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 which bear some sort of cause-effect relation 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 which can constitute the relata. It has long been disputed whether individual events or only classes of events can sustain cause-effect relations. The relation itself has sometimes been taken to be that of sufficient condition, sometimes necessary condition, or perhaps a combination of the two. Some authors have even proposed that certain sorts of statistical relations constitute causal 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 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.

1. Two Basic Concepts

There are, I believe, two fundamental causal concepts which 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 production and propagation, and both are familiar to common sense. 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 starts a forest fire we mean that the electrical discharge produces ignition. 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 which 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. 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 "fired the shot heard 'round the world." 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.

2. Processes

One of the fundamental changes which 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 Bertrand 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 which persist through time. As I shall use 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. Given two
events, in Newtonian mechanics, both the spatial distance and the tem-
poral separation between them were absolute magnitudes. 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. How-
ever, 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 collection of events which bear spacetime relations to one
another. These considerations offer support for what is sometimes
called an "event ontology".

There is, however, another way (developed originally 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 con-
struct the Minkowski light cone—a two-sheeted cone whose surface is
generated by the paths of all possible light pulses which converge upon
that point (past light cone) and the paths of all possible light pulses
which could be emitted from that point (future light cone). When all
of the light cones are given, the entire spacetime 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 gravi-
tational test particles are also processes (see Grünbaum 1973, pp.
735-750). It therefore appears to be entirely legitimate to approach
the spacetime 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".

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

Consider a simple example. Suppose that we have a very large cir-
cular building—a sort of super-Astrodome, if you will—with a spot-
light mounted at its center. When the light is turned on in the other-
wise 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 which makes it rotate. If the light is turned on and set into rotation, the spot of light which 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 which 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 which 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 which 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.

Now, let us consider the spot of light which 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 up. 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 reaches about 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 which is quite analogous to the rotating spotlight. There is a pulsar in the Crab nebula which is about 6500 light years away. This pulsar is thought to be a rapidly rotating neutron star which sends out a beam of radiation. When the beam is directed toward us, it sends out radiation which 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 6500 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. There is no upper limit on the speed of pseudo-processes.

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 which do and those which 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 modifications in that structure. Radio broadcasting presents a clear example. The transmitting station sends a carrier wave which 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 which transmit their own structure 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. Pseudo-processes can do no such things.

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 below, causal processes constitute precisely the causal connections which Hume sought, but was unable to find.5

3. Conjunctive Forks

In order to approach the second basic causal concept, production, it will be necessary to consider the nature of causal forks. There are three types with which we must deal—namely, conjunctive, interactive, and perfect forks. All three types are concerned with situations in which a common cause gives rise to two or more effects which are somehow correlated with one another. The point of departure for this discussion is Reichenbach's principle of the common cause, and his statistical characterization of the conjunctive fork as a device to elaborate that fundamental causal principle (1956, §19).

The principle of the common cause states, roughly, that when improbable coincidences recur too frequently to attribute them to chance, they can be explained by reference to a common causal antecedent. Consider some familiar examples. If two students in a class turn in identical term 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. If two friends, who have spent a pleasant day in the country together, both suffer acute gastrointestinal distress in the evening, we may find that their illnesses can be traced to poisonous mushrooms they collected and consumed. Many such examples have been mentioned in the literature, and others come readily to mind. A recent astronomical discovery, which has considerable scientific significance, furnishes a particularly fine example. The twin quasars 0975+561 A and B are separated by an angular width of 5.7 seconds 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 which was entertained quite early was that twin quasars had somehow (no one really had the slightest idea how this could happen in reality) developed from a common ancestor. Another hypothesis was the gravitational lens effect—that is, that there are not in fact two distinct quasars, but that the two images were pro-
duced from a single body by the gravitational effect upon the light by
an intervening massive object. This result might be produced by a
massive 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 which
would be adequate to produce the gravitational splitting of the image.
This explanation is now, to the best of my knowledge, accepted vir-
tually universally by the experts (Chaffee 1980).

