussion, I have attempted to show how these tools enable us to capture much of the involvement of explanation with causality, but I have not attempted to provide an analysis of causation in terms of these statistical concepts alone. Reichenbach has attempted such an analysis,[11] but whether his—or any other—can succeed is a difficult question. I should be inclined to harbor serious misgivings about the adequacy of my view of statistical explanation if the statistical analysis of causation cannot be carried through successfully, for the relation between causation and explanation seems extremely intimate.

2. Causal Connections*

Earlier I have made frequent reference to the role of causality in scientific explanation, but I have done nothing to furnish an analysis of the concept of causality or its subsidiary notions. The time has come to focus attention specifically upon this issue, and to see whether we can provide an account of causality adequate for a causal theory of scientific explanation. I shall not attempt to sidestep the fundamental philosophical issues. It seems to me that intellectual integrity demands that we squarely face Hume's incisive critique of causal relations and come to terms with the profound problems he raised.[12]

Basic Problems

As a point of departure for the discussion of causality, it is appropriate for us to take a look at the reasons that have led philosophers to develop theories of explanation that do not require causal components. To Aristotle and Laplace it must have seemed evident that scientific explanations are inevitably causal in character. Laplacian determinism is causal determinism, and I know of no reason to suppose that Laplace made any distinction between causal and noncausal laws. In their 1948 paper, Hempel and Oppenheim make the same sort of identification in an offhand manner (Hempel, 1965, p. 250; but see note 6, same page, added in 1964); however, in subsequent writings, Hempel has explicitly renounced this view (e.g., 1965, pp. 352–54).

It might be initially tempting to suppose that all laws of nature are causal laws, and that explanation in terms of laws is *ipso facto* causal explanation. It is, however, quite easy to find law-statements that do not express causal relations. Many regularities in nature are not direct cause-effect relations. Night follows day, and day follows night; nevertheless, day does not cause night, and night does not cause day. Kepler's laws of planetary motion describe the orbits of the planets, but they offer no causal account of these motions.[13] Similarly, the ideal gas law

$$PV = nRT$$

relates pressure (P), volume (V), and temperature (T) for a given sample of gas, and it tells how these quantities vary as functions of one another, but it says nothing whatever about causal relations among them. An increase in pressure might be brought about by moving a piston so as to decrease the volume, or it might be caused by an increase in temperature. The law itself is entirely noncommittal concerning such causal considerations. Each of these regularities—the alternation of night with day; the regular motions of the planets; and the functional relationship among temperature, pressure, and volume of an ideal gas—can be *explained* causally, but they do not *express* causal relations. Moreover, they do not afford causal explanations of the events subsumed under them. For this reason, it seems to me, their value in providing scientific explanations of particular events is, at best, severely limited. These are regularities that need to be explained, but that do not, by themselves, do much in the way of explaining other phenomena.

To untutored common sense, and to many scientists uncorrupted by philosophical training, it is evident that causality plays a central role in scientific explanation. An appropriate answer to an explanation-seeking why-question normally begins with the word "because," and the causal involvements of the answer are usually not hard to find.[14] The concept of causality has, however, been philosophically suspect ever since David Hume's devastating critique, first published in 1739 in his *Treatise of Human Nature*. In the "Abstract" of that work, Hume wrote:

> Here is a billiard ball lying on the table, and another ball moving toward it with rapidity. They strike; the ball which was formerly at rest now acquires a motion. This is as perfect an instance of the relations of cause and effect as any which we know either by sensation or reflection. Let us therefore examine it. It is evident that the two balls touched one another before the motion was communicated, and that there was no interval betwixt the shock and the motion. *Contiguity* in time and place is therefore a requisite circumstance to the operation of all causes. It is evident, likewise, that the motion which was the cause is prior to the motion which was the effect. *Priority* in time is, therefore, another requisite circumstance in every cause. But this is not all. Let us try any other balls of the same kind in a like situation, and we shall always find that the impulse of the one produces motion in the other. Here, therefore, is a *third* circumstance, viz. that of *constant conjunction* betwixt the cause and the effect. Every object like the cause produces always some object like the effect. Beyond these three circumstances of contiguity, priority, and constant conjunction I can discover nothing in this cause (1955, p. 186–87)

This discussion is, of course, more notable for factors Hume was unable to find than for those he enumerated. In particular, he could not discover any 'necessary connections' relating causes to effects, or any 'hidden powers' by which the cause "brings about" the effect. This classic account of causation is rightly regarded as a landmark in philosophy.

In an oft-quoted remark that stands at the beginning of a famous 1913 essay, Bertrand Russell warns philosophers about the appeal to causality:

> All philosophers, of every school, imagine that causation is one of the fundamental axioms or postulates of science, yet, oddly enough, in advanced sciences such as gravitational astronomy, the word "cause" never occurs. . . . To me it seems that . . . the reason why physics has ceased to look for causes is that, in fact, there are no such things. The law of causality, I believe, like much that passes muster among philosophers, is a relic of a bygone age, surviving, like the monarchy, only because it is erroneously supposed to do no harm (1929, p. 180)

It is hardly surprising that, in the light of Hume's critique and Russell's resounding condemnation, philosophers with an empiricist bent have been rather wary of the use of causal concepts. By 1927, however, when he wrote *The Analysis of Matter*, Russell recognized that causality plays a fundamental role in physics; in *Human Knowledge*, four of the five postulates he advanced as a basis for all scientific knowledge make explicit reference to causal relations (1948, pp. 487–96). It should be noted, however, that the causal concepts he invokes are *not* the same as the traditional philosophical ones he had rejected earlier.[15] In contemporary physics, causality is a pervasive ingredient (Suppes, 1970, pp. 5–6).

Two Basic Concepts

A standard picture of causality has been around at least since the time of Hume. The general idea is that we have two (or more) distinct events that bear some sort of cause-effect relations to one another. There has, of course, been considerable controversy regarding the nature of both the relation and the relata. It has sometimes been maintained, for instance, that facts or propositions (rather than events) are the sorts of entities that can constitute relata. It has long been disputed whether causal relations can be said to obtain among individual events, or whether statements about cause-effect relations implicitly involve assertions about classes of events. The relation itself has sometimes been taken to be that of sufficient condition, sometimes necessary condition, or perhaps a combination of the two.[16] Some authors have even proposed that certain sorts of statistical relations constitute causal relations.

The foregoing characterization obviously fits J. L. Mackie's sophisticated account in terms of INUS conditions—that is, *insufficient but non-redundant* parts of *unnecessary* but *sufficient* conditions (1974, p. 62). The idea is this. There are several different causes that might account for the burning down of a house: careless smoking in bed, an electrical short circuit, arson, being struck by lightning. With certain obvious qualifications, each of these may be taken as a sufficient condition for the fire, but none of them can be considered necessary. Moreover, each of the sufficient conditions cited involves a fairly complex combination of conditions, each of which constitutes a nonredundant part of the particular sufficient condition under consideration. The careless smoker, for example, must fall asleep with his cigarette, and it must fall upon something flammable. It must not awaken the smoker by burning him before it falls from his hand. When the smoker does become aware of the fire, it must have progressed beyond the stage at which he can extinguish it. Any one of these necessary components of some complex sufficient condition can, under certain circumstances, qualify as a cause. According to this standard approach, events enjoy the status of fundamental entities, and these entities are "connected" to one another by cause-effect relations.

It is my conviction that this standard view, in all of its well-known variations, is profoundly mistaken, and that a radically different notion should be developed. I shall not, at this juncture, attempt to mount arguments against the standard conception [. . .]. Instead, I shall present a rather different approach for purposes of comparison. I hope that the alternative will stand on its own merits.

There are, I believe, two fundamental causal concepts that need to be explicated, and if that can be achieved, we will be in a position to deal with the problems of causality in general. The two basic concepts are *propagation* and *production*, and both are familiar to common sense. The first of these will be treated in this [part]; the second will be handled in the next [part]. When we say that the blow of a hammer drives a nail, we mean that the impact produces penetration of the nail into the wood. When we say that a horse pulls a cart, we mean that the force exerted by the horse produces the motion of the cart. When we say that lightning ignites a forest, we mean that the electrical discharge produces a fire. When we say that a person's embarrassment was due to a thoughtless remark, we mean that an inappropriate comment produced psychological discomfort. Such examples of causal production occur frequently in everyday contexts.

Causal propagation (or transmission) is equally familiar. Experiences that we had earlier in our lives affect our current behavior. By means of memory, the influence of these past events is transmitted to the present (see Rosen, 1975). A sonic boom makes us aware of the passage of a jet airplane overhead; a disturbance in the air is propagated from the upper atmosphere to our location on the ground. Signals transmitted from a broadcasting station are received by the radio in our home. News or music reaches us because electromagnetic waves are propagated from the transmitter to the receiver. In 1775, some Massachusetts farmers—in initiating the American Revolutionary War—"fired the shot heard 'round the world" (Emerson, 1836). As all of these examples show, what happens at one place and time can have significant influence upon what happens at other places and times. This is possible because causal influence can be propagated through time and space. Although causal production and causal propagation are intimately related to one another, we should, I believe, resist any temptation to try to reduce one to the other.

Processes

One of the fundamental changes that I propose in approaching causality is to take processes rather than events as basic entities. I shall not attempt any rigorous definition of processes; rather I shall cite examples and make some very informal remarks. The main difference between events and processes is that events are relatively localized in space and time, while processes have much greater temporal duration, and in many cases, much greater spatial extent. In space-time diagrams, events are represented by points, while processes are represented by lines. A baseball colliding with a window would count as an event; the baseball, traveling from the bat to the window, would constitute a process. The activation of a photocell by a pulse of light

would be an event; the pulse of light, traveling, perhaps from a distant star, would be a process. A sneeze is an event. The shadow of a cloud moving across the landscape is a process. Although I shall deny that all processes qualify as causal processes, what I mean by a process is similar to what Russell characterized as a causal line:

> A causal line may always be regarded as the persistence of something—a person, a table, a photon, or what not. Throughout a given causal line, there may be constancy of quality, constancy of structure, or a gradual change of either, but not sudden changes of any considerable magnitude. (1948, p. 459)

Among the physically important processes are waves and material objects that persist through time. As I shall use these terms, even a material object at rest will qualify as a process.

Before attempting to develop a theory of causality in which processes, rather than events, are taken as fundamental, I should consider briefly the scientific legitimacy of this approach. In Newtonian mechanics, both spatial extent and temporal duration were absolute quantities. The length of a rigid rod did not depend upon a choice of frame of reference, nor did the duration of a process (such as the length of time between the creation and destruction of a material object). Given two events, in Newtonian mechanics, both the spatial distance and the temporal separation between them were absolute magnitudes. A 'physical thing ontology' was thus appropriate to classical physics. As everyone knows, Einstein's special theory of relativity changed all that. Both the spatial distance and the temporal separation were relativized to frames of reference. The length of a rigid rod and the duration of a temporal process varied from one frame of reference to another. However, as Minkowski showed, there is an invariant quantity—the space-time interval between two events. This quantity is independent of the frame of reference; for any two events, it has the same value in each and every inertial frame of reference. Since there are good reasons for according a fundamental physical status to invariants, it was a natural consequence of the special theory of relativity to regard the world as a collection of events that bear space-time relations to one another. These considerations offer support for what is sometimes called an 'event ontology.'

There is, however, another way (originally developed by A. A. Robb) of approaching the special theory of relativity; it is done entirely with paths of light pulses. At any point in space-time, we can construct the Minkowski light cone—a two-sheeted cone whose surface is generated by the paths of all possible light pulses that converge upon the point (past light cone) and the paths of all possible light pulses that could be emitted from the point (future light cone). When all of the light cones are given, the entire space-time structure of the world is determined (see Winnie, 1977). But light pulses, traveling through space and time, are processes. We can, therefore, base special relativity upon a 'process ontology.' Moreover, this approach can be extended in a natural way to general relativity by taking into account the paths of freely falling material particles; these moving gravitational test particles are also processes (see Grünbaum, 1973, pp. 735–50). It is, consequently, entirely legitimate to approach the space-time structure of the physical world by regarding physical processes as the basic types of physical entities. The theory of relativity does not mandate an 'event ontology.'

Whether one adopts the event-based approach or the process-based approach, causal relations must be accorded a fundamental place in the special theory of relativity. As we have seen, any given event E_0, occurring at a particular space-time point P_0, has an associated double-sheeted light cone. All events that could have a causal influence upon E_0 are located in the interior or on the surface of the past light cone, and all events upon which E_0 could have any causal influence are located in the interior or on the surface of the future light cone. All such events are *causally connectable* with E_0. Those events that lie on the surface of either sheet of the light cone are said to have a *lightlike separation* from E_0, those that lie within either part of the cone are said to have a *timelike separation* from E_0, and those that are outside of the cone are said to have a *spacelike separation* from E_0. The Minkowski light cone can, with complete propriety, be called "the cone of causal relevance," and the entire space-time structure of special relativity can be developed on the basis of causal concepts (Winnie, 1977).

