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The Causal Structure of the World

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Abstract

The aim of this talk unpublished until now, and that constitutes the last contribution of the author to this topic, is to show how Hans Reichenbach's work "Die Kausalstruktur der Welt und der Unterschied zwischen Vergangenheit und Zukunft" ("The Causal Structure of the World and the Difference between Past and Future"), published in 1925, and significantly expanded and revised in the posthumously published book in 1956, *The Direction of Time*, inspires substantially part of the work that is carried out in the domain of causality at the beginning of the twenty first century.

Keywords: Reichenbach - causality - time asymmetry - causal structure of the world

Resumen

El objetivo de esta conferencia inédita hasta ahora, y que constituye el último aporte del autor a esta temática, es mostrar cómo el trabajo de Hans Reichenbach "Die Kausalstruktur der Welt und der Unterschied zwischen Vergangenheit und Zukunft" ("La estructura causal del mundo y la diferencia entre pasado y futuro"), publicado en 1925, y significativamente expandido y revisado en el libro publicado póstumamente en 1956, *The Direction of Time*, inspira sustancialmente parte del trabajo que se está realizando en el ámbito de la causalidad al comienzo del siglo XXI.

Palabras clave: Reichenbach - causalidad - asimetría del tiempo - estructura causal del mundo

The story I want to tell begins a little over 75 years ago, in 1925 to be precise. In that year Hans Reichenbach published one of his most seminal papers, "The Causal Structure of the World and the Difference Between Past and Future." Although he worked on many other topics in the meantime, he had returned to the same set of issues shortly before his death in 1953, as the title of his posthumous book *The Direction of Time* (1956) clearly indicates. Let me make clear from the outset that I am *not* saying merely that philosophers today are working on a topic that Reichenbach treated in the 1925 essay. My aim will be to show how the work contained in his 1925 paper broke the ground for a

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 We would like to thank Merrilee Salmon for giving us this paper to be published for the first time in *Metatheoria*. It is the lecture that her husband, the late Wesley C. Salmon, would have given in a hommage to Reichenbach if he had not lost his life in a car accident. The abstract and the keywords were introduced by the editors.

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development that flourishes today. I intend to show how the work published in 1925–significantly expanded and revised in the 1956 book–substantially informs work being done at the turn of the 21st century. Moreover, it is likely to continue doing so for a long time to come.

Reichenbach's main concern in 1925 centered on causal determinism–the thesis, famously articulated by Laplace, that throughout the history of the universe what happens in the future is rigidly determined by what has happened in the past. He articulates his conception in terms of a fictitious super-intelligence that could infer the entire past history and future development of the world in every detail from a complete knowledge of the laws of nature and a complete description of its state at any one time.[1] Reichenbach believed that the obvious asymmetry of time–the difference between past and future–could not be captured in this sort of deterministic framework. He maintained that, at any given moment, the past is completely determined and the future is at least partly undetermined. He claimed that this distinction could be drawn in terms of certain probabilistic structures, and this led him to formulate a theory of probabilistic causality. "[T]he causal structure of the universe can be comprehended with the help of the concept of *probable determination* alone." ([1925]1978, p. 83, italics in original.) No principle of complete causal determination is required even by classical physics. Notice that Reichenbach's paper precedes by two years the publication of Heisenberg's indeterminacy principle. Reichenbach was not the only indeterminist at the time, but, to the best of my knowledge, he was the first to attempt to define a concept of probabilistic causality–a concept many still hold to be unintelligible. At the same time, it is a topic to which a great deal of current research is devoted.

Let's look at a simple everyday example of a type that plays a prime role in both the 1925 paper and the 1956 book. Although he handled it quite differently in these two works, it is the key to the direction of time in both places. In the book it is called the *conjunctive fork* and it lies at the heart of his *principle of the common cause.* Suppose two people, going out together for a walk in the woods, come upon some mushrooms, which they pick, take home, and eat. That night they both suffer severe gastrointestinal distress. Let's be explicit about the probabilistic character of this example. There's a small probability that, on any given night, either of them might fall victim to some such ailment. Since there are more than a thousand nights in three years, a probability value of 1/1000 does not seem unrealistically small. Moreover, there's an extremely small probability that the two of them would suffer the same sort of illness on the same night just by chance. If the two events were genuinely independent, that probability would be one in a million. (Note that the malady I've chosen is not contagious.) When such an improbable coincidence occurs, we look for a common cause. The mushrooms are prominent among the 'usual suspects.'

