A QUANTUM THEORY OF CAUSALITY

I

The statement "*x* is the cause of *y*" is usually taken to mean one of two things - either, in common-sense contexts, that the occurrence of *x* is a "jointly-sufficient condition"[1] for the occurrence of *y*, where *x* and *y* are distinct events (e.g. the throwing of a stone and the breaking of a window), or, in scientific contexts, that *x* and *y* both belong to a "causal line"[2] and *x* is antecedent to *y*, where *x* and *y* are states of some system undergoing continuous variation (e.g. the position of the moon yesterday and its position today). There is, it is true, something odd about saying "the moon's being where it was yesterday is the cause of its being where it is today," but this way of putting it is generally avoided by saying instead that the moon obeys a "causal law." Discussions of the philosophy of physics tend to take the latter meaning as paradigmatic; after all, the form of expression of most physical laws is

$$s_t = f(t) \tag{1}$$

where s_t is the state of some physical system at time *t* and *f* is a (preferably continuous) function of time. Time here is the independent variable, which means that its passage is taken as conceptually prior to the variations in state described by the law. This point of view, generalized to an S_t which represents the state of the universe at time *t* and an *F* which represents the totality of causal laws governing all physical processes whatever, leads to the "single formula"

$$S_t = F(t) \tag{2}$$

referred to by Laplace in his classical statement of mechanistic determinism: "We must thus envisage the present state of the universe as the effect of its previous state, and as the cause of that which will follow. An intelligence that could know, at a given instant, all the forces governing the natural world, and the respective positions of the entities which compose it, if in addition it was great enough to analyze all this information, would be able to embrace in a single formula the movements of the largest bodies in the universe and those of the lightest atom: nothing would be uncertain for it, and the future, like the past, would be directly present to its observation."[3]

Whether or not one wishes to assert the possibility, in principle, of carrying out the determinist program, there remains something puzzling about the use of the word "cause" in this connection. Laplace's statement, in fact, seems to fall into two clearly separable parts - the first sentence, which is a comparatively modest remark about causality, and the rest, which is an extravagant dream about determinism, usually associated by us with the idea of "causal law". This latter part does not really have much to do with causality, although it does have something to do with law, and Russell's remark that "the whole conception of 'cause' is resolved into that of 'law'"[4] is, in these circumstances, very apt. I do not agree that the *whole* conception of "cause" can be resolved into that of "law," but at least this conception of it can. What Laplace's demon needs for his predictions is a set of lawlike statements about the way in which certain systems behave when they are left alone. It does not make much sense to ask whether or not this behaviour is "causal" as long as it is continuous, periodic, etc. It is clear that this is the sort of thing Laplace was thinking of because he goes on to say, immediately after the passage quoted above, "The human mind, in the perfection that it has been able to give to the science of

Astronomy, presents a faint outline of such an intelligence."[5]

Taking the first sentence by itself, however, leads to some interesting reflections. "We must envisage *the present state* of the universe as the effect of *its previous state."* It would be unfair to burden Laplace with the consequences of this innocent remark, and I do not wish to pretend that he is responsible for what follows. But, supposing ourselves able to take instantaneous readings of all variables and thus to characterize the present state of the universe, what is "its previous state?" If we were to take seriously Hume's statement that "every effect is a distinct event from its cause,"[6] and to use as the paradigm of a causality statement not Equation (1) but instead the equation

$$s_n = f(s_{n-1}) \tag{3}$$

where *n* assumes discrete values, what would be the consequences for the philosophy of science? This is the question I wish to discuss here. I shall start by considering cases in which it is obviously possible to identify "the previous state", and then go on to deal with apparently continuous variations where this possibility is not so obvious.

II

This new paradigm, which I shall call, for obvious reasons, the "quantum paradigm", is rather closer to the common-sense jointly-sufficient condition meaning of "cause" than it is to the causal-line meaning. Consider the example of the commonsense meaning given at the beginning - the breaking of a window by a stone. At first we might think of the throwing of the stone as the cause, and the breaking of the window as the effect, but this has several disadvantages. First, it leads to awkward questions about whether the throwing of the stone was really the cause - whether it was not really the delinquency of the student who threw it, or the failure of his parents to show him proper affection, and so on into an infinite disjunction. Second, it overlooks an essential part of the situation, namely the availability in the first place of an unbroken window. Third, it focuses attention on something which is very hard to observe or describe, the *breaking* of the window. It is true that we have a preference for the dramatic rather than the prosaic, for *events* rather than *states.* But the breaking of the window is over in a moment, and when the flying glass has settled the significant thing is that it is *broken.* One might say that it had undergone a state-transformation; before, it was whole (s_{n-1}); now it is broken (s_n). Clearly, however, the stone had something to do with it; one might say of it that it provided the condition under which the state-transformation could take place. Perhaps Equation (3) ought to be re-written to take account of this, so that our paradigm for causality-statements would become

$$s_n = f(s_{n-1}, c) \tag{4}$$

where *c* stands for the condition. This will take care of the majority of cases. On the other hand, the extra term could be avoided by taking *s* to refer to the state of the whole system (stone + window).