Special relativity demands that we make a distinction between *causal processes* and *pseudo-processes*. It is a fundamental principle of that theory that light is a *first signal*—that is, no signal can be transmitted at a velocity greater than the velocity of light in a vacuum. There are, however, certain processes that can transpire at arbitrarily high velocities—at velocities vastly exceeding that of light. This fact does not violate the basic relativistic principle, however, for these 'processes' are incapable of serving as signals or of transmitting information. Causal processes are those that are capable of transmitting signals; pseudo-processes are incapable of doing so.

Consider a simple example. Suppose that we have a very large circular building—a sort of super-Astrodome, if you will—with a spotlight mounted at its center. When the light is turned on in the otherwise darkened building, it casts a spot of light upon the wall. If we turn the light on for a brief moment, and then off again, a light pulse travels from the light to the wall. This pulse of light, traveling from the spotlight to the wall, is a paradigm of what we mean by a causal process. Suppose, further, that the spotlight is mounted on a mechanism that makes it rotate. If the light is turned on and set into rotation, the spot of light that it casts upon the wall will move around the outer wall in a highly regular fashion. This 'process'—the moving spot of light—seems to fulfill the conditions Russell used to characterize causal lines, but it is not a causal process. It is a paradigm of what we mean by a pseudo-process.

The basic method for distinguishing causal processes from pseudo-processes is the criterion of mark transmission. A causal process is capable of transmitting a mark; a pseudo-process is not. Consider, first, a pulse of light that travels from the spotlight to the wall. If we place a piece of red glass in its path at any point between the spotlight and the wall, the light pulse, which was white, becomes and remains red until it reaches the wall. A single intervention at one point in the process transforms it in a way that persists from that point on. If we had not intervened, the light pulse would have remained white during its entire journey from the spotlight to the wall. If we do intervene locally at a single place, we can produce a change that is transmitted from the point of intervention onward. We shall say, therefore, that the light pulse constitutes a causal process whether it is modified or not, since in either case it is capable of transmitting a mark. Clearly, light pulses can serve as signals and can transmit messages; remember Paul Revere, "One if by land and two if by sea."

Now, let us consider the spot of light that moves around the wall as the spotlight rotates. There are a number of ways in which we can intervene to change the spot at some point; for example, we can place a red filter at the wall with the result that the spot of light becomes red at that point. But if we make such a modification in the traveling spot, it will not be transmitted beyond the point of interaction. As soon as the light spot moves beyond the point at which the red filter was placed, it will become white again. The mark can be made, but it will not be transmitted. We have a 'process,' which, in the absence of any intervention, consists of a white spot moving regularly along the wall of the building. If we intervene at some point, the 'process' will be modified *at that point*, but it will continue on beyond that point just as if no intervention had occurred. We can, of course, make the spot red at other places if we wish. We can install a red lens in the spotlight, but that does not constitute a *local* intervention at an isolated point in the process itself. We can put red filters at many places along the wall, but that would involve *many* interventions rather than a single one. We could get someone to run around the wall holding a red filter in front of the spot continuously, but that would not constitute an intervention *at a single point* in the 'process.'

This last suggestion brings us back to the subject of velocity. If the spot of light is moving rapidly, no runner could keep up with it, but perhaps a mechanical device could be set up. If, however, the spot moves too rapidly, it would be physically impossible to make the filter travel fast enough to keep pace. No material object, such as the filter, can travel at a velocity greater than that of light, but no such limitation is placed upon the spot on the wall. This can easily be seen as follows. If the spotlight rotates at a fixed rate, then it takes the spot of light a fixed amount of time to make one entire circuit around the wall. If the spotlight rotates once per second, the spot of light will travel around the wall in one second. This fact is independent of the size of the building. We can imagine that without making any change in the spotlight or its rate of rotation, the outer walls are expanded indefinitely. At a certain point, when the radius of the building is a little less than 50,000 kilometers, the spot will be traveling at the speed of light (300,000 km/sec). As the walls are moved still farther out, the velocity of the spot exceeds the speed of light.

To make this point more vivid, consider an actual example that is quite analogous to the rotating spotlight. There is a pulsar in the crab nebula that is about 6,500 light-years away. This pulsar is thought to be a rapidly rotating neutron star that sends out a beam of radiation. When the beam is directed toward us, it sends out radiation that we detect later as a pulse. The pulses arrive at the rate of 30 per second; that is the rate at which the neutron star rotates. Now, imagine a circle drawn with the pulsar at its center, and with a radius equal to the distance from the pulsar to the earth. The electromagnetic radiation from the pulsar (which travels at the speed of light) takes 6,500 years to traverse the radius of this circle, but the "spot" of radiation sweeps around the circumference of this circle in 1/30th of a second; at that rate, it is traveling at about 4×10^{13} times the speed of light. There is no upper limit on the speed of pseudo-processes.[17]

Another example may help to clarify this distinction. Consider a car traveling along a road on a sunny day. As the car moves at 100 km/hr, its shadow moves along the shoulder at the same speed. The moving car, like any material object, constitutes a causal process; the shadow is a pseudo-process. If the car collides with a stone wall, it will carry the marks of that collision—the dents and scratches—

along with it long after the collision has taken place. If, however, only the shadow of the car collides with the stone wall, it will be deformed momentarily, but it will resume its normal shape just as soon as it has passed beyond the wall. Indeed, if the car passes a tall building that cuts it off from the sunlight, the shadow will be obliterated, but it will pop right back into existence as soon as the car has returned to the direct sunlight. If, however, the car is totally obliterated—say, by an atomic bomb blast—it will not pop back into existence as soon as the blast has subsided.

A given process, whether it be causal or pseudo, has a certain degree of uniformity—we may say, somewhat loosely, that it exhibits a certain structure. The difference between a causal process and a pseudo-process, I am suggesting, is that the causal process transmits its own structure, while the pseudo-process does not. The distinction between processes that do and those that do not transmit their own structures is revealed by the mark criterion. If a process—a causal process—is transmitting its own structure, then it will be capable of transmitting certain modifications in that structure.

In *Human Knowledge*, Russell placed great emphasis upon what he called "causal lines," which he characterized in the following terms:

> A "causal line," as I wish to define the term, is a temporal series of events so related that, given some of them, something can be inferred about the others whatever may be happening elsewhere. A causal line may always be regarded as the persistence of something—a person, table, a photon, or what not. Throughout a given causal line, there may be constancy of quality, constancy of structure, or gradual change in either, but not sudden change of any considerable magnitude. (1948, p. 59)

He then goes on to comment upon the significance of causal lines:

> That there are such more or less self-determined causal processes is in no degree logically necessary, but is, I think, one of the fundamental postulates of science. It is in virtue of the truth of this postulate—if it is true—that we are able to acquire partial knowledge in spite of our enormous ignorance. (Ibid.)

Although Russell seems clearly to intend his causal lines to be what we have called causal processes, his characterization may appear to allow pseudo-processes to qualify as well. Pseudo-processes, such as the spot of light traveling around the wall of our Astrodome, sometimes exhibit great uniformity, and their regular behavior can serve as a basis for inferring the nature of certain parts of the pseudo-process on the basis of observation of other parts. But pseudo-processes are not self-determined; the spot of light is determined by the behavior of the beacon and the beam it sends out. Moreover, the inference from one part of the pseudo-process to another is *not* reliable *regardless of what may be happening elsewhere*, for if the spotlight is switched off or covered with an opaque hood, the inference will go wrong. We may say, therefore, that our observations of the various phenomena going on in the world around us reveal processes that exhibit considerable regularity, but some of these are genuine causal processes and others are pseudo-processes. The causal processes are, as Russell says, self-determined; they transmit their own uniformities of qualitative and structural features. The regularities exhibited by the pseudo-processes, in contrast, are parasitic upon causal regularities exterior to the 'process'

itself—in the case of the Astrodome, the behavior of the beacon; in the case of the shadow traveling along the roadside, the behavior of the car and the sun. The ability to transmit a mark is the criterion that distinguishes causal processes from pseudo-processes, for if the modification represented by the mark is propagated, the process is transmitting its own characteristics. Otherwise, the 'process' is not self-determined, and is not independent of what goes on elsewhere.

Although Russell's characterization of causal lines is heuristically useful, it cannot serve as a fundamental criterion for their identification for two reasons. First, it is formulated in terms of our ability to infer the nature of some portions from a knowledge of other portions. We need a criterion that does not rest upon such epistemic notions as knowledge and inference, for the existence of the vast majority of causal processes in the history of the universe is quite independent of human knowers. This aspect of the characterization could, perhaps, be restated nonanthropocentrically in terms of the persistence of objective regularities in the process. The second reason is more serious. To suggest that processes have regularities that persist "whatever may be happening elsewhere" is surely an overstatement. If an extremely massive object should happen to be located in the neighborhood of a light pulse, its path will be significantly altered. If a nuclear blast should occur in the vicinity of a mail truck, the letters that it carries will be totally destroyed. If sunspot activity reaches a high level, radio communication is affected. Notice that, in each of these cases, the factor cited does not occur or exist on the world line of the process in question. In each instance, of course, the disrupting factor initiates processes that intersect with the process in question, but that does not undermine the objection to the claim that causal processes transpire in their self-determined fashion regardless of what is happening elsewhere. A more acceptable statement might be that a causal process would persist even if it were isolated from external causal influences. This formulation, unfortunately, seems at the very least to flirt with circularity, for external causal influences must be transmitted to the locus of the process in question by means of other processes. We shall certainly want to keep clearly in mind the notion that causal processes are not parasitic upon other processes, but it does not seem likely that this rough idea could be transformed into a useful basic criterion.

It has often been suggested that the principal characteristic of causal processes is that they transmit energy. While I believe it is true that all and only causal processes transmit energy, there is, I think, a fundamental problem involved in employing this fact as a basic criterion—namely, we must have some basis for distinguishing situations in which energy is transmitted from those in which it merely appears in some regular fashion. The difficulty is easily seen in the "Astrodome" example. As a light pulse travels from the central spotlight to the wall, it carries radiant energy; this energy is present in the various stages of the process as the pulse travels from the lamp to the wall. As the spot of light travels around the wall, energy appears at the places occupied by the spot, but we do not want to say that this energy is transmitted. The problem is to distinguish the cases in which a given bundle of energy is transmitted through a process from those in which different bundles of energy are appearing in some regular fashion. The key to this distinction is, I believe, the mark method. Just as the detective makes his mark on the murder weapon for purposes of later identification, so also do we make marks in processes so that the energy present at one space-time locale can be identified when it appears at other times and places.

A causal process is one that is self-determined and not parasitic upon other causal influences. A causal process is one that transmits energy, as well as information and causal influence. The fundamental criterion for distinguishing self-determined energy transmitting processes from pseudo-processes is the capability of such processes of transmitting marks. In the next section, we shall deal with the concept of transmission in greater detail.

Our main concern with causal processes is their role in the propagation of causal influences; radio broadcasting presents a clear example. The transmitting station sends a carrier wave that has a certain structure—characterized by amplitude and frequency, among other things—and modifications of this wave, in the form of modulations of amplitude (AM) or frequency (FM), are imposed for the purpose of broadcasting. Processes that transmit their own structures are capable of transmitting marks, signals, information, energy, and causal influence. Such processes are the means by which causal influence is propagated in our world. Causal influences, transmitted by radio, may set your foot to tapping, or induce someone to purchase a different brand of soap, or point a television camera aboard a spacecraft toward the rings of Saturn. A causal influence transmitted by a flying arrow can pierce an apple on the head of William Tell's son. A causal influence transmitted by sound waves can make your dog come running. A causal influence transmitted by ink marks on a piece of paper can gladden one's day or break someone's heart.

It is evident, I think, that the propagation or transmission of causal influence from one place and time to another must play a fundamental role in the causal structure of the world. As I shall argue next, causal processes constitute precisely the causal connections that Hume sought, but was unable to find.

The 'At-At' Theory of Causal Propagation

In the preceding section, I invoked Reichenbach's mark criterion to make the crucial distinction between causal processes and pseudo-processes. Causal processes are distinguished from pseudo-processes in terms of their ability to transmit marks. In order to qualify as causal, a process need not actually be transmitting a mark; the requirement is that it be capable of doing so.

When we characterize causal processes partly in terms of their ability to transmit marks, we must deal explicitly with the question of whether we have violated the kinds of strictures Hume so emphatically expounded. He warned against the uncritical use of such concepts as 'power' and 'necessary connection.' Is not the *ability to transmit* a mark an example of just such a mysterious power? Kenneth Sayre expressed his misgivings on this score when, after acknowledging the distinction between causal interactions and causal processes, he wrote:

> The causal process, continuous though it may be, is made up of individual events related to others in a causal nexus. . . . it is by virtue of the relations among the members of causal series that we are enabled to make the inferences by which causal processes are characterized. . . . if we do not have an adequate conception of the relatedness between individual members in a causal series, there is a sense in which our conception of the causal process itself remains deficient. (1977, p. 206)

The 'at-at' theory of causal transmission is an attempt to remedy this deficiency.