[1] His demon would, of course, be a super-mathematician.

As a matter of fact, many so-called 'poisonous' mushrooms do not affect everyone adversely, so there is a probability that someone who eats such a mushroom will not become sick. But given the circumstances and the associated probabilities, we blame the two sickenings on a common cause–the mushrooms–not on a rare (one in a million, or as the British say, a thousand thousand) coincidence.

Improbable coincidences do, of course, happen just by chance. A number of years ago, I cited a particular example. Over a period of many years, I had had only two flat tires on my car.[2] One occurred when I went to the airport in Tucson to pick up a visiting speaker, namely, David Kaplan. The other occurred in Pittsburgh when I was taking a visiting speaker to the airport–you guessed it: David Kaplan. I've not had another since. Ian Fleming's famous spy chaser James Bond remarked, "Once is happenstance, twice is coincidence, and thrice is enemy action." I'll be extremely suspicious if I get a flat *this* weekend.

Getting back to the mushrooms, let A stand for the sickening of one person, B for the sickening of the other person, and C for eating the mushrooms. We have the following probability relations:

$$P(A.B|C) = P(A|C).P(B|C) \tag{1}$$
$$P(A.B|\neg C) = P(A|\neg C).P(B|\neg C) \tag{2}$$
$$P(A|C) > P(A|\neg C) \tag{3}$$
$$P(B|C) > P(B|\neg C) \tag{4}$$

These four relations define a conjunctive fork; they entail (but not obviously)

$$P(A.B) > P(A).P(B) \tag{5}$$

Note that in the example of mushroom poisoning, none of these probabilities takes an extreme value of 0 or 1.

Regarding the direction of time and the difference between past and future, Reichenbach held that conjunctive forks are open only to the future, not to the past. Common causes can explain coincidences. The probabilistic dependency between A and B is absorbed by the common cause, in the sense that, as equations (1) and (2) show, A and B are conditionally independent, given C. Common effects cannot explain coincidences. Consider a dice shooter in a fair game (not craps) in which a double 6 is the winning result. The fact that a win will produce money needed to pay for his mother's life-saving operation E has no effect on the probability of shooting that combination. As Reichenbach puts it in 1925, "[i]t is only the common *cause,* not the common *effect,* that produces a probability relation between simultaneous events" (p. 97).

To the best of my knowledge, Reichenbach never said that, in every triple of events A, B, C satisfying (1)-(4), C is a common cause of A and B. An example given by Ellis Crasnow[3] shows that such a claim would be untenable. It goes

[2] The time span now covers several decades.

[3] Crasnow was a student of Bas van Fraassen at the University of Southern California in the early 1980s.

like this. A certain business executive usually arrives at her office at about 9:00 a.m., makes a cup of coffee, and settles down to read the morning paper. On some occasions, however, she arrives promptly at 8:00 a.m., and on these very same mornings, her secretary has arrived somewhat earlier and prepared a fresh pot of coffee. Almost invariably, on these mornings she is met at her office by an associate who normally works at a different location. Let *A* stand for the fact that the coffee is already made and *B* for the arrival of the associate. As it happens, on the days when the coffee is ready and the associate arrives, she takes the 7:00 a.m. bus (*C*), whereas usually she takes the 8:00 o'clock bus. Although *A, B,* and *C* form a conjunctive fork, taking the earlier bus is not the common cause of the coincidence. There is a common cause, of course, an appointment made by phone on the previous day. The question is how to distinguish those conjunctive forks that characterize common causes from those that don't.

The way I have just characterized the conjunctive fork comes from *The Direction of Time.* Reichenbach's treatment of the same sort of causal structure in the 1925 article is quite different.[4] The earlier treatment doesn't involve numerical values of probabilities in any way. The conjunctive fork is defined *topologically* rather than *metrically.*[5] In this treatment, Reichenbach says that probability relations among *A, B,* and *C* exist pairwise in both directions, i.e., from *A* to *B* and from *B* to *A* (though the values of these two probabilities are not, in general, equal), and so on for the remaining pairs. In the fork that points toward the future–e.g., the dice game mentioned above, where *A* and *B,* are the results of the toss–, probability relations between *A* and *E* and between *B* and *E* exist, but no probability relation exists between *A* and *B.* This is the fundamental difference between the past and the future according to the 1925 article.