What kind of function is *f*? It seems likely that, whatever else may be true of it, it will contain elements of probability. Stones do not always break windows, and although one could certainly specify states and conditions (weak glass, stones of certain shapes and sizes thrown at angles and speeds above given values) under which the window would definitely break, and others under which it would definitely not break, still there would be a finite range within which one could only guess whether it would break or not. One might even place bets. For the purposes of insurance against damage to property this probability for the individual event would be concealed under a statistical ratio, but on the level of particular state-transformations such probabilities have become a familiar feature of the world.

In itself this discussion of stones and windows is of little interest to the philosophy of science, but the pattern of causal relation brought out in it is seen to carry over into recent developments in physics. There is a well- known thought experiment due to Landé[7], in which particles in a state *B* arrive at a state-filter which passes only particles in another state *A.* If *A* and *B* are unlike all the particles will be rejected, and if they are like all will be passed, but if they are fractionally like some will be passed and some rejected. Once a particle has passed the *A*-filter, however, it will always pass any *A*-filter it arrives at; similarly, if it is rejected, it will always be rejected. This state of affairs is explained by saying that a particle in state *B* jumps to state *A* (or to state $\overline{A}$) on arrival at the filter; such a state-transformation is of course a *quantum jump.* If the fractional likeness between *A* and *B* is 0.25, say, one fourth of all *B*-particles will pass the *A* -filter, but from the point of view of an individual particle this means that there is a probability of 0.25 that it will jump from state *B* to state *A.* This case is clearly analogous to the macroscopic one already discussed. The filter is the analogue of the stone, i.e. it provides the occasion for the state-transformation of the particle; and there is an irreducible probability-relation between state *B* $(s_n\text{-}i)$ and state *A* (s_n). In neither case is it necessary to talk about the time at which the transformation occurs, since the states between which it takes place are relatively stable and obviously qualify as successive in the histories of the particle and the window. But if one asks for a causal explanation of the present state of the system, the answer can only be that previously it was in another state, but that the supervention of a certain condition occasioned - in fact demanded - a quantum jump. (The previous state is an indispensable part of the cause; nothing is demanded by the filter of a particle already in state *A.* and stones pass freely through windows already broken.)

Let us now consider another familiar case of state-transformation, namely that between the excited state of an atom in a source of radiation and its ground state. Here I should like to digress for a moment in order to deal with an ambiguity of meaning of the word “state.” The Bohr atom (long out of date, it is true, but good enough for the purposes of this discussion) is sometimes said to be like a solar system; the electrons go round and round in their orbits, accompanied by probability-waves or whatever the latest theory demands, and all this activity continues unabated even though, as far as radiation is concerned, the atom has not changed its state at all. On the other hand the state of the real solar system is regarded as changing continuously as, and in fact because, the planets go round and round in their orbits. The two meanings of “state” are quite apparent; in the first case it means “being characterized by a certain set of equations” (the wave-equations for the unexcited atom) and in the second case it means “having parts disposed instantaneously in certain ways with respect to one another”. The first represents a judgement external to the system, the second one internal to it. And yet one can certainly say that the solar system is characterized by a set of equations, namely Kepler’s laws and their subsequent refinements, and according to some physicists it even makes sense to talk about the instantaneous disposition of the parts of atoms with respect to one another. The latter is the more difficult, however, and at this point in the discussion it is not required. Under the quantum hypothesis we would want to maintain that apparently continuous changes in the relative distribution of parts of a system, such changes being internal to the system, do not constitute changes in the state of the system. This means that the solar system has not undergone any state-transformations for a long time. The fact that the equations do not change with time may be taken as an indication of the stability of the system, although as usual the introduction of time brings its own complications. If the equations were changing gradually with time (for example if the system were "running down") it would always be possible, by the introduction of extra factors, to obtain a set of equations which did not change in this way.

To return to the excited atom: in this case the causal relation seems to revert to the form given in (3), since, although there is the required probability-relation between the excited state and the ground state, no known condition has to obtain before the transformation takes place. These transformations are quantum jumps in the purest sense (we might call what happens at the state-filter an "induced" quantum jump). A similar case is encountered in radioactive decay, when the emission of a particle from a given nucleus does not depend on the satisfying of conditions, although the half-life of the isotope in question may be known with great accuracy. One would nevertheless wish to say, I think, that the emission of a photon from a hydrogen atom was causally dependent on its being in an excited state, and that the emission of an alpha-particle from a radium nucleus was causally dependent on the instability of the nucleus. It is true that this is exactly what some physicists have refused to say, maintaining that quantum transitions are in some way acausal; but if the alternatives are to have uncaused events or a new interpretation of the causal relation, it would seem wise to explore the possibilities of the latter before settling for the former. Kant's remark that "everything that happens has its cause"[8] may not be apodictically certain, but it is not something one wishes to abandon casually.