Does this remedy illicitly invoke the sort of concept Hume proscribed? I think not. Ability to transmit a mark can be viewed as a particularly important species of constant conjunction—the sort of thing Hume recognized as observable and admissible. It is a matter of performing certain kinds of experiments. If we place a red filter in a light beam near its source, we can observe that the mark—redness—appears at all places to which the beam is subsequently propagated. This fact can be verified by experiments as often as we wish to perform them. If, contrariwise (returning to our Astrodome example of the preceding section), we make the spot on the wall red by placing a filter in the beam at one point just before the light strikes the wall (or by any other means we may devise), we will see that the mark—redness—is not present at all other places in which the moving spot subsequently appears on the wall. This, too, can be verified by repeated experimentation. Such facts are straightforwardly observable.

The question can still be reformulated. What do we mean when we speak of *transmission*? How does the process *make* the mark appear elsewhere within it? There is, I believe, an astonishingly simple answer. The transmission of a mark from point A in a causal process to point B in the same process *is* the fact that it appears at each point between A and B *without further interactions*. If A is the point at which the red filter is inserted into the beam going from the spotlight to the wall, and B is the point at which the beam strikes the wall, then only the interaction at A is required. If we place a white card in the beam at any point between A and B, we will find the beam red at that point.

The basic thesis about mark transmission can now be stated (in a principle I shall designate MT for "mark transmission") as follows:

> MT: Let P be a process that, in the absence of interactions with other processes, would remain uniform with respect to a characteristic Q, which it would manifest consistently over an interval that includes both of the space-time points A and B ($A \neq B$). Then, a mark (consisting of a modification of Q into Q'), which has been introduced into process P by means of a single local interaction at point A, is transmitted to point B if P manifests the modification Q' at B and at all stages of the process between A and B without additional interventions.

This principle is clearly counterfactual, for it states explicitly that the process P would have continued to manifest the characteristic Q if the specific marking interaction had not occurred. This subjunctive formulation is required, I believe, to overcome an objection posed by Nancy Cartwright (in conversation) to previous formulations. The problem is this. Suppose our rotating beacon is casting a white spot that moves around the wall, and that we mark the spot by interposing a red filter at the wall. Suppose further, however, that a red lens has been installed in the beacon just a tiny fraction of a second earlier, so that the spot on the wall becomes red at the moment we mark it with our red filter, but it remains red from that point on because of the red lens. Under these circumstances, were it not for the counterfactual condition, it would appear that we had satisfied the requirement formulated in MT, for we have marked the spot by a single interaction at point A, and the spot remains red from that point on to any other point B we care to designate, without any additional interactions. As we have just mentioned, the installation of the red lens on the spotlight does not constitute a marking of the spot on the wall. The counterfactual stipulation given in the first sentence of MT blocks situations of the sort mentioned by Cartwright, in which we would most certainly want to deny that any mark transmission occurred via the spot moving around the wall. In this case, the moving spot would have turned red because of the lens even if no marking interaction had occurred locally at the wall.

A serious misgiving arises from the use of counterfactual formulations to characterize the distinction between causal processes and pseudo-processes; it concerns the question of objectivity. The distinction is fully objective. It is a matter of fact that a light pulse constitutes a causal process, while a shadow is a pseudo-process. Philosophers have often maintained, however, that counterfactual conditionals involve unavoidably pragmatic aspects. Consider the famous example about Verdi and Bizet. One person might say, "If Verdi had been a compatriot of Bizet, then Verdi would have been French," whereas another might maintain, "If Bizet had been a compatriot of Verdi, then Bizet would have been Italian." These two statements seem incompatible with one another. Their antecedents are logically equivalent; if, however, we accept both conditionals, we wind up with the conclusion that Verdi would be French, that Bizet would be Italian, and they would still not be compatriots. Yet both statements can be true. The first person could be making an unstated presupposition that the nationality of Bizet is fixed in this context, while the second presupposes that the nationality of Verdi is fixed. What remains fixed and what is subject to change—which are established by pragmatic features of the context in which the counterfactual is uttered—determine whether a counterfactual is true or false. It is concluded that counterfactual conditional statements do not express objective facts of nature; indeed, van Fraassen (1980, p. 118) goes so far as to assert that science contains no counterfactuals. If that sweeping claim were true (which I seriously doubt),[18] the foregoing criterion MT would be in serious trouble.

Although MT involves an explicit counterfactual, I do not believe that the foregoing difficulty is insurmountable. Science has a direct way of dealing with the kinds of counterfactual assertions we require, namely, the experimental approach. In a well-designed controlled experiment, the experimenter determines which conditions are to be fixed for purposes of the experiment and which allowed to vary. The result of the experiment establishes some counterfactual statements as true and others as false under well-specified conditions. Consider the kinds of cases that concern us; such counterfactuals can readily be tested experimentally. Suppose we want to see whether the beam traveling from the spotlight to the wall is capable of transmitting the red mark. We set up the following experiment. The light will be turned on and off one hundred times. At a point midway between the spotlight and the wall, we station an experimenter with a random number generator. Without communicating with the experimenter who turns the light on and off, this second experimenter uses his device to make a random selection of fifty trials in which he will make a mark and fifty in which he will not. If all and only the fifty instances in which the marking interaction occurs are those in which the spot on the wall is red, as well as all the intervening stages in the process, then we may conclude with reasonable certainty that the fifty cases in which the beam was red subsequent to the marking interaction are cases in which the beam would not have been red if the marking interaction had not occurred. On any satisfactory analysis of counterfactuals, it seems to me, we would be justified in drawing such a conclusion. It should be carefully noted that I am *not* offering the foregoing experimental procedure as an analysis of counterfactuals; it is, indeed, a result that we should expect any analysis to yield.

A similar experimental approach could obviously be taken with respect to the spot traversing the wall. We design an experiment in which the beacon will rotate one hundred times, and each traversal will be taken as a separate process. We station an experimenter with a random number generator at the wall. Without communicating with the experimenter operating the beacon, the one at the wall makes a random selection of fifty trials in which to make the mark and fifty in which to refrain. If it turns out that some or all of the trials in which no interaction occurs, are, nevertheless, cases in which the spot on the wall turns red as it passes the second experimenter, then we know that we are *not* dealing with cases in which the process will not turn from white to red if no interaction occurs. Hence, if in some cases the spot turns red and remains red after the mark is imposed, we know we are not entitled to conclude that the mark has actually been transmitted.

The account of mark transmission embodied in principle MT—which is the proposed foundation for the concept of propagation of causal influence—may seem too trivial to be taken seriously. I believe such a judgment would be mistaken. My reason lies in the close parallel that can be drawn between the foregoing solution to the problem of mark transmission and the solution of an ancient philosophical puzzle.

About twenty-five hundred years ago, Zeno of Elea enunciated some famous paradoxes of motion, including the well-known paradox of the flying arrow. This paradox was not adequately resolved until the early part of the twentieth century. To establish an intimate connection between this problem and our problem of causal transmission, two observations are in order. First, a physical object (such as the arrow) moving from one place to another constitutes a causal process, as can be demonstrated easily by application of the mark method—for example, initials carved on the shaft of the arrow before it is shot are present on the shaft after it hits its target. And there can be no doubt that the arrow propagates causal influence. The hunter kills his prey by releasing the appropriately aimed arrow; the flying arrow constitutes the causal connection between the cause (release of the arrow from the bow under tension) and the effect (death of a deer). Second, Zeno's paradoxes were designed to prove the absurdity not only of motion, but also of every kind of process or change. Henri Bergson expressed this point eloquently in his discussion of what he called "the cinematographic view of becoming." He invites us to consider any process, such as the motion of a regiment of soldiers passing in review. We can take many snapshots—static views—of different stages of the process, but, he argues, we cannot really capture the movement in this way, for,

> every attempt to reconstitute change out of states implies the absurd proposition, that movement is made out of immobilities.
>
> Philosophy perceived this as soon as it opened its eyes. The arguments of Zeno of Elea, although formulated with a very different intention, have no other meaning.
>
> Take the flying arrow. (1911, p. 308; quoted in Salmon, 1970a, p. 63).

Let us have a look at this paradox. At any given instant, Zeno seems to have argued, the arrow is where it is, occupying a portion of space equal to itself. During the instant it cannot move, for that would require the instant to have parts, and an instant is *by definition* a minimal and indivisible element of time. If the arrow did move during the instant, it would have to be in one place at one part of the instant and in a different place at another part of the instant. Moreover, for the arrow to move during the instant would require that during that instant it must occupy a space larger than itself, for otherwise it has no room to move. As Russell said:

> It is never moving, but in some miraculous way the change of position has to occur *between* the instants, that is to say, not at any time whatever. This is what M. Bergson calls the cinematographic representation of reality. The more the difficulty is meditated, the more real it becomes (1929, p. 187; quoted in Salmon, 1970a, p. 51)

There is a strong temptation to respond to this paradox by pointing out that the differential calculus provides us with a perfectly meaningful definition of instantaneous velocity, and that this quantity *can* assume values other than zero. Velocity is change of position with respect to time, and the derivative dx/dt furnished an expression that can be evaluated for particular values of t. Thus an arrow can be at rest at a given moment—that is, dx/dt may equal 0 for that particular value of t. Or it can be in motion at a given moment—that is, dx/dt might be 100 km/hr for another particular value of t. Once we recognize this elementary result of the infinitesimal calculus, it is often suggested, the paradox of the flying arrow vanishes.

This appealing attempt to resolve the paradox is, however, unsatisfactory, as Russell clearly realized. The problem lies in the definition of the derivative; dx/dt is defined as the limit as Δt approaches 0 of $\Delta x/\Delta t$, where Δt represents a non-zero interval of time and Δx may be a non-zero spatial distance. In other words, instantaneous velocity is defined as the limit, as we take decreasing time intervals, of the noninstantaneous average velocity with which the object traverses what is—in the case of non-zero values— a non-zero stretch of space. Thus in the definition of instantaneous velocity, we employ the concept of non-instantaneous velocity, which is precisely the problematic concept from which the paradox arises. To put the same point in a different way, the concept of instantaneous velocity does not genuinely characterize the motion of an object at an isolated instant all by itself, for the very definition of instantaneous velocity makes reference to neighboring instants of time and neighboring points of space. To find an adequate resolution of the flying arrow paradox, we must go deeper.

To describe the motion of a body, we express the relation between its position and the moments of time with which we are concerned by means of a mathematical function; for example, the equation of motion of a freely falling particle near the surface of the earth is

$$x = f(t) = 1/2gt^2 \tag{1}$$

where $g = 9.8$ m/sec^2. We can therefore say that this equation furnishes a function $f(t)$ that relates the position of x to the time t. But what is a mathematical function? It is a set of pairs of numbers; for each admissible value of t, there is an associated value of x. To say that an object moves in accordance with equation (1) is simply to say that *at* any given moment t it is *at* point x, where the correspondence between the values of t and of x is given by the set of pairs of numbers that constitute the function represented by equation (1). To move from point A to point B is simply to be *at* the appropriate point of space *at* the appropriate moment of time—no more, no less. The resulting theory is therefore known as "the 'at-at' theory of motion." To the best of my knowledge, it was first clearly formulated and applied to the arrow paradox by Russell.

According to the 'at-at' theory, to move from A to B is simply to occupy the intervening points at the intervening instants. It consists in being *at* particular points of space *at* corresponding moments. There is no *additional* question as to how the arrow *gets from* point A to point B; the answer has already been given—by being at the intervening points at the intervening moments. The answer is emphatically *not* that it gets from A to B by zipping through the intermediate points at high speed. Moreover, there is no additional question about how the arrow gets from one intervening point to another—the answer is the same, namely, by being at the points between them at the corresponding moments. And clearly, there can be no question about how the arrow gets from one point to the next, for in a continuum there is no next point. I am convinced that Zeno's arrow paradox is a profound problem concerning the nature of change and motion, and that its resolution by Russell in terms of the 'at-at' theory of motion represents a distinctly nontrivial achievement.[19] The fact that this solution can—if I am right—be extended in a direct fashion to provide a resolution of the problem of mark transmission is an additional laurel.

The 'at-at' theory of mark transmission provides, I believe, an acceptable basis for the mark method, which can in turn serve as the means to distinguish causal processes from pseudo-processes. The world contains a great many types of causal processes—transmission of light waves, motion of material objects, transmissions of sound waves, persistence of crystalline structure, and so forth. Processes of any of these types may occur without having any mark imposed. In such instances, the processes still qualify as causal. *Ability* to transmit a mark is the criterion of causal processes; processes that are *actually* unmarked may be causal. Unmarked processes exhibit some sort of persistent structure, as Russell pointed out in his characterization of causal lines; in such cases, we say that the structure is transmitted within the causal process. Pseudo-processes may also exhibit persistent structure; in these cases, we maintain that the structure is *not transmitted* by means of the "process" itself, but by some other external agency.