The obvious question at this point is how to decide whether a probability relation exists between two classes of events. According to Reichenbach's official definition of probability, a probability is a limiting frequency of the occurrence of a member of one class given the occurrence of a member of the other. In the 1925 article, however, the existence or nonexistence of a probability is actually decided on the basis of the existence or nonexistence of a *causal chain* (pp. 96-97).

Although Reichenbach says almost nothing about causal chains in this article,[6] he did provide a detailed answer in his 1928 book, *The Philosophy of Space and Time.* In his discussion of simultaneity, he equates the notion of a causal chain to the concept of a *signal,* which he defines in terms of *mark transmission* ([1928]1958, p. 138). In this context, mark transmission serves two purposes. First, it is used to define *causal direction,* distinguishing causes from effects; he

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[4] In the 1925 essay, the conjunctive fork is called a "saddle fork."

[5] Even though metrical probability relations are treated later in the same essay, they don't enter the definition.

[6] The only hint he offers is to identify them with *inference chains* (p. 89). Though not very illuminating, this suggests a similarity to the *causal lines* Bertrand Russell introduced in *Human Knowledge: Its Scope and Limits* (1948).

had used the mark method in this way since the early 1920s.[7] I believe that Adolf Grünbaum, in the early 1960s, successfully demonstrated the inadequacy of the mark method for this purpose (1963, pp. 180-188; 2nd ed., 1973, same pagination). Second, it is used to distinguish signals from "unreal sequences" (pp. 147-149). One of Reichenbach's examples, which I have found especially helpful, involves a rotating beacon. Given a lighthouse that sends out beams of light in different directions as it rotates, we can mark any one of those beams by placing a red filter in its path. As the light passes through the filter, it becomes red and remains red from that point on. The mark is transmitted. The beacon also creates a moving spot of light on distant clouds or landscape. This spot cannot *transmit* a mark. You can make it red at any given point of its trajectory, but without additional interventions it will not continue to be red beyond the point of marking. As a graduate student at UCLA, I found this a vivid example, because at each opening of a new gas station or supermarket in LA, search lights were brought out in great numbers to call attention to the event. In *The Direction of Time,* Reichenbach adopted a process terminology, which is preferable to such terms as "causal chains" or "unreal sequences" because of the implication of discreteness of the latter terms. A process, as I see it, is a continuous entity. As John Venn wrote 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 subject will wear" (1866, p. 320). I've used the terms "causal process" and "pseudo-process" to make Reichenbach's distinction between signals and unreal sequences.[8]

Let's return to Reichenbach's conjunctive forks. Chapter 4 of *The Direction of Time* is entitled "The Time Direction of Macrostatistics." Its aim is to show how it is possible to establish time direction without recourse to the microstatistical resources of thermodynamics, particularly entropy. Concepts such as conjunctive forks and causal *betweenness* are used. In the same chapter, Reichenbach introduces a second approach to the problem. It employs the mark method and causal processes as well as purely statistical relations among macro-entities. He limits marks to changes that are produced in irreversible interactions, for example, a red filter can change white light to red, but it cannot change red light to white (by supplying light of varying frequencies). He explicitly acknowledges that he is using the microstatistical concept of time direction that came from the preceding chapter. He claims that the two approaches are, as an empirical matter of fact, extensionally equivalent. He fails, however, to answer the question left over from the 1925 paper, namely, how to tell in which cases probability relations exist. In that paper, the question hinges on the existence or nonexistence of causal chains.

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[7] See Reichenbach ([1924]1969, pp. 117-118).

[8] Russell's concept of a causal line was deeply flawed because of his failure to distinguish causal processes from pseudo-processes. Many pseudo-processes would qualify as causal under Russell's characterization.

Let's return to Crasnow's example. He presents us with two triplets of events that satisfy the statistical conditions for a conjunctive fork. One of them contains an actual common cause of the coincidence; the other does not. The difference is that, in the case of the appointment made by telephone, there are suitable causal processes connecting the coincidental events to the common cause, whereas, in the case of taking the 7:00 a.m. bus, no such causal connections exist. What happens is that the telephone appointment is the common cause of three distinct events, taking the 7:00 o'clock bus, meeting the colleague, and finding the awaiting coffee. It seems to me that causal processes can do the needed job without attributing time asymmetry to them. Basically, I believe, we can use symmetric causal processes to distinguish conjunctive forks representing genuine common cause configurations from those that do not. This is what is required to complete the program of the 1925 paper and to resolve Crasnow's counterexample.