In an attempt to characterize the structure of such examples of
common causes, Reichenbach (1956, §19) introduced the notion of a con-
junctive fork, defined in terms of the following four conditions:

\begin{equation}
P(A \land B \mid C) = P(A \mid C) \times P(B \mid C)
\end{equation}

\begin{equation}
P(A \land B \mid \overline{C}) = P(A \mid \overline{C}) \times P(B \mid \overline{C})
\end{equation}

\begin{equation}
P(A \mid C) > P(A \mid \overline{C})
\end{equation}

\begin{equation}
P(B \mid C) > P(B \mid \overline{C})
\end{equation}

For reasons which will be made clear below, 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

\begin{equation}
P(A \land B) > P(A) \times P(B)
\end{equation}

These relations apply quite straightforwardly in concrete situations.
Given two effects A and B, which 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,
and which 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 simul-
taneous illness, the cause C is the common meal which 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; i.e.,

\begin{equation}
P(X \land Y) = P(X) \times P(Y)
\end{equation}

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 relation-
ship among the conditional probabilities in equation (1) shows. Thus,
in the case of illness, the fact that the probability of both individ-
uals 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. Moreover, let us assume for the sake of simplicity that, in this situation, there are no other potential common causes of severe gastro-intestinal illness. Then, in the absence of the common cause \( C \)--that is, when \( C \) 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,

\[
P(A, B | C) = P(A | C) \times P(B | A, C)
\]

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

\[
P(B | C) = P(B | A, C).
\]

In Reichenbach's terminology, this says that \( C \) screens off \( A \) from \( B \). A similar argument shows that \( C \) 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 which are rolled together. If the first die comes to rest with side 6 on 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 embedded in it. 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 \( \overline{C} \).

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 die is 1/6, and the probability of getting double 6 is 1/36. 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 which controls the switch, and
which realizes this equi-probability 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 × 1/3 = 1/9 ≠ 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. Nevertheless, they are, indeed, non-independent, and this non-independence arises from a clustering of sixes which is due simply to the fact that in a subset of the class of all tosses the probability of 6 is enhanced for each die. The dependency arises, not because of any physical interaction between the dice, but because of special background conditions which obtain on certain of the tosses. 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 example, the illness of one friend 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 which come from a common source, but which 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 which 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 two dice which add up to seven, one may win a prize. Reichenbach distinguished three situations:
(i) a common cause \( C \) giving rise to two separate effects, \( A \) and \( B \), without any common effect arising from \( A \) and \( B \) conjointly; (ii) two events \( A \) and \( B \) which, in the absence of a common cause \( C \), jointly produce a common effect \( E \); and (iii) a combination of (i) and (ii) in which the events \( A \) and \( B \) have both a common cause \( C \) and a common effect \( E \). He characterized situations (i) and (ii) as "open forks", while (iii) is closed on both ends. Reichenbach's asymmetry thesis was that situations of type (ii) never represent conjunctive forks; conjunctive forks which are open are always open to the future and never to the past. Since the statistical relations which are found in conjunctive forks are said to explain otherwise improbable coincidences, it follows that such coincidences are explained only in terms of common causes, never common effects. I believe that an even stronger claim is warranted—though I shall not try to argue it here—namely, 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 (iii), 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 \( E \) which explains the coincidental occurrence of \( A \) and \( B \). I doubt that, even in these circumstances, \( A \), \( B \), and \( E \) can form a conjunctive fork.  

It would be a mistake to suppose that the statistical relations given in conditions (1)-(4) are sufficient to characterize common causes in their role as explanations of correlated effects, as an example, due to Ellis Crasnow, clearly demonstrates. 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 (\( C \)). 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 \( C \).

In order to distinguish the cases in which the event \( C \) in a conjunctive fork constitutes a bona fide common cause from those in which it does not, let us add the condition that there must be a suitable causal process connecting \( C \) with \( A \) and another connecting \( C \) with \( B \). These causal processes constitute the mechanisms by which causal influence is transmitted from the cause to each of the effects. These causal connections are an essential part of the causal fork, and without them, the event \( C \) at the vertex of a conjunctive fork cannot
qualify as a common cause.

4. Interactive Forks

There is another, basically different, type of common cause which violates the statistical conditions used to define the conjunctive fork. 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 which 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 which occurs when the player executes the shot. We may reasonably assume that the probability of the 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 A and B from one another. Given that the shot is attempted the probability that the cue ball will fall into the pocket (appx. 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 (appx. 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 which consist in portions of the histories of the two balls. For this reason, I have suggested that forks which are exemplified by such cases be called interactive forks (see Salmon 1978). Since the common cause C does not statistically screen 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 spatio-temporal 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 which 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 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 which 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. This is nicely illustrated by the Compton scattering of an energetic photon off of an electron which 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.

When two processes intersect, and they undergo correlated modifications which 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:

$$P(A \cap B \mid C) > P(A \mid C) \times P(B \mid C)$$

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 outset. 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 modification 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 which 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—i.e., 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 which 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. If an intersection occurs which does not qualify as an interaction, we can draw no conclusion as to whether the processes involved are causal or pseudo. If two processes intersect in a manner which does qualify as a causal interaction, then we may conclude that both processes are causal, for each has been marked (i.e., modified) in the interaction with the other, and each process transmits the mark beyond the point of intersection. Thus, 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.