The basis for saying that the regularity in the causal process is transmitted via the process itself lies in the ability of the causal process to transmit a modification in its structure—a mark—resulting from an interaction. Consider a brief pulse of white light; it consists of a collection of photons of various frequencies, and if it is not polarized, the waves will have various spatial orientations. If we place a red filter in the path of this pulse, it will absorb all photons with frequencies falling outside of the red range, allowing only those within that range to pass. The resulting pulse has its structure modified in a rather precisely specifiable way, and the fact that this modification persists is precisely what we mean by claiming that the mark is transmitted. The counterfactual clause in our principle MT is designed to rule out structural changes brought about by anything other than the marking interaction. The light pulse could, alternatively, have been passed through a polarizer. The resulting pulse would consist of photons having a specified spatial orientation instead of the miscellaneous assortment of orientations it contained before encountering the polarizer. The principle of structure transmission (ST) may be formulated as follows:

ST: If a process is capable of transmitting changes in structure due to marking interactions, then that process can be said to transmit its own structure.

The fact that a process does not transmit a particular type of mark, however, does not mean that it is not a causal process. A ball of putty constitutes a causal process, and one kind of mark it will transmit is a change in shape imposed by indenting it with the thumb. However, a hard rubber ball is equally a causal process, but it will not transmit the same sort of mark, because of its elastic properties. The fact that a particular sort of structural modification does not persist, because of some inherent tendency of the process to resume its earlier structure, does not mean it is not transmitting its own structure; it means only that we have not found the appropriate sort of mark for that kind of process. A hard rubber ball can be marked by painting a spot on it, and that mark will persist for a while.

Marking methods are sometimes used in practice for the identification of causal processes. As fans of Perry Mason are aware, Lieutenant Tragg always placed "his mark" upon the murder weapon found at the scene of the crime in order to be able to identify it later at the trial of the suspect. Radioactive tracers are used in the investigation of physiological processes—for example, to determine the course taken by a particular substance ingested by a subject. Malodorous substances are added to natural gas used for heating and cooking in order to ascertain the presence of leaks; in fact, one large chemical manufacturer published full-page color advertisements in scientific magazines for its product "La Stink."

One of the main reasons for devoting our attention to causal processes is to show how they can transmit causal influence. In the case of causal processes used to transmit signals, the point is obvious. Paul Revere was caused to start out on his famous night ride by a light signal sent from the tower of the Old North Church. A drug, placed surreptitiously in a drink, can cause a person to lose consciousness because it retains its chemical structure as it is ingested, absorbed, and circulated through the body of the victim. A loud sound can produce a painful sensation in the ears because the disturbance of the air is transmitted from the origin to the hearer. Radio signals sent to orbiting satellites can activate devices aboard because the wave retains its form as it travels from earth through space. The principle of propagation of causal influence (PCI) may be formulated as follows:

PCI: A process that transmits its own structure is capable of propagating a causal influence from one space-time locale to another.

The propagation of causal influence by means of causal processes *constitutes*, I believe, the mysterious connection between cause and effect which Hume sought.

In offering the 'at-at' theory of mark transmission as a basis for distinguishing causal processes from pseudo-processes, we have furnished an account of the transmission of information and propagation of causal influence without appealing to any of the secret powers which Hume's account of causation soundly proscribed. With this account we see that the mysterious connection between causes and effects is not very mysterious after all.

Our task is by no means finished, however, for this account of transmission of marks and propagation of causal influence has used the unanalyzed notion of a causal interaction that produces a mark. Unless a satisfactory account of causal interaction and mark production can be provided, our theory of causality will contain a severe lacuna. We will attempt to fill that gap in the next [section]. Nevertheless, we have made significant progress in explicating the fundamental concept, introduced at the beginning of the chapter, of *causal propagation* (or *transmission*).

This [section] is entitled "Causal Connections," but little has actually been said about the way in which causal processes provide the connection between cause and effect. Nevertheless, in many common-sense situations, we talk about causal relations between pairs of spatiotemporally separated events. We might say, for instance, that turning the key causes the car to start. In this context we assume, of course, that the electrical circuitry is intact, that the various parts are in good working order, that there is gasoline in the tank, and so forth, but I think we can make sense of a cause-effect relation only if we can provide a *causal connection* between the cause and the effect. This involves tracing out the causal processes that lead from the turning of the key and the closing of an electrical circuit to various occurrences that eventuate in the turning over of the engine and the ignition of fuel in the cylinders. We say, for another example, that a tap on the knee causes the foot to jerk. Again, we believe that there are neural impulses traveling from the place at which the tap occurred to the muscles that control the movement of the foot, and processes in those muscles that lead to movement of the foot itself. The genetic relationship between parents and offspring provides a further example. In this case, the molecular biologist refers to the actual process of information via the DNA molecule employing the genetic code.

In each of these situations, we analyze the cause-effect relations in terms of three components—an event that constitutes the cause, another event that constitutes the effect, and a causal process that connects the two events. In some cases, such as the starting of the car, there are many intermediate events, but in such cases, the successive intermediate events are connected to one another by spatiotemporally continuous causal processes. A splendid example of multiple causal connections was provided by David Kaplan. Several years ago, he paid a visit to Tucson, just after completing a boat trip through the Grand Canyon with his family. The best time to take such a trip, he remarked, is when it is very hot in Phoenix. What is the causal connection to the weather in Phoenix, which is about 200 miles away? At such times, the air conditioners in Phoenix are used more heavily, which places a greater load on the generators at the Glen Canyon Dam (above the Grand Canyon). Under the circumstances, more water is allowed to pass through the turbines to meet the increased demand for power, which produces a greater flow of water down the Colorado River. This results in a more exciting ride through the rapids in the Canyon.

In the next [section], we shall consider events—especially causal interactions—more explicitly. It will then be easier to see how causal processes constitute precisely the physical connections between causes and effects that Hume sought—what he called "the cement of the universe." These causal connections will play a vital role in our account of scientific explanation.

It is tempting, of course, to try to reduce causal processes to chains of events; indeed, people frequently speak of causal chains. Such talk can be seriously misleading if it is taken to mean that causal processes are composed of discrete events that are serially ordered so that any given event has an immediate successor. If, however, the continuous character of causal processes is kept clearly in mind, I would not argue that it is philosophically incorrect to regard processes as collections of events. At the same time, it does seem heuristically disadvantageous to do so, for this practice seems almost inevitably to lead to the puzzle (articulated by Sayre in the quotation given previously) of how these events, which make up a given process, are causally related to one another. The point of the 'at-at' theory, it seems to me is to show that no such question about the causal relations among the constituents of the process need arise—for the same reason that, aside from occupying intermediate positions at the appropriate times, there is no further question about how the flying arrow gets from one place to another. With the aid of the 'at-at' theory, we have a complete answer to Hume's penetrating question about the nature of causal connections. For this heuristic reason, then, I consider it advisable to resist the temptation always to return to formulations in terms of events.

3. Causal Forks and Common Causes

There is a familiar pattern of causal reasoning that we all use every day, usually without being consciously aware of it. Confronted with what appears to be an improbable coincidence, we seek a common cause. If the common cause can be found, it is invoked to explain the coincidence.

Conjunctive Forks

Suppose, for example, that several members of a traveling theatrical company who have spent a pleasant day in the country together become violently ill that evening. We infer that it was probably due to a common meal of which they all partook. When we find that their lunch included some poisonous mushrooms that they had gathered and cooked, we have the explanation. There is a certain small chance that a particular actor or actress will, on any given evening, suffer severe gastrointestinal distress—the probability need not, of course, be the same for each person. If the illnesses were statistically independent of one another, then the probability of all the picnickers becoming ill on the same night would be equal to the product of all of these individual small probabilities. Even though a chance coincidence of this sort is possible, it is too improbable to be accepted as such. The evidence for a common cause is compelling.

Although reasoning of this type seems simple and straightforward, philosophers have paid surprisingly little explicit attention to it. Hans Reichenbach is the outstanding exception. In his posthumous book, *The Direction of Time* (1956), he enunciated *the principle of the common cause,* and he attempted to explicate the principle in terms of a statistical structure that he called a *conjunctive fork*. The principle of the common cause states, roughly, that when apparent coincidences occur that are too improbable to be attributed to chance, they can be explained by reference to a common causal antecedent. This principle is by no means trivial or vacuous. Among other things, it denies that such apparent coincidences are to be explained teleologically in terms of subsequent common effects. If the aforementioned theatrical troupe had been scheduled to put on a performance that evening, it would in all likelihood have been canceled. This common effect would not, however, explain the coincidence. We shall have to consider why this is so later [. . .].

Other examples, from everyday life and from science, are easy to find. If, for instance, two students in a class turn in identical papers, and if we can rule out the possibility that either copied directly from the other, then we search for a common cause—for example, a paper in a fraternity file from which both of them copied independently of each other.

A recent astronomical discovery, which has considerable scientific significance, furnished a particularly fine example. The twin quasars 0975 + 561 A and B are separated by an angular width of 5.7 sec of arc. Two quasars in such apparent proximity would be a rather improbable occurrence given simply the observed distribution of quasars. Examination of their spectra indicates equal red shifts, and hence, equal distances. Thus these objects are close together in space, as well as appearing close together as seen from earth. Moreover, close examination of their spectra reveals a striking similarity—indeed, they are indistinguishable. This situation is in sharp contrast to the relations between the spectra of any two quasars picked at random. Astronomers immediately recognized the need to explain this astonishing coincidence in terms of some sort of common cause. One hypothesis that was entertained quite early was that twin quasars had somehow (no one had the slightest idea how this could happen in reality) developed from a common ancestor. Another hypothesis was the gravitational lens effect—that is, there are not in fact two distinct quasars, but the two images were produced from a single body by the gravitational bending of the light by an intervening massive object. This result might be produced by a black hole, it was theorized, or by a very large elliptical galaxy. Further observation, under fortuitously excellent viewing conditions, has subsequently revealed the presence of a galaxy that would be adequate to produce the gravitational splitting of the image. This explanation is now, to the best of my knowledge, accepted by virtually all of the experts (Chaffee, 1980).

In an attempt to characterize the structure of such examples of common causes, Reichenbach (1956, section 19) introduced the notion of a *conjunctive fork,* defined in terms of the following four conditions.[20]

(1) $$P(A.B|C = P(A|C) \times P(B|C)$$

(2) $$P(A.B|\bar{C}) = P(A|\bar{C}) \times P(B|\bar{C})$$

(3) $$P(A|C) > P(A|\bar{C})$$

(4) $$P(B|C) > P(B|\bar{C}).$$

For reasons that will be made clear [. . .], we shall stipulate that none of the probabilities occurring in these relations is equal to zero or one. Although it is not immediately obvious, conditions (1)–(4) entail

(5) $$P(A.B) > P(A) \times P(B)$$

(see Reichenbach, 1956, pp. 160–61).[21] These relations apply quite straightforwardly in concrete situations. Given two effects, A and B, that occur together more frequently than they would if they were statistically independent of one another, there is some prior event C, which is a cause of A and is also a cause of B, that explains the lack of independence between A and B. In the case of plagiarism, the cause C is the presence of the term paper in the file to which both students had access. In the case of simultaneous illness, the cause C is the common meal that included the poisonous mushrooms. In the case of the twin quasar image, the cause C is the emission of radiation in two slightly different directions by a single luminous body.

To say of two events, X and Y, that they occurred independently of one another means that they occur together with a probability equal to the product of the probabilities of their separate occurrences; that is,

$$P(X.Y) = P(X) \times P(Y). \tag{6}$$

Thus in the examples we have considered, as relation (5) states, the two effects A and B are not independent. However, given the occurrence of the common cause C, A, and B do occur independently, as the relationship among the conditional probabilities in equation (1) shows. Thus in the case of illness, the fact that the probability of two individuals being ill at the same time is greater than the product of the probabilities of their individual illnesses is explained by the common meal. In this example, we are assuming that the fact that one person is afflicted does not have any direct causal influence upon the illness of the other.[22] Moreover, let us assume for the sake of simplicity that in this situation, there are no other potential common causes of severe gastrointestinal illness.[23] Then, in the absence of the common cause C—that is, when $\bar{C}$ obtains—A and B are also independent of one another, as the relationship among the conditional probabilities in equation (2) states. Relations (3) and (4) simply assert that C is a positive cause of A and B, since the probability of each is greater in the presence of C than in the absence of C.

There is another useful way to look at equations (1) and (2). Recalling that, according to the multiplication theorem,

$$P(A.B|C) = P(A|C) \times P(B|A.C), \tag{7}$$

we see that, provided $P(A|C) \neq 0$, equation (1) entails

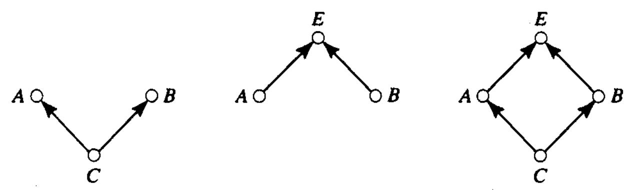
$$P(B|C) = P(B|A.C). \tag{8}$$

In Reichenbach's terminology, this says that C screens off A from B. A similar argument shows that $\bar{C}$ screens off B from A. To screen off *means* to make statistically irrelevant. Thus, according to equation (1), the common cause C makes each of the two effects A and B statistically irrelevant to one another. By applying the same argument to equation (2), we can easily see that it entails that the absence of the common cause also screens off A from B.