For the initial issue of the *Pacific Philosophical Quarterly* (1980), I contributed a paper entitled "Probabilistic Causality," in which I reviewed the only three reasonably well-developed theories that were extant at that time, namely, those of Reichenbach, I. J. Good (1961-1962), and Patrick Suppes (1970).[9] Good's theory was mathematically formidable, but I was able, without getting into very serious complexity, to show that it was deeply–I would say irreparably–flawed. The theories of Suppes and Reichenbach differed on an extremely fundamental point. Reichenbach attempted to develop a causal theory of time; consequently he could not use temporal criteria to distinguish causes from effects. He used the conjunctive fork for that purpose. Suppes, in contrast, placed temporal indices on his events and required causes to be temporally prior to their effects. In other ways, however, these two theories had much in common. I think both were deeply flawed by a common basic assumption.

The fundamental assumption is that causes must be *positively* statistically relevant to their effects, that is, the probability of the effect must be higher in the presence of the cause than in its absence. This assumption occurs explicitly at the outset in both theories. For example, if exposure to a disease is a probabilistic cause of contracting that disease, then exposure must increase the probability of contracting it. This principle seems too plausible to doubt. However, it was unwittingly called into question by Deborah Rosen, a student of Suppes.[10] It's a simple story. A golfer hits a shot that goes wildly astray, but the ball strikes a tree limb and falls into the hole for a spectacular birdie. Rosen and Suppes originally saw this as a problem of highly improbable occurrences, but it is actually a problem of negative relevance. The ball would much more probably have gone in the hole as a result of a very good shot. This fictitious example has been in the literature for several decades, and it has taken on baroque

[9] The almost complete lack of cross-references indicated that they had been constructed independently of one another.

[10] This example is discussed by Suppes (1970, p. 41).

elaborations in the writings of other authors (especially Good).[11] Not long ago, I heard of an actual case. A golfer made a hole-in-one when his ball bounced off of the putter of a player who was still on the green.

Various exotic examples of putative negative relevance were given in the literature, but it eventually occurred to me that the problem is altogether commonplace. We often speak of someone doing something 'the hard way.' In the game of craps, the shooter who wins is much more likely to do it by throwing 7 or 11 on the first roll than by rolling 4 and making that point. And to make the point by getting double 2, rather than 3 and 1, is again making it 'the hard way.' The fact is that, in many of life's situations, we have more than one way to try to accomplish a goal. One way will have a greater probability of reaching that goal; others have smaller probabilities. Nevertheless, sometimes a less probable alternative yields success. To my mind, the obvious way to deal with all such examples is by requiring that causal processes connect the events in suitable ways. That's the approach I applied to Crasnow's example a few minutes ago.

In order to work out a general theory of causation, it's necessary to analyze more precisely and systematically certain basic causal concepts. To this end, I shall *temporarily* refrain from using the terms "cause" and "effect." I want to begin instead with the concept of *process.* In the most basic sense, a process is something that transpires over a period of time. A material object in motion is a process; so is the propagation of a sound wave or a pulse of light. A moving shadow is a process, so is the image of a golf ball on a TV screen. A material object at rest is a process.[12] Roughly, a process is something that is represented in a spacetime diagram as a line; an event, in contrast, is represented by a point.[13] The essential task is to distinguish pseudo-processes from genuine causal processes. Reichenbach employed the mark method to accomplish this aim. *A process is causal if and only if it has the capacity to transmit a mark.* Thus, a pulse of light emitted from a beacon can, as we have seen, transmit a mark. The moving spot of light it casts upon the clouds is not able to transmit a mark; it is a pseudo-process. A car traveling along a road on a sunny day is a causal process; its shadow is a pseudo-process. If the shadow encounters a utility pole, its shape will be momentarily modified, but it will return to its former shape as if nothing had happened as soon as it passes the post. If the car encounters the pole, it will receive marks that will endure well after it moves beyond the pole or is towed away. Until the early 1990s, I adopted satisfaction of the mark criterion as the basic distinction between causal processes and pseudo-processes.