5. 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 which 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 \( P(A|C,B) = P(B|C,A) = 1 \). 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
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 which 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.

There is a further important point of contrast between conjunctive and interactive forks. Conjunctive forks possess a kind of temporal asymmetry which was described above. 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 has different characteristics on the two sides of the intersection. We do not try to say which part of the process comes earlier and which later. 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 which are furnished by causal processes as symmetric connections. Causal processes and causal interactions do not furnish temporal asymmetry; conjunctive forks fulfill that function.

6. 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 zero or one. The main reason is that the relation

$$P(A \cdot B | C) = P(A | C) \times P(B | C) = 1$$  \hspace{1cm} (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 which 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—that is by no means always the case—that anyone who consumes a significant amount of the mushroom 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 gastro-intestinal 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. Perfect forks need to be distinguished from the other two types mainly to guard against this possible source of confusion.

7. 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 which stands 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). For another example, we say 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 spacetime 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 which 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 basic laws of nature in ways which 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 Newton'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 which occur in the processes involved are governed—in most, if not all, cases—by fundamental physical conser-
vation laws. Although I am not prepared to argue the case in detail, it seems plausible to suppose that all fundamental physical interactions can be regarded as exemplifications of the interactive fork.

 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 above. In the plagiarism example, it is a non-lawful 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 two participants sup together out of a common pot. In the twin quasar example, it is a de facto condition that the quasar and the elliptic galaxy are situated in such a way that light coming to us from two different directions arises from a source which 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, chap. III) and Grünbaum (1973, chap. VIII) have said about entropy and the second law of thermodynamics. Consider the simplest sort of example. Suppose that we have a box with two compartments connected by a window which can be opened or closed. The box contains equal numbers of nitrogen (N\textsubscript{2}) and oxygen (O\textsubscript{2}) molecules. The window is open, and all of the N\textsubscript{2} molecules are in the left-hand compartment, while all of the O\textsubscript{2} molecules are in the right-hand compartment. Suppose that there are 2 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.\textsuperscript{14} If there are 5 molecules of each type, the chance of finding all of the N\textsubscript{2} molecules in the left compartment and all of the O\textsubscript{2} molecules in the right is a bit less than 1/1000—fairly improbable. If the box contains 50 molecules of each type, the probability of the same sort of segregation would be $2^{-100} \approx 10^{-30}$—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 which 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 is available beforehand. The explanation depends upon an antecedent state of the world which displays de facto orderliness.

 Reichenbach generalized this point in his "hypothesis of the branch structure" (1956, §16). It articulates the manner in which new sorts
of order arise from pre-existing 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 which we get from conjunctive forks, we must ask the cosmologist how and why the universe evolved into a state which is characterized by vast supplies of available energy. It does not seem plausible to suppose that order can emerge except from de facto prior order.

8. 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 above 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 which 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 which 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 and interactive forks. Thus, strictly speaking, when we invoke something like the principle of the common cause, we are implicitly making assertions which involve statistical generalizations. Causal relations, it seems to me, have both particular and general aspects.

Throughout this 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 non-contiguous 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. The difficulty is circumvented, I believe, if we look to processes to provide the causal connections (see Salmon 1977). 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 This material is based upon work supported by the National Science Foundation under Grant No. SES-7809146.

2 See Mackie (1974) for an excellent historical and systematic survey of the various approaches.

3 See Salmon (1980) for a survey of statistical approaches.

4 Some are given in Salmon (1980).

5 In Salmon (1977) I have attempted to provide a detailed analysis of the notion of transmission or propagation of causal influence by causal processes, and a justification for the claim that they legitimately qualify as causal connections.

6 The variables A, B, C which appear in the probability expressions are taken by Reichenbach to denote classes, and the probabilities themselves are understood as statistical frequencies.

7 This is demonstrated by Reichenbach (1956, pp. 160-161).

8 If other potential common causes exist we can form a partition C_1, C_2, C_3 ... and the corresponding relations will obtain.

9 We are assuming that the magnet in one die does not affect the behavior of the other die.

10 The reader is urged to compare the illuminating account of causal
asymmetry offered by Paul W. Humphreys in his contribution to this symposium.

11 I had previously attributed this erroneous view to Reichenbach, but Paul Humphreys kindly pointed out that my attribution was incorrect.

12 For a valuable discussion of the role of energy and momentum transfer in causality, see Fair (1979).

13 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 below).

14 Strictly, each of the probabilities mentioned in this example should be doubled, for a distribution consisting of all O₂ in the left and all N₂ 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 2 makes no real difference to the example.
References