To make quite clear the nature of the conjunctive fork, I should like to use an example deliberately contrived to exhibit the relationships involved. Suppose we have a pair of dice that are rolled together. If the first die comes to rest with side 6 on the top, that is an event of the type A; if the second die comes to rest with side 6 uppermost, that is an event of type B. These dice are like standard dice except for the fact that each one has a tiny magnet embedded in it. In addition, the table on which they are thrown has a powerful electromagnet beneath its surface. This magnet can be turned on or off with a concealed switch. If the dice are rolled when the electromagnet is on, it is considered an instance of the common cause C; if the magnet is off when the dice are tossed, the event is designated as $\bar{C}$. Let us further assume that when the electromagnet is turned off, these dice behave exactly as standard dice. The probability of getting 6 with either dies is 1/6, and the probability of getting double 6 is 1/36.[24] If the electromagnet is turned on, let us assume, the chance of getting 6 with either die is 1/2, and the probability of double 6 is 1/4. It is easily seen that conditions (1)–(4) are fulfilled. Let us make a further stipulation, which will simplify the arithmetic, but which has no other bearing upon the essential features of the example—namely, that half of the tosses of this pair of dice are made with the electromagnet turned on, and half are made with it turned off. We might imagine some sort of random device that controls the switch, and that realizes this equiprobability condition. We can readily see that the overall probability of 6 on each die, regardless of whether the electromagnet is on or off, is 1/3. In addition, the overall probability of double 6 is the arithmetical average of 1/4 and 1/36, which equals 5/36. If the occurrence of 6 on one die were independent of 6 occurring on the other, the overall probability of double 6 would be $1/3 \times 1/3 = 1/9 \neq 5/36$. Thus the example satisfies relation (5), as of course it must, in addition to relations (1)–(4).

It may initially seem counterintuitive to say that the results on the two dice are statistically independent if the electromagnet is off, and they are statistically independent if it is on, but that overall they are not independent. But they are, indeed, nonindependent, and this nonindependence arises from a clustering of 6's, which is due simply to the fact that in a subset of the class of all tosses the probability of 6 is enhanced for both dice. Thus dependency arises, not because of any physical interaction between the dice, but because of special background conditions that obtain on certain of the tosses but not on others. The same consideration applies to the earlier, less contrived, cases. When the two students each copy from a paper in a fraternity file, there is no direct physical interaction between the process by which one of the papers is produced and that by which the other is produced—in fact, if either student had been aware that the other was using that source, the unhappy coincidence might have been avoided. Likewise, as explicitly mentioned in the mushroom poisoning case—where, to make the example fit formulas (1)–(4), we confine attention to just two of the performers—the illness of one of them had no effect upon the illness of the other. The coincidence resulted from the fact that a common set of background conditions obtained, namely, a common food supply from which both ate. Similarly, in the twin quasar example, the two images are formed by two separate radiation processes that come from a common source, but do not directly interact with each other anywhere along the line.

Reichenbach claimed—correctly, I believe—that conjunctive forks possess an important asymmetry. Just as we can have two effects that arise out of a given common cause, so also may we find a common effect resulting from two distinct causes. For example, by getting results on a roll of two dice that add up to 7, one may win a prize. Reichenbach distinguished three situations: (1) a common cause C giving rise to two separate effects, A and B, without any common effect arising from A and B conjointly; (2) two events A and B that, in the absence of a common cause C, jointly produce a common effect E; and (3) a combination of (1) and (2) in which the events A and B have both a common cause C and a common effect E. He characterized situations (1) and (2) as *open forks*, while (3) is closed on both ends. Reichenbach's asymmetry thesis was that situations of type (2) never represent conjunctive forks; conjunctive forks that are open are always open to the future and never to the past. Since the statistical relations found in conjunctive forks are said



(1) (2) (3)

FIGURE 1

to explain otherwise improbable coincidences, it follows that such coincidences are explained only in terms of common causes, never common effects. In the case of a prize being awarded for the result 7 on a toss of two dice, we do not explain the occurrence of 7 in terms of the awarding of the prize. This is not a mere philosophical prejudice against teleological explanations. Assuming a fair game, we believe, in fact, that the probability of getting a 7 is the same regardless of whether a prize is involved. In situations of type (2), in which there is no common cause to produce a statistical dependency, A and B occur independently; the common effect E, unlike a common cause, does not create a correlation between A and B. This is a straightforward factual assertion, which can, in cases like the tossing of dice, be tested empirically. If, contrary to expectation, we should find that the result 7 does not occur with a probability of $^1/_6$ in cases where a prize is at stake, we could be confident that the (positive or negative) correlation between the outcomes on the two dice was a result of some prior tampering—recall the magnetic dice, where the electromagnet had to be turned on before the dice came to rest to affect the probability of the result—rather than "events conspiring" to reward one player or to prevent another from receiving a benefit. A world in which teleological causation operates is not logically impossible, but our world does not seem, as a matter of fact, to be of such a kind.

In order to appreciate fully the import of Reichenbach's asymmetry thesis, let us look at an initially plausible putative counterexample provided by Frank Jackson.[25] It will be instructive to make an explicit comparison between his example and a bona fide instance of a common cause. Let us begin with the common cause. Suppose that two siblings contract mumps at the same time, and assume that neither caught the disease from the other. The coincidence is explained by the fact that they attended a birthday party and, by virtue of being in the same locale, both were exposed to another child who had the disease. This would constitute a typical example of a conjunctive fork.

Now, with that kind of example in mind, consider a case that involves Hansen's disease (leprosy). One of the traditional ways of dealing with this illness was by segregating its victims in colonies. Suppose that Adams has Hansen's disease (A) and Baker also has it (B). Previous to contracting the disease, Adams and Baker had never lived in proximity to one another, and there is no victim of the disease with whom both had been in contact. We may therefore assume that there is no common cause. Subsequently, however, Adams and Baker are transported to a colony, where both are treated with chaulmoogra oil (the traditional treatment). The fact that both Adams and Baker are in the colony and exposed to chaulmoogra oil is a common effect of the fact that each of them has Hansen's disease. This situation, according

to Jackson, constitutes a conjunctive fork A, E, B, where we have a common effect E, but no common cause. We must see whether it does, in fact, qualify. It is easy to see that relations (3) and (4) are satisfied, for

$$P(A|E) > P(A|\bar{E})$$

and

$$P(B|E) > P(B|\bar{E}),$$

that is, the probability of Adams having Hansen's disease is greater if he and Baker are members of the colony than it would be if they were not. If not both Adams and Baker are members of the colony, it might be that Adams is a member and Baker is not (in which case the probability that Adams has the disease is high), but it might also be that Baker is a member and Adams is not, or that neither of them is (in which cases the probability that Adams has the disease would be very low). The same reasoning holds for Baker, *mutatis mutandis*.

The crucial question concerns relations (1) and (2). Substituting "E" for "C" in those two equations, let us recall that they say, respectively, that A and B are statistically independent of one another, given that condition E holds, and they are statistically indpendent when E does not hold. Now, if A and B are independent of one another, it follows immediately that their negations $\bar{A}$ and $\bar{B}$ are independent; thus relation (1) implies

$$P(\bar{A}.\bar{B}|E) = P(\bar{A}|E) \times P(\bar{B}|E).$$

This tells us, as we saw previously, that E screens off $\bar{A}$ from $\bar{B}$, that is,

$$P(\bar{B}|E) = P(\bar{B}|\bar{A}.E).$$

Let us therefore ask whether the fact that both Adams and Baker are members of the colony (and both are exposed to chaulmoogra oil) would make the fact that Adams did not have Hansen's disease statistically irrelevant to Baker's failure to have that disease. The answer is clearly negative. Among the members of the colony, a small percentage—doctors, nurses, missionaries—do not have Hansen's disease, and those involved in actual treatment of the victims are exposed to chaulmoogra oil. Suppose, for example, that Adams and Baker both belong to the colony and are exposed to chaulmoogra oil, but that Baker does not have leprosy. To make the situation concrete, suppose that there are one hundred members of the colony who are exposed to chaulmoogra oil, and among them are only two medical personnel who do not have Hansen's disease. If Baker has Hansen's disease, the probability that Adams does not have it is about 0.02, while if Baker does not have it, the probability for Adams is about 0.01—a difference of a factor of two. As stipulated in this example, the fact that Adams has the disease has no direct causal relevance to the fact that Baker also has it, and conversely, but given the circumstances specified, they are statistically relevant to one another.

Although we know that A, B, and E do not form a conjunctive fork, let us look also at relation (2). For this purpose, we shall ask whether $\bar{E}$ screens off A and B from each other—that is, whether

$$P(B|\bar{E}) = P(B|A.\bar{E}).$$

Let us suppose, for the sake of this argument, that there is only one colony for victims of Hansen's disease, and that almost every afflicted person belongs to it—indeed, let us assume for the moment that only two people in the world have Hansen's disease who have not yet joined the colony. Thus, if a pair of people are chosen at random, and if not both belong to the colony, it is quite unlikely that even one of them has Hansen's disease. However, among the many pairs not both of whom are in the colony, but at least one of whom has Hansen's disease, there is only one consisting of two individuals who both have this disease. Thus, under our extreme temporary assumption about the colony, it is clear that $\bar{E}$ does not screen off A from B. Given that not both Adams and Baker are members of the colony receiving the traditional treatment, it is quite unlikely that Baker has Hansen's disease, but given in addition that Adams has the disease, it becomes even more unlikely that Baker has it. The assumption that there are only two victims of Hansen's disease in the world who are not members of the colony is, of course, altogether unrealistic; however, given the relative rarity of the disease among the population at large, the failure of screening off, though not as dramatic, must still obtain. We see from the failure of relations (1) and (2) that Jackson's example does not constitute a conjunctive fork. In spite of the great superficial similarity between the mumps and leprosy situations, there is a deep difference between them. This comparison exemplifies Reichenbach's asymmetry thesis.

Although Reichenbach held only that there are no conjunctive forks that are open toward the past, I believe that an even stronger claim is warranted—though I shall merely illustrate it but not try to argue it here. I am inclined to believe that conjunctive forks, whether open or closed by a fourth event, always point in the same temporal direction. Reichenbach allowed that in situations of type (3), the two events A and B along with their common effect E could form a conjunctive fork. Here, of course, there must also be a common cause C, and it is C rather than E that explains the coincidental occurrence of A and B. I doubt that, even in these circumstances, A, B, and E can form a conjunctive fork.

Suppose—to return to the mushroom poisoning example mentioned previously—that among the afflicted troupers are the leading lady and leading man, and that the performance scheduled for that evening is canceled. I shall assume, as before, that the two illnesses along with the common cause form a conjunctive fork. The analysis that shows that the fork consisting of the two illnesses and the cancellation of the performance is not conjunctive is similar to the analysis of the leprosy example. Let us focus upon equation (2), and consider it from the standpoint of screening off. We must compare the probability that the leading lady is ill, given that the performance is not canceled, with the probability that the leading lady is ill, given that the leading man is ill and the performance is not canceled. It is implausible to suppose that the two are equal, for it seems much more likely that the show could go on if only one of the leading characters is ill than it would be if both were ill. It should be recalled that we are discussing a traveling theatrical company, so we should not presume that a large complement of stand-ins is available. Therefore, the performance of the play does not screen off the one illness from the other, and relation (2) in the definition of the conjunctive fork does not hold. One could use a similar argument to show, in this case, that relation (1) is also violated.

I do not have any compelling argument to prove that in the case of the double fork [in the previous figure], A, C, B and A, E, B cannot both be conjunctive. Such combinations are logically possible, for one can find sets of probability values that satisfy the eight relations—four for each fork.[26] Nevertheless, I have not been able to find or construct a physically plausible example, and Reichenbach never furnished one. It would be valuable to know whether double conjunctive forks of this sort would violate some basic physical principle. I do not know the answer to this question.

Reichenbach's principle of the common cause asserts the existence of common causes in cases of improbable coincidences, but it does not assert that *any* event C that fulfills relations (1)–(4) qualifies *ipso facto* as a common cause of A and B.[27] The following example, due to Ellis Crasnow, illustrates this point. Consider a man who usually arrives at his office about 9:00 A.M., makes a cup of coffee, and settles down to read the morning paper. On some occasions, however, he arrives promptly at 8:00 A.M., and on these very same mornings his secretary has arrived somewhat earlier and prepared a fresh pot of coffee. Moreover, on just these mornings, he is met at his office by one of his associates who normally works at a different location. Now, if we consider the fact that the coffee is already made when he arrives (A) and the fact that his associate shows up on that morning (B) as the coincidence to be explained, then it might be noted that on such mornings he always catches the 7:00 A.M. bus (C), while on other mornings he usually takes the 8:00 A.M. bus ($\bar{C}$). In this example, it is plausible enough to suppose that A, B, and C form a conjunctive fork satisfying (1)–(4), but obviously C cannot be considered a cause either of A or of B. The actual common cause is an entirely different event C', namely a telephone appointment made the day before by his secretary. C' is, in fact, the common cause of A, B, and C.