Marking a process requires a *causal interaction*; this concept needs to be defined. It is based on the geometrical notion of an intersection of *worldlines* of processes (causal or pseudo) in four dimensional spacetime. We can say that *an*

[11] Philosophers have offered various analyses of such examples to show how positive relevance could be restored, but I think they all fail. See Salmon (1984, chap. 7) for details.

[12] An object at rest in one frame of reference will be moving with respect to other reference frames.

[13] The idea of process that I am introducing at this point bears a close resemblance to Russell's causal lines.

intersection of two processes is a causal interaction if and only if each process undergoes a change in the locus of intersection which persists beyond the intersection. Consider two airplanes flying at different altitudes on a sunny day. Suppose that their paths cross. The shadows of the planes will intersect, and in the intersection their shapes will be modified. When the shadows emerge from the superposition they will continue as if nothing had happened. This is not a causal interaction. If, however, the planes were at the same altitude and collided, lasting changes occur (as the recent incident with China reminds us). Such a collision is, of course, a causal interaction.[14]

A third concept is also needed. Reichenbach has written about mark transmission; the concept of *transmission* requires clarification. Somewhat surprisingly, perhaps, this project takes us back about 2500 years to Zeno of Elea and his paradox of the arrow. It seems that Zeno claimed that an arrow, at any moment in its flight, is where it is, occupying a space equal to its size. Since it can't be where it is not, it has no space to move. Moreover, since the moment has no parts, the arrow has no time to move. Therefore, the arrow is always at rest and never moves.[15] Our first temptation might be to invoke the derivative in the infinitesimal calculus, and the resulting well-defined concept of instantaneous velocity. On that basis we could distinguish being at rest at a moment from being in motion at a moment. Russell ([1903]1943) points out, however, that the derivative at a moment is defined in terms of the limit of a sequence of finite motions during finite time intervals–precisely what Zeno claimed to be impossible. This answer thus turns out to beg the question. In its place, Russell articulates the "at-at" theory of motion. Motion of a body consists simply in being *at* certain places *at* corresponding times. The arrow moves from its starting point to the midpoint of its trajectory by being at the intervening points of space at the corresponding moments of time.[16] The question of how it gets from one point to the next is not well posed, since in a continuum there is no next point.

It seems to me that Russell's strategy can be applied to mark transmission. A mark is said to be transmitted by a process by virtue of the fact that it is *at* the appropriate points of the process *at* the appropriate stages of the process without any interactions after the initial interaction that created the mark. For example, the red filter in the beam of light imposes a mark, and no further marking interactions are required to sustain the mark. In contrast, if we mark the moving spot on the wall at one place, it will not remain red as it moves along unless further marking interactions occur.[17]

[14] The word "causal" is redundant; all interactions are causal. Those intersections that fail to qualify as causal are simply intersections.

[15] I say that he seems to have claimed because we must rely on secondary sources. No texts of Zeno have survived.

[16] My reference to the arrow being at a point can be construed in terms of the location of its center of mass.

[17] In conversation in the early 1980s, Nancy Cartwright posed a counterexample that required a counterfactual qualification that I found distressing; see (Salmon, 1984, pp. 148-149) for the example and my response to it.

Very early in the 1990s, a young Australian philosopher, Phil Dowe, published a critique of my process theory of causation. Among other things, he criticized the use of the mark method for identifying causal processes, and he proposed instead that we characterize causal processes in terms of the possession of conserved quantities, for example, linear momentum or electric charge. This modification had several advantages. First, Reichenbach's characterization of causal processes in terms of marks invoked the *capacity* to transmit a mark. This involves the counterfactual claim that many processes are causal even if they are not actually transmitting marks. Dowe's formulation referred to the actual possession of conserved quantities. Second, it avoided another counterfactual I had adopted in order to evade a counterexample posed by Nancy Cartwright. Third, it greatly strengthened the concept of causal interaction. For all of these reasons, I eagerly adopted Dowe's CQ theory (aside from a few quibbles). One major difference remains. I insist that we need the concept of *causal transmission,* whereas Dowe maintains that *possession* of conserved quantities is sufficient. I shall maintain that this difference involves a huge philosophical issue, but before doing so, I want to present systematically the version of the CQ theory that I now hold.

The most basic concept is *causal interaction.* It is fundamental because it can be introduced without using any other causal concept. A causal interaction is an intersection of processes (causal or pseudo) in which at least one conserved quantity is exchanged. That means simply that the incoming process or processes possess different amounts of some conserved quantity. When a moving billiard ball collides with one at rest, linear momentum is exchanged; while at rest, the ball's momentum is zero. In the collision, some or all of the momentum of the moving ball is transferred to the ball that was at rest before the collision. Please note that the concept of a spacetime *intersection* is purely geometric. So also is the concept of a process prior to distinguishing causal from pseudo. Change is also a noncausal notion.[18]

Causal interactions come in three basic patterns. First, in the collision of the two billiard balls, we have two incoming processes and two outgoing processes. This illustrates an X-type interaction. Since this interaction is time-symmetric, designation of a pair of processes as 'incoming' is arbitrary. Another sort of interaction occurs when one process splits in two; for example, when an amoeba splits by fission into two daughter organisms, or when a hen lays an egg. The spacetime diagrams of such examples suggest calling them Y-type interactions. In a temporal mirror image, we have cases in which two processes merge into a single process. A snake ingesting a mouse is an example. The spacetime diagram in this case suggests calling them Y-type interactions. Inasmuch as the mark method seems unable to deal with these latter two types of interactions, I

[18] Pseudo-processes cannot interact because they have no conserved quantities to transfer. Causal processes can intersect without interacting. Light rays, for example, interfere when they intersect, but when they leave the locus of intersection, they continue as if nothing had happened. Their energy, momentum, etc. are no different after the intersection than before.

consider it a distinct advantage of the conserved-quantity approach to be able to handle them straightforwardly.

The concept of causal interaction can be used to define the notion of *causal transmission. A process (causal or pseudo) transmits a conserved quantity between points* P *and* Q *if and only if it possesses the same amount of that quantity at every point between* P *and* Q *without any interactions between those two points.* This expresses the basic idea of the "at-at" theory of causal transmission. The conserved quantity is *at* the appropriate place *at* the appropriate stage in the process.[19] The only causal concept used in this definition is causal interaction.

The concept of transmission enables us to distinguish causal processes from pseudo processes quite simply. *A process is causal if and only if it transmits a conserved quantity.* Although Reichenbach used such terms as "interaction" and "transmission," he never, to the best of my knowledge, provided explicit explications of these concepts. Moreover, from what has already been said, we see that the conserved quantity approach has distinct advantages over the mark method.

I should like to mention three significant philosophical morals that can, I believe, be drawn from this discussion. First, and most significant to my mind, is an answer to David Hume's decisive critique of causation.[20] At this point, I will bring back the terms "cause" and "effect" that I temporarily banished. Recall that Hume, in his examination of cause-effect relations, finds only three features: spatiotemporal contiguity, temporal priority, and constant conjunction. He fails to find any 'secret power' in the cause to produce the effect, or any 'necessary connection' between the cause and the effect. Causation is in the human imagination, not in the physical world. It is a matter of 'habit' and 'custom,' rather similar to Pavlov's famous conditioning of his dogs. After seeing a certain type of event followed regularly by another type, we come to expect one of the second type whenever we observe an event of the first type. To put the matter quite simply, the "connection" Hume sought unsuccessfully is a causal process, the kind of entity that propagates causal influence from one region of spacetime to another. Suppose, for example, that a child hits a pitched baseball that breaks a window in a neighboring house. According to the theory I am proposing, the bat and ball are two separate causal processes that exchange momentum in an interaction, the ball is a causal process that transmits momentum from the collision with the bat, and the ball subsequently interacts with another causal process–the window–which shatters. The causal processes we find in the world provide the connections Hume sought but, as Reichenbach showed, these need not be Humean '*necessary* connections.'

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19 David Fair's 1979 theory of causation as the flow of energy fails to distinguish merely having energy from the transmission of energy.

20 Reichenbach took Hume's problem of induction very seriously, and made a valiant attempt to solve it. I'm not aware that he took Hume's critique of causation as a serious problem. Dowe, also, seems to have little concern with Hume's problem of causation.