This example leaves us with an important question. Given an event C that, along with A and B, forms a conjunctive fork, how can we tell whether C is a bona fide common cause? The answer, I think, is quite straightforward. C must be connected to A and B by suitable causal processes of the sort discussed in the preceding [part]. These causal processes constitute the mechanisms by which causal influence is transmitted from the cause to each of the effects.

Interactive Forks

There is another, basically different, sort of common cause situation that cannot appropriately be characterized in terms of conjunctive forks. Consider a simple example. Two pool balls, the cue ball and the 8-ball, lie upon a pool table. A relative novice attempts a shot that is intended to put the 8-ball into one of the far corner pockets, but given the positions of the balls, if the 8-ball falls into one corner pocket, the cue ball is almost certain to go into the other far corner pocket, resulting in a "scratch." Let A stand for the 8-ball dropping into the one corner pocket, let B stand for the cue ball dropping into the other corner pocket, and let C stand for the collision between the cue ball and the 8-ball that occurs when the player executes the shot. We may reasonably assume that the probability of the 8-ball going into the pocket is $^1/_2$ if the player tries the shot, and that the probability of the cue ball going into the pocket is also about $^1/_2$. It is immediately evident that A, B, and C do not constitute a conjunctive fork, for C does not screen off A and B from one another. Given that the shot is attempted, the probability that the cue ball will fall into the pocket (approximately $^1/_2$) is not equal to the probability that the cue ball will go into the pocket, given that the shot has been attempted and that the 8-ball has dropped into the other far corner pocket (approximately 1).

In discussing the conjunctive fork, I took some pains to point out that forks of that sort occur in situations in which separate and distinct processes, which do not directly interact, arise out of special background conditions. In the example of the pool balls, however, there is a direct interaction—a collision—between the two causal processes consisting of portions of the histories of the two balls. For this reason, I have suggested that forks that are exemplified by such cases be called *interactive forks*.[28] Since the common cause C does not statistically screen off the two effects A and B from one another, interactive forks violate condition (1) in the definition of conjunctive forks.

The best way to look at interactive forks, I believe, is in terms of spatiotemporal intersections of processes. In some cases, two processes may intersect without producing any lasting modification in either. This will happen, for example, when both processes are pseudo-processes. If the paths of two airplanes, flying in different directions at different altitudes on a clear day, cross one another, the shadows on the ground may coincide momentarily. But as soon as the shadows have passed the intersection, both move on as if no such intersection had ever occurred. In the case of the two pool balls, however, the intersection of their paths results in a change in the motion of each that would not have occurred if they had not collided. Energy and momentum are transferred from one to the other; their respective states of motion are altered. Such modifications occur, I shall maintain, only when (at least) two causal processes intersect. If either or both of the intersecting processes are pseudo-processes, no such mutual modification occurs. However, it is entirely possible for two causal processes to intersect without any subsequent modification in either. Barring the extremely improbable occurrence of a particle-particle type collision between two photons, light rays normally pass right through one another without any lasting effect upon either one of them. The fact that two intersecting processes are both causal is a necessary but not sufficient condition of the production of lasting changes in them.

When two causal processes intersect and suffer lasting modifications after the intersection, there is some correlation between the changes that occur in them. In many cases—and perhaps all—energy and/or momentum transfer occurs, and the correlations between the modifications are direct consequences of the respective conservation laws.[29] This is illustrated by the Compton scattering of an energetic photon off of an electron that can be considered, for practical purposes, initially at rest. The difference in energy between the incoming photon $h\nu$ and the scattered photon $h\nu'$ is equal to the kinetic energy of the recoiling electron. Similarly, the momentum change in the photon is exactly compensated by the momentum change in the electron.[30]

When two processes intersect, and they undergo correlated modifications that persist after the intersection, I shall say that the intersection constitutes a *causal interaction*. This is the basic idea behind what I want to take as a fundamental causal concept. Let C stand for the event consisting of the intersection of two processes. Let A stand for a modification in one and B for a modification in the other. Then, in many cases, we find a relation analogous to equation (1) in the definition of the conjunctive fork, except that the equality is replaced by an inequality:

(9) $$P(A.B|C) > P(A|C) \times P(B|C).$$

Moreover, given a causal interaction of the foregoing sort, I shall say that the change in each process is *produced* by the interaction with the other process.

I have now characterized, at least partially, the two fundamental causal concepts mentioned at the beginning of [section 2]. Causal processes are the means by which causal influence is *propagated*, and changes in processes are *produced* by causal interactions. We are now in a position to see the close relationship between these basic notions. The distinction between causal processes and pseudo-processes was formulated in terms of the criterion of mark transmission. A mark is a modification in a process, and if that mark persists, the mark is transmitted. Modifications in processes occur when they intersect with other processes; if the modifications persist beyond the point of intersection, then the intersection constitutes a causal interaction and the interaction has produced marks that are transmitted. For example, a pulse of white light is a process, and a piece of red glass is another process. If these two processes intersect—that is, if the light pulse goes through the red glass—then the light pulse becomes and remains red, while the filter undergoes an increase in energy as a result of absorbing some of the light that impinges upon it. Although the newly acquired energy may soon be dissipated into the surrounding environment, the glass retains some of the added energy for some time beyond the actual moment of interaction.

We may, therefore, turn the presentation around in the following way. We live in a world which is full of processes (causal or pseudo), and these processes undergo frequent intersections with one another. Some of these intersections constitute causal interactions; others do not. Let us attempt to formulate a principle CI (for causal interaction) that will set forth the condition explicitly:

> CI: Let P_1 and P_2 be two processes that intersect with one another at the space-time point S, which belongs to the histories of both. Let Q be a characteristic that process P_1 would exhibit throughout an interval (which includes subintervals on both sides of S in the history of P_1) if the intersection with P_2 did not occur; let R be a characteristic that process P_2 would exhibit throughout an interval (which includes subintervals on both sides of S in the history of P_2) if the intersection with P_2 did not occur. Then, the intersection of P_1 and P_2 at S constitutes a causal interaction if:
>
> (1) P_1 exhibits the characteristic Q before S, but it exhibits a modified characteristic Q' throughout an interval immediately following S; and
>
> (2) P_2 exhibits the characteristic R before S, but it exhibits a modified characteristic R' throughout an interval immediately following S.

The modifications that Q and R undergo will normally—perhaps invariably—be correlated to one another in accordance with some conservation law, but it seems unnecessary to include this as a requirement in the definition.

This principle, like the principle MT (mark transmission), is formulated in counterfactual terms, for reasons similar to those that induced us to employ a counterfactual formulation in MT. Consider the following example. Two spots of light, one red and the other green, are projected on a white screen. The red spot moves diagonally across the screen from the lower left-hand corner to the upper right-hand corner, and the green spot moves diagonally from the lower right-hand corner to the upper left-hand corner. Let these spots be projected in such a way that they meet and merge momentarily at the center of the screen; at that moment, a yellow spot appears (the result of combining red and green light—mixing colored light is altogether different from mixing colored paints), but each resumes its former color as soon as it leaves the region of intersection. Since no modification of color persists beyond the intersection, we are not tempted to suppose, on the basis of this observation, that a causal interaction has occurred.

Now let us modify the set up. Again, we have the two spots of light projected upon the screen, but in the new situation they travel in different paths. The red spot moves diagonally from the lower left-hand corner to the center of the screen, and then it travels from the center to the upper left-hand corner. The green spot moves from the lower right-hand corner to the center, and then to the upper right-hand corner. Assuming, as before, that the two spots of light meet at the center of the screen, we could describe what we see in either of two ways. First, we could say that the red spot collides with the green spot in the center of the screen, and the directions of motion of the two spots are different after the collision. Second, we could say that the spot that travels from the lower left to the upper right changes from red to green as it goes through the intersection in the middle of the screen, while the spot that travels from lower right to upper left changes from green to red as it goes through the intersection. It seems that each spot changes color in the intersection, and the change persists beyond the locus of the intersection. Under either of these descriptions, it may appear that we have observed a causal interaction, but such an appearance is illusory. Two pseudo-processes intersected, but no causal interaction occurred.

The counterfactual formulation of principle CI is designed to deal with examples of this sort. Under the conditions specified in the physical setup, the red spot moves from the lower left corner to the center and then to the upper left corner of the screen regardless of whether the green spot is present or not. It would be false to say that the red spot would have traveled across the screen from lower left to upper right if it had not met the green spot. Parallel remarks apply, *mutatis mutandis,* to the behavior of the green spot. Similarly, it would be false to say that the color of the spot that traveled from lower left to upper right would not have changed color if it had not encountered the spot traveling from lower right to upper left. CI is not vulnerable to putative counterexamples of this sort.

Examples of another sort, which were presented independently by Patrick Maher and Richard Otte, are more difficult to handle. Suppose (to use Otte's version) that two billiard balls roll across a table with a transparent surface and that they collide with one another in the center, with the result that their directions of motion are changed. This is, of course, a bona fide causal interaction, and it qualifies as such under CI. We are entitled to say that the direction of motion of the one ball would not have changed in the middle of the table if the collision with the second had not occurred. It is easy to see how that counterfactual could be tested in a controlled experiment. Assume, further, that because of a bright light above the table the billiard balls cast shadows on the floor. When the balls collide the shadows meet, and

their directions of motion are different after the intersection. In this case, we would appear to be entitled to say that the direction of motion of the one shadow would not have changed if it had not encountered the other shadow. It looks as if the intersection of the two shadows qualifies as a causal interaction according to CI.

In order to handle examples of this kind, we must consider carefully how our counterfactuals are to be interpreted. This issue arose in connection with the principle of mark transmission (MT) in [part 2], and we made appeal in that context to the testing of counterfactual assertions by means of controlled experiments. We must, I think, approach the question in the same way in this context. We must therefore ask what kind of controlled experiment would be appropriate to test the assertion about the shadows of the colliding billiard balls.

If we just sit around watching the shadows, we will notice some cases in which a shadow, encountering no other shadows, moves straight along the floor. We will notice other cases in which two shadows intersect, and their directions of motions are different after the interesection than they were before. So we can see a correlation between alterations of direction of motion and intersections with other shadows. This procedure, however, consists merely of the collection of available data; it hardly constitutes experimentation. So we must give further thought to the design of some experiments to test our counterfactuals.

Let us formulate the assertion that is to be tested as follows: If shadow #1 had not met shadow #2, then shadow #1 would have continued to move in a straight line instead of changing directions. In order to perform a controlled experiment, we need a situation in which the phenomena under investigation occur repeatedly. Let us mark off a region of the floor that is to be designated as the experimental region. Assume that we have many cases in which two shadows enter that region moving in such a way that they will meet within it, and that their directions of motion after the intersection are different from their prior directions of motion. How this is to be accomplished is no mystery. We could study the behavior of the shadows that occur as many games of billiards are played, or we could simply arrange for an experimenter to roll balls across the table in such a way that they collide with one another in the desired place. Consider one hundred such occurrences. Using some random device, we select fifty of them to be members of the experimental group and fifty to be members of the control group. That selection is not communicated to the experimenter who is manipulating the balls on the table top. When an event in the control group occurs, we simply do nothing and observe the outcome. When an event in the experimental group occurs, we choose one of the entering shadows—call it shadow #2—and shine a light along the path it would have taken if the light had not been directed toward it. This extra illumination obliterates shadow #2; nevertheless, shadow #1 changes its direction in the experimental cases just as it does in the control cases. We have thereby established the falsity of the counterfactual that was to be tested. It is not true that the direction of travel of shadow #1 would not have changed if it had not encountered shadow #2. We have fifty instances in which shadow #1 changed its direction in the absence of shadow #2. The intersection of the two shadows thus fails, according to CI, to qualify as a causal interaction.

As formulated, CI states only a sufficient condition for a causal interaction, since there might be other characteristics, F and G, that suffer the requisite mutual modification even if Q and R do not. In order to transform CI into a condition that is necessary as well as sufficient, we need simply to say that a causal interaction occurs if and only if there exist characteristics Q and R that fulfill the conditions stated previously. It should be noted that the statistical relation (9), which may be a true statement about a given causal interaction, does not enter into the definition of causal interactions.[31]

If two processes intersect in a manner that qualifies as a casual interaction, we may conclude that both processes are causal, for each has been marked (that is, modified) in the intersection with the other and each process transmits the mark beyond the point of intersection. Thus each fulfills the criterion MT; each process shows itself capable of transmitting marks since each one has transmitted a mark generated in the intersection. Indeed, the operation of marking a process is accomplished by means of a causal interaction with another process. Although we may often take an active role in producing a mark in order to ascertain whether a process is causal (or for some other purpose), it should be obvious that human agency plays no essential part in the characterization of causal processes or causal interactions. We have every reason to believe that the world abounded in causal processes and causal interactions long before there were any human agents to perform experiments.

Relations Between Conjunctive and Interactive Forks

Suppose that we have a shooting gallery with a number of targets. The famous sharpshooter Annie Oakley comes to this gallery, but it presents no challenge to her, for she can invariably hit the bull's-eye of any target at which she aims. So, to make the situation interesting, a hardened steel knife-edge is installed in such a position that a direct hit on the knife-edge will sever the bullet in a way that makes one fragment hit the bull's-eye of target A while the other fragment hits the bull's-eye of target B. If we let A stand for a fragment striking the bull's-eye of target A, B for a fragment striking the bull's-eye of target B, and C for the severing of the bullet by the knife-edge, we have an interactive fork quite analogous to the example of the pool balls. Indeed, we may use the same probability values, setting $P(A|C) = P(B|C) = 1/2$, while $P(A|C.B) = P(B|C.A) \simeq 1$. Statistical screening off obviously fails.

We might, however, consider another event C^*. To make the situation concrete, imagine that we have installed between the knife-edge and the targets a steel plate with two holes in it. If the shot at the knife edge is good, then the two fragments of the bullet will go through the two holes, and each fragment will strike its respective bull's-eye with probability virtually equal to 1. Let C^* be the event of the two fragments going through their respective holes. Then, we may say, A, B, and C^* will form a conjunctive fork. That happens because C^* refers to a situation that is subsequent to the physical interaction between the parts of the bullet. By the time we get to C^*, the bullet has been cut into two separate pieces, and each is going its way independently of the other. Even if we should decide to vaporize one of the fragments with a powerful laser, that would have no effect upon the probability of the other fragment finding its target. This example makes quite vivid, I believe, the distinction between the interactive fork, which characterizes direct physical interactions, and the conjunctive fork, which characterizes independent processes arising under special background conditions.[32]

There is a further important point of contrast between conjunctive and interactive forks. Conjunctive forks possess a kind of temporal asymmetry, which was described

previously. Interactive forks do not exhibit the same sort of temporal asymmetry. This is easily seen by considering a simple collision between two billiard balls. A collision of this type can occur in reverse; if a collision C precedes states of motion A and B in the two balls, then a collision C can occur in which states of motion just like A and B, except that the direction of motion is reversed, precede the collision. Causal interactions and causal processes do not, in and of themselves, provide a basis for temporal asymmetry.

Our ordinary causal language is infused with temporal asymmetry, but we should be careful in applying it to basic causal concepts. If, for example, we say that two processes are modified as a result of their interaction, the words suggest that we have already determined which are the states of the processes prior to the interaction, and which are the subsequent states. To avoid begging temporal questions, we should say that two processes intersect, and each of the processes had different characteristics on the two sides of the intersection. We do not try to say which part of the process came earlier and which later.[33] The same is true when we speak of marking. To erase a mark is the exact temporal reverse of imposing a mark; to speak of imposing or erasing is to presuppose a temporal direction. In many cases, of course, we know on other grounds that certain kinds of interactions are irreversible. Light filters absorb some frequencies, so that they transform white light into red. Filters do not furnish missing frequencies to turn red light into white. But until we have gone into the details of the physics of irreversible processes, it is best to think of causal interactions in temporally symmetric terms, and to take the causal connections furnished by causal processes as symmetric connections. Causal processes and causal interactions do not furnish temporal asymmetry; conjunctive forks fulfill that function.

It has been mentioned [. . .] that the cause C in an interactive fork does not *statistically* screen off the effect A from the effect B. There is, however, a kind of *causal* screening off that is a feature of macroscopic interactive forks.[34] In order for ABC to form an interactive fork, there must be causal processes connecting C to A and C to B. Suppose we mark the process that connects C to A at some point between C and A. If we do not specify the relations of temporal priority, then the mark may be transmitted to A or it may be transmitted to C. But whichever way it goes, the mark will not be transmitted to the process connecting C to B. Similarly, a mark imposed upon the process connecting C to B will not be transmitted to the process connecting C to A. This means that no causal influence can be transmitted from A to B or from B to A via C. C constitutes an effective causal barrier between A and B even if A and B exhibit the sort of statistical correlation formulated in (9). The same kind of causal screening occurs in the conjunctive fork, of course, but in forks of this type C statistically screens off A from B as well.

It may be worth noting that marks can be transmitted through interactions, so that if A, C, and B have a linear causal order, a mark made in the process connecting A with C may be transmitted through C to B. For example, if A stands for the impulsion of a cue ball by a cue stick, C for the collision of the cue ball with the 8-ball, and B for the cue ball dropping into the pocket, then it may happen that the tip of the cue stick leaves a blue chalk mark on the cue ball, and that this mark remains on the cue ball until it drops into the pocket. More elaborate examples are commonplace. If a disk jockey at a radio station plays a record that has a scratch on its surface, the mark will persist through all of the many physical processes that take place between the contact of the stylus with the scratch and the click that is perceived by someone who is listening to that particular station.

Perfect Forks

In dealing with conjunctive and interactive forks, it is advisable to restrict our attention to the cases in which $P(A|C)$ and $P(B|C)$ do not assume either of the extreme values of zero or one. The main reason is that the relation

$$P(A.B|C) = P(A|C) \times P(B|C) = 1 \tag{10}$$

may represent a limiting case of either a conjunctive or an interactive fork, even though (10) is a special case of equation (1) and it violates relation (9).

Consider the Annie Oakley example once more. Suppose that she returns to the special shooting gallery time after time. Given that practice makes perfect (at least in her case), she improves her skill until she can invariably hit the knife-edge in the manner that results in the two fragments finding their respective bull's-eyes. Up until the moment that she has perfected her technique, the results of her trials exemplified interactive forks. It would be absurd to claim that when she achieves perfection, the splitting of the bullet no longer constitutes a causal interaction, but must now be regarded as a conjunctive fork. The essence of the interactive fork is to achieve a high correlation between two results; if the correlation is perfect, we can ask no more. It is, one might say, an arithmetical accident that when perfection occurs, equation (1) is fulfilled while the inequality (9) must be violated. If probability values were normalized to some value other than 1, that result would not obtain. It therefore seems best to treat this special case as a third type of fork—the *perfect fork*.

Conjunctive forks also yield perfect forks in the limit. Consider the example of illness due to consumption of poisonous mushrooms. If we assume—what is by no means always the case—that anyone who consumes a significant amount of the mushrooms in question is certain to become violently ill, then we have another instance of a perfect fork. Even when these limiting values obtain, however, there is still no direct interaction between the processes leading respectively to the two cases of severe gastrointestinal distress.

The main point to be made concerning perfect forks is that when the probabilities take on the limiting values, it is impossible to tell from the statistical relationships alone whether the fork should be considered interactive or conjunctive. The fact that relations (1)–(4), which are used in the characterization of conjunctive forks, are satisfied does not constitute a sufficient basis for making a judgment about the temporal orientation of the fork. Only if we can establish, on separate grounds, that the perfect fork is a limiting case of a conjunctive (rather than an interactive) fork, can we conclude that the event at the vertex is a common cause rather than a common effect.[35] Perfect forks need to be distinguished from the other two types mainly to guard against this possible source of confusion.

The Causal Structure of the World

In everyday life, when we talk about cause-effect relations, we think typically (though not necessarily invariably) of situations in which one event (which we call the cause) is linked to another event (which we call the effect) by means of a causal process. Each of the two events in this relation is an interaction between two (or more) intersecting processes. We say, for example, that the window was broken by boys playing baseball. In this situation, there is a collision of a bat with a ball (an interactive fork), the motion of the ball through space (a causal process), and a collision of the ball with the window (an interactive fork). We say, for another example, that turning a switch makes the light go on. In this case, an interaction between a switching mechanism and an electrical circuit leads to a process consisting of a motion of electric charges in some wires, which in turn leads to emission of light from a filament. Homicide by shooting provides still another example. An interaction between a gun and a cartridge propels a bullet (a causal process) from the gun to the victim, where the bullet then interacts with the body of the victim.

The foregoing characterization of causal processes and various kinds of causal forks provides, I believe, a basis for understanding three fundamental aspects of causality:

1. *Causal processes* are the means by which structure and order are *propagated* or transmitted from one space-time region of the universe to other times and places.
2. *Causal interactions*, as explicated in terms of interactive forks, constitute the means by which *modifications in structure* (which are propagated by causal processes) are *produced*.
3. Conjunctive *common causes*—as characterized in terms of conjunctive forks—play a vital role in the *production* of structure and order. In the conjunctive fork, it will be recalled, two or more processes, which are physically independent of one another and which do not interact directly with each other, arise out of some special set of background conditions. The fact that such special background conditions exist is the source of a correlation among the various effects that would be utterly improbable in the absence of the common causal background.

There is a striking difference between conjunctive common causes on the one hand and causal processes and interactions on the other. Causal processes and causal interactions seem to be governed by the basic laws of nature in ways that do not apply to conjunctive forks. Consider two paradigms of causal processes, namely, an electromagnetic wave propagating through a vacuum and a material particle moving without any net external forces acting upon it. Barring any causal interactions in both cases, the electromagnetic wave is governed by Maxwell's equations and the material particle is governed by Maxwell's first law of motion (or its counterpart in relativity theory). Causal interactions are typified by various sorts of collisions. The correlations between the changes that occur in the processes involved are governed—in most, if not all, cases—by fundamental physical conservation laws.

Conjunctive common causes are not nearly as closely tied to the laws of nature. It should hardly require mention that to the extent that conjunctive forks involve causal processes and causal interactions, the laws of nature apply as sketched in the preceding paragraph. However, in contrast to causal processes and causal interactions, conjunctive forks depend crucially upon de facto background conditions. Recall some of the examples mentioned previously. In the plagiarism example, it is a nonlawful fact that two members of the same class happen to have access to the same file of term papers. In the mushroom poisoning example, it is a non-lawful fact that the players sup together out of a common pot. In the twin quasar example, it is a de facto condition that the quasar and the elliptical galaxy are situated in such a way that light coming to us from two different directions arises from a source that radiates quite uniformly from extended portions of its surface.

There is a close parallel between what has just been said about conjunctive forks and what philosophers like Reichenbach (1956, chapter 3) and Grünbaum (1973, chapter 8) have said about entropy and the second law of thermodynamics. Consider the simplest sort of example. Suppose we have a box with two compartments that are connected by a window that can be opened or closed. The box contains equal numbers of nitrogen (N_2) and oxygen (O_2) molecules. The window is open, and all of the N_2 molecules are in the left-hand compartment, while all of the O_2 molecules are in the right-hand compartment. Suppose that there are two molecules of each type. If they are distributed randomly, there is a probability of $2^{-4} = {}^1/_{16}$ that they would be segregated in just that way—a somewhat improbable coincidence.[36] If there are five molecules of each type, the chance of finding all of the N_2 molecules in the left compartment and all of the O_2 molecules in the right is a bit less than 1/1000—fairly improbable. If the box contains fifty molecule of each type, the probability of the same sort of segregation would equal $2^{-100} \approx 10^{-30}$—extremely improbable. If the box contains Avogadro's number of molecules—forget it! In a case of this sort, we would conclude without hesitation that the system had been prepared by closing the window that separates the two compartments, and by filling each compartment separately with its respective gas. The window must have been opened just prior to our examination of the box. What would be a hopelessly improbable coincidence if attributed to chance is explained straightforwardly on the supposition that separate supplies of each of the gases were available beforehand. The explanation depends upon an antecedent state of the world that displays de facto orderliness.

Reichenbach generalized this point in his *hypothesis of the branch structure* (1956, section 16). It articulates the manner in which new sorts of order arise from preexisting states of order. In the thermodynamic context, we say that low entropy states (highly ordered states) do not emerge spontaneously in isolated systems, but, rather, they are produced through the exploitation of the available energy in the immediate environment. Given the fundamentality and ubiquity of entropy considerations, the foregoing parallel suggests that the conjunctive fork also has basic physical significance. If we wonder about the original source of order in the world, which makes possible both the kind of order we find in systems in states of low entropy and the kind of order that we get from conjunctive forks, we must ask the cosmologist how and why the universe evolved into a state characterized by vast supplies of available energy. It does not seem plausible to suppose that order can emerge except from de facto prior order.

In dealing with the interactive fork, I defined it in terms of the special case in which two processes come into an intersection and two processes emerge from it. The space-time diagram has the shape of an x. It does not really matter whether, strictly speaking, the processes that come out of the intersection are the same as the processes that entered. In the case of Compton scattering, for instance, it does not matter whether we say that the incident photon was scattered, with a change in frequency and a loss of energy, or say that one photon impinged upon the electron and another photon emerged. With trivial revisions, the principle CI can accommodate either description.

There are, of course, many other forms that interactions may exhibit. In the Annie Oakley example, two processes (the bullet and the knife-edge) enter the interaction, but three processes (the two bullet fragments and the knife-edge) emerge. We must be prepared to deal with even more complicated cases, but that should present no difficulty, for the basic features of causal interactions can be seen quite easily in terms of the x-type.