Second, we have found two distinct aspects of causal structures. In the first place, we discussed conjunctive forks and causal *betweenness* relations, which are defined strictly in terms of probabilistic relations. In the second place, we dealt with such physical entities as causal processes and causal interactions. Although processes and interactions may be indeterministic–I think they sometimes are–they are not defined probabilistically. In a famous paper, "Causal Relations," Donald Davidson argued, against so-called regularity views, that relations between singular causes and effects cannot be identified with sentential connectives such as "if," "only if," or "unless." I think he was right about this matter, and I would extend his conclusion to probabilistic relations as well. Reichenbach's *probability implication* is strongly related to the material conditional. Although my view goes against current trends, I believe that there is no such thing as probabilistic causality in the strict sense, because the probability relations require supplementation by such physical entities as processes and interactions. Reichenbach evidently regarded probabilistic structures and physical structures as distinct ways of approaching probabilistic causality. I believe that they need to be combined to yield a satisfactory concept of causality. I'd call it "physical (indeterministic) causality" rather than "probabilistic causality." Although I disagree on some details, I consider Phil Dowe's *Physical Causation* (2000) the best exposition of physical causality currently available.

Third, within the past year, I've come to believe that the "cause-effect" terminology is heavily context-dependent–involving human background knowledge, interests, and purposes–but that there is an underlying causal structure involving causal processes and interactions, which is thoroughly objective. In his classic work, *The Cement of the Universe* (1974), J. L. Mackie sought a concept of causality that is entirely "in the objects," in contrast to Hume's, which is "in the imagination." I think he failed because he did not go deep enough. My approach is to define the *complete causal structure* of a spacetime region as the complete set of all causal processes and interactions in that region, along with the conserved quantities they transmit and exchange. It must also include those processes that enter and leave the region, and the conserved quantities they transmit. This structure would include, for example, the collisions of the baseball with molecules in the air as it travels from the bat to the window. These were omitted in my presentation of that example because they were irrelevant to the point I was making. This is a contextual consideration. If, however, we were concerned with the curve ball thrown by the pitcher, these collisions with air molecules would have played an essential role in the discussion.

One prominent way in which contextual considerations enter is in the choice of processes and interactions we take as elementary. For example, to a traffic engineer, a moving–or, in LA a nonmoving–car may be treated as a single process. To an automotive engineer, who is concerned with the way automobiles work, an auto is an extremely complex combination of processes and interactions. Only rarely, if ever, do we seek to represent the complete causal structure in full detail. The parts we want to examine are determined by our interests. However, given a context generated by human knowledge and goals, the relevant cause-effect relations are fully objective.

In concluding this paper, I must issue a couple of caveats. First, in no sense am I attempting a conceptual analysis that would be valid in all possible worlds. I am trying to find the facts of nature that constitute causal relations. I don't even believe that this analysis applies to all domains of our world. In the realm of quantum mechanics, Reichenbach wrote of "causal anomalies," which certainly would not be captured in the framework I'm presenting. Let me mention parenthetically an interesting incident. In 1979, Bernard d'Espagnat published an article in *Scientific American* on problems connected with perplexing quantum correlations. He laid heavy emphasis on the way we use the common cause principle in macroscopic domains, showing how this principle breaks down in quantum mechanics. Although my knowledge of the literature of quantum mechanics was quite restricted, I had never come across explicit reference to the common cause principle. At about that time, Bas van Fraassen and I were engaged in discussions of common causes. I remarked on d'Espagnat's article, and Bas informed me that he had been talking with d'Espagnat shortly before he wrote the *Scientific American* article. I think this incident illustrates to degree to which Reichenbach's book, *The Direction of Time,* had been largely overlooked. I believe it still deserves much more attention than it has received.

Finally, although my tone in this talk has been rather reductionistic, I do not hold a reductionist point of view. It is quite possible that other kinds of causation are present in such areas as psychology and sociology, where human intentions and interrelations are involved. Physical causation must apply at the basic level of perception and communication, but there may be more. I would not commit myself to a reductionist–or antireductionist–viewpoint unless I had at least an acceptable solution to the mind-body problem, and that is something I don't have at present, and I doubt that I'll ever find one in my lifetime.

I very much hope that the story I have told supports my initial claim about Reichenbach's work on causality. His work continues to inform current efforts on the part of those who are committed to indeterministic physical causality and the large numbers of people in many different fields of philosophy or science who deal with probabilistic causality.

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