Two simpler kinds of interactions deserve at least brief mention. The first of these consists of two processes that come together and fuse into a single outgoing process. Because of the shape of the space-time diagram, I shall call this a λ-type interaction. As one example, consider a snake and a mouse as two distinct processes that merge into one as the snake ingests and digests the mouse. A hydrogen atom, which absorbs a photon and then exists for a time in an excited state, furnishes another.

The other simple interaction involves a single process that bifurcates into two processes. The shape of the space-time diagram suggests that we designate it a y-type interaction. An amoeba that divides to form two daughter amoebas illustrates this sort of interaction. A hydrogen atom in an excited state, which emits a photon in decaying to the ground state, provides another instance.

Since a large number of fundamental physical interactions are of the y-type or the λ-type (see, e.g., Feynman, 1962, or Davies, 1979) there would appear to be a significant advantage in defining interactive forks in terms of these configurations, instead of the x-type. Unfortunately, I have not seen how this can be accomplished, for it seems essential to have two processes going in and two processes coming out in order to exploit the idea of mutual modification. I would be more than pleased if someone could show how to explicate the concept of causal interaction in terms of these simpler types.

Concluding Remarks

There has been considerable controversy since Hume's time regarding the question of whether causes must precede their effects, or whether causes and effects might be simultaneous with each other. It seems to me that the foregoing discussion provides a reasonable resolution of this controversy. If we are talking about the typical cause-effect situation, which I characterized previously in terms of a causal process joining two distinct interactions, then we are dealing with cases in which the cause must precede the effect, for causal propagation over a finite time interval is an essential feature of cases of this type. If, however, we are dealing simply with a causal interaction—an intersection of two or more processes that produces lasting changes in each of them—then we have simultaneity, since each process intersects the other at the same time. Thus it is the intersection of the white light pulse with the red filter that produces the red light, and the light becomes red at the very time of its passage through the filter. Basically, propagation involves lapse of time, while interaction exhibits the relation of simultaneity.

Another traditional dispute has centered upon the question of whether statements about causal relations pertain to individual events, or whether they hold properly only with respect to classes of events. Again, I believe, the foregoing account furnishes a straightforward answer. I have argued that causal processes, in many instances, constitute the causal connections between cause and effect. A causal process is an individual entity, and such entities transmit causal influence. An individual process can sustain a causal connection between an individual cause and an individual effect. Statements about such relations need not be construed as disguised generalizations. At the same time, it should be noted, we have used statistical relations to characterize conjunctive forks. Thus, strictly speaking, when we invoke something like the principle of the common cause, we are implicitly making assertions involving statistical generalizations. Causal relations, it seems to me, have both particular and general aspects.

Throughout the discussion of causality [. . .] I have laid particular stress upon the role of causal processes, and I have even suggested the abandonment of the so-called event ontology. It might be asked whether it would not be possible to carry through the same analysis, within the framework of an event ontology, by considering processes as continuous series of events. I see no reason for supposing that this program could not be carried through, but I would be inclined to ask why we should bother to do so. One important source of difficulty for Hume, if I understand him, is that he tried to account for causal connections between noncontiguous events by interpolating intervening events. This approach seemed only to raise precisely the same questions about causal connections between events, for one had to ask how the causal influence is transmitted from one intervening event to another along the chain. As I argued in [part 2], the difficulty can be circumvented if we look to processes to provide the causal connections. Focusing upon processes rather than events has, in my opinion, enormous heuristic (if not systematic) value. As John Venn said in 1866, "Substitute for the time honoured 'chain of causation,' so often introduced into discussions upon this subject, the phrase a 'rope of causation,' and see what a very different aspect the question will wear" (Venn, 1866, p. 320).

Notes

1. Carnap (1950), section 44.
2. Ibid., sections 50–51.
3. Salmon (1968). Because of this difference with Carnap—that is, my claim that inductive logic requires rules of acceptance for the purpose of establishing statistical generalizations—I do not have the thoroughgoing "pragmatic" or "instrumentalist" view of science Hempel attributes to Richard Jeffrey and associates with Carnap's general conception of inductive logic. Cf. Hempel (1962), pp. 156–63.
4. Salmon (1967), pp. 90–95.
5. See Hempel (1965a), sections 3.2–3.3. In the present essay I am not at all concerned with explanations of the type Hempel calls "deductive-statistical." For greater specificity, what I am calling "statistical explanation" might be called "statistical-relevance explanation," or "S-R explanation" as a handy abbreviation to distinguish it from Hempel's D-N, D-S, and I-S types.
6. Hempel (1962), section 3.
7. Rudolf Carnap (1949).
8. Reichenbach (1949), section 69.
9. Hempel (1962), section 13, and (1965a), section 3.6. Here, Hempel says, "Nonconjunctiveness presents itself as an inevitable aspect of [inductive-statistical explanation], and thus as one of the fundamental characteristics that set I-S explanation apart from its deductive counterparts."

10. See Nelson Goodman (1965), chapter III. I have suggested a resolution in (Salmon 1963) pp. 252–61.
11. Reichenbach (1956) chapter IV.
12. I find the attempts of Harré and Madden (1975) and Wright (1976) to evade this issue utterly unconvincing. It will be evident [. . .] that the problems of explicating such concepts as causal connections, causal interactions, and cause-effect relations cannot be set aside as mere philosophical quibbles.
13. It might be objected that the alternation of night with day, and perhaps Kepler's 'laws,' do not constitute genuine lawful regularities. This consideration does not really affect the present argument, for there are plenty of regularities, lawful and nonlawful, that do not have explanatory force, but that stand in need of causal explanation.
14. Indeed, in Italian, there is one word, *perchè*, which means both "why" and "because." In interrogative sentences it means "why" and in indicative sentences it means "because." No confusion is engendered as a result of the fact that Italian lacks two distinct words.
15. In this latter work (1948), regrettably, Russell felt compelled to relinquish empiricism. I shall attempt to avoid such extreme measures.
16. See (Mackie, 1974) for an excellent historical and systematic survey of the various approaches.
17. (Rothman, 1960) contains a lively discussion of pseudo-processes.
18. For example, our discussion of the Minkowski light cone made reference to paths of possible light rays; such a path is one that would be taken by a light pulse if it were emitted from a given space-time point in a given direction. Special relativity seems to be permeated with reference to possible light rays and possible causal connections, and these involve counterfactuals quite directly. See (Salmon, 1976) for further elaborations of this issue, not only with respect to special relativity but also in relation to other domains of physics. A strong case can be made, I believe, for the thesis that counterfactuals are scientifically indispensable.
19. Zeno's arrow paradox and its resolution by means of the 'at-at' theory of motion are discussed in (Salmon, 1975; 2nd ed., 1980, chapter 2). Relevant writings by Bergson and Russell are reprinted in (Salmon, 1970a); the introduction to this anthology also contains a discussion of the arrow paradox.
20. The probabilities that appear in these formulas must, I think, be construed as physical probabilities—that is, as frequencies or propensities. In [Salmon, 1984] I give my reasons for rejecting the propensity interpretation; hence, I construe them as frequencies. Thus I take the variables $A, B, C, \ldots$ which appear in the probability expressions to range over classes.
21. Reichenbach's proof goes as follows. By the theorem on total probability, we may write;

(a) $$P(A.B) = P(C) \times P(A.B|C) + P(\bar{C}) \times P(A.B|\bar{C})$$

(b) $$P(A) = P(C) \times P(A|C) + P(\bar{C}) \times P(A|\bar{C})$$

(c) $$P(B) = P(C) \times P(B|C) + P(\bar{C}) \times P(B|\bar{C}).$$

By virtue of equations (1) and (2), (a) can be rewritten:

(d) $$P(A.B) = P(C) \times P(A|C) \times P(B|C) + P(\bar{C}) \times P(A|\bar{C}) \times P(B|\bar{C}).$$

Now (b), (c), and (d) can be combined to yield:

(e) $$\begin{aligned} P(A.B) - P(A) \times P(B) = {} & P(C) \times P(A|C) \times P(B|C) + P(\bar{C}) \\ & \times P(A|\bar{C}) \times P(B|\bar{C}) - [P(C) \times P(A|C) + P(\bar{C}) \times P(A|\bar{C})] \\ & \times [P(C) \times P(B|C) + P(\bar{C}) \times P(B|\bar{C})]. \end{aligned}$$

Recalling that $P(\bar{C}) = 1 - P(C)$, we can, by elementary algebraic operations, transform the right-hand side of (e) into the following form:

$$\text{(f)} \qquad P(C) \times [1 - P(C)] \times [P(A|C) - P(A|\bar{C})] \times [P(B|C) - P(B|\bar{C})].$$

Assuming that $0 < P(C) < 1$, we see immediately from formulas (3) and (4) that (f) is positive. That result concludes the proof that inequality (5) follows from formulas (1)–(4).

22. Because only two effects, A and B, appear in formulas (1)–(4), I mention only two individuals in this example. The definition of the conjunctive fork can obviously be generalized to handle a larger number of cases.

23. If other potential common causes exist, we can form a partition, $C_1, C_2, \ldots, C_n, \bar{C}$, and the corresponding relations will obtain. Equation (1) would be replaced by

$$P(A.B|C_i) = P(A|C_i) \times P(B|C_i)$$

and equations (3) and (4) would be replaced by

$$P(A|C_i) > P(A|\bar{C})$$
$$P(B|C_i) > P(B|\bar{C}).$$

24. I am assuming that the magnet in one die does not affect the behavior of the other die.

25. This example was offered at a meeting of the Victoria Section of the Australasian Association for History and Philosophy of Science at the University of Melbourne in 1978.

26. As a matter of fact, Crasnow's example, described in the next paragraph, illustrates this point. In that example, we have two events A and B that form a conjunctive fork with an earlier event C, and also with another earlier event C'. Hence, the four events C', A, B, and C form a double conjunctive fork with vertices at C' and C. In this example, C' qualifies as a bona fide common cause, but C is a spurious common cause. Since C precedes A and B, it cannot be a common effect of those two events; nevertheless, the four events fulfill all of the mathematical relations that define conjunctive forks, which shows that double conjunctive forks are logically possible. If it is difficult—or impossible—to find double conjunctive forks that include both a bona fide common cause and a bona fide common effect, the problem is one of physical, rather than mathematical, constraints. The fact that C occurs before A and B rather than after is a physical fact upon which the probability relations in formulas (1)–(4) have no bearing.

27. In (Salmon, 1980), I took Crasnow's example as a counterexample to Reichenbach's theory; but, as Paul Humphreys kindly pointed out in a private communication, this was an error.

28. I am deeply indebted to Philip von Bretzel (1977, note 13) for the valuable suggestion that causal interactions might be explicated in terms of causal forks. For further elaboration of the relations between the two kinds of forks, see (Salmon, 1978.)

29. For an important discussion of the role of energy and momentum transfer in causality, see (Fair, 1979).

30. As explained in (Salmon, 1978), the example of Compton scattering has the advantage of being irreducibly statistical, and thus, not analyzable, even in principle, as a perfect fork (discussed in a subsequent section of this essay).

31. In (Salmon, 1978), I suggested that interactive forks could be defined statistically, in analogy with conjunctive forks, but I now think that the statistical characterization is inadvisable.

32. In an article entitled "When are Probabilistic Explanations Possible?" Suppes and Zanotti begin with the assertion: "The primary criterion of adequacy of a probabilistic causal analysis is that the causal variable should render the simultaneous phenomenological data conditionally independent. The intuition back of this idea is that the common cause of the phenomena should factor out the observed correlations. So we label the principle the *common cause criterion*" (1981, p. 191, italics in original). This statement amounts to the claim that all common cause explanations involve conjunctive forks; they seem to overlook the possibility that interactive forks may be involved. One could, of course, attempt to defend this principle on the ground that for any interactive cause C, it is possible to find a conjunctive cause C^*. While this argument may be acceptable for macroscopic phenomena, it does not seem plausible for such microscopic phenomena as Compton scattering.

33. The principle CI, as formulated previously, involves temporal commitments of just this sort. However, these can be purged easily by saying that P_1 and P_2 exhibit Q and R, respectively, on one side of the intersection at S, and they exhibit Q' and R', respectively, on the other side of S. With this reformulation, CI becomes temporally symmetric. When one is dealing with questions of temporal anisotropy or 'direction,' this symmetric formulation should be adopted. Problems regarding the structure of time are not of primary concern in this essay; nevertheless, I am trying to develop causal concepts that will fit harmoniously with a causal theory of time.

34. As Bas van Fraassen kindly pointed out at a meeting of the Philosophy of Science Association, the restriction to macroscopic cases is required by the kinds of quantum phenomena that give rise to the Einstein-Podolsky-Rosen problem.

35. It must be an open rather than a closed fork. In suggesting previously that all conjunctive forks have the same temporal orientation, it was to be understood that we were talking about bona fide conjunctive forks, not limiting cases that qualify as perfect forks.

36. Strictly speaking, each of the probabilities mentioned in this example should be doubled, for a distribution consisting of all O_2 molecules in the left and all N_2 molecules in the right would be just as remarkable a form of segregation as that considered in the text. However, it is obvious that a factor of two makes no real difference to the example.

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