The only strange thing about quantum jumps is why they should happen when they do, and this question can only be asked from a point of view which makes time prior to the events that happen in it. The principal reason for the rejection of the second meaning of "state" at this level of analysis was that it appealed to the notion of time ("instantaneous dispositions"), and in the quantum paradigm there is no reference to time. Everything that happens has its cause, but in the solar system viewed as a whole (to revert to an earlier topic of discussion) nothing happens. From our limited perspective (which takes account of only part of the system, e.g. the alignment of the sun and the moon in eclipses) we observe changes, it is true, but that is only against a background of local state-transformations which provide us with a time-scale. Now I am outside my house, now I am inside; now it is night, now it is day. In the light of transformations such as these (and they are much more basic to our notion of time than the smooth passage of hands round clock-faces) I may be tempted to say that the solar system is in a new state, but it is I who am in a new state. In fact it may be taken as fundamental to the position advocated in this paper that in the last analysis state-transformations determine the passage of time, and not the other way round. Time does not pass for a system which is not undergoing transformation, except from the point of view of another system which is, and consequently it makes no sense to ask why quantum jumps take place when they do. There would be no meaning to "when" if there were no jumps.

III

What then becomes of the notion of "law" into which the second of our meanings of "cause" was to be resolved? Equation (1) now appears to express merely the correlation of the states of one system with the statetransformations of another taken as standard. But the appearance of continuity remains, and the states which are correlated with the standard are still states in the unsatisfactory sense rejected a short while ago. Nobody can deny, however, that such internal rearrangements do take place in otherwise undisturbed systems, and it may be useful to know how they occur. Perhaps the quantum paradigm can be shown to apply to them too. There is really not such a great difference between a change regarded as continuous and a change regarded as proceeding by discrete steps; Ashby remarks that "in natural phenomena the observations are almost invariably made at discrete intervals; the 'continuity' ascribed to natural events has often been put there by the observer's imagination, not by actual observation at each of an infinite number of points."[9] And we are becoming increasingly familiar with processes in which an apparent continuity is known to be the product of very many individual stepwise transformations, in thermodynamics for example. A "causal law" may therefore be nothing but the smoothing over on the macroscopic level of a large number of causal transformations on the microscopic level.

The quantum paradigm, then, appears to be adequate for all the standard cases of causal relation, and to cover also cases in modern physics which under other interpretations seemed to involve acausal relations. It may be asked what difference its adoption would make in our outlook on the world and on science. Its greatest advantage is to be found, I think, in a directing of attention away from notions like time, law, and so on, which seem to be transcendent with respect to our immediate experience and which have always been subjects of controversy, and a directing of attention towards the present state of the world and its possible modifications. One might envisage the universe as something like a rather large pointillist painting; there are so many spots of blue, so many spots of red, and so on, and what the painting looks like at any moment depends on their distribution on the canvas. The spots are to be regarded as movable, however, and the scene is therefore constantly changing. The old emphasis corresponds to a search for regularities in the movement of some spots with respect to each other and the canvas, such movement being thought of as continuous and taking place in a time through which the canvas itself endures. It would make sense, according to this view, to think of some scene as remaining unchanged for a period of time, which of course is to us the normal behaviour of paintings. But it is not the normal behaviour of the universe. What would it mean for all change to cease? It would entail the cessation of the passage of time; as maintained above, time does not pass unless some change takes place.

Even if, to revert to the painting, one were to see the absurdity of the notion of its existing unchanged through time (or even of its needing a canvas), one might still look for continuous functions ("causal laws") relating the movements of the spots to some regular movement - say an oscillation of one spot in a corner - which was taken as establishing a time-scale, and this would be all right as far as it went. But suppose on closer inspection it was found that at least some spots (and possibly the time-determining spot itself) did not move continuously, but jumped from place to place. This would not signal general chaos, since one would not expect to find any particular spot jumping very far, but it might occur to somebody that instead of looking for long-term regularities of an absolute sort he might just as well ask the more limited question about state-transformations: Where can this particular spot jump next, and with what probabilities? In order to find answers to these questions he would have to make very minute observations, but instead of taking readings at long intervals (as judged by what the observer does in between) and plotting "best curves" to fit them, it would be necessary to concentrate on just three states, the last state, the present state, and the next state, as elements of a Markov chain.

One advantage of doing things in this way is that the process is continually self-correcting - the refusal to make long-range commitments prevents extremes of error. Its great disadvantage is that it is so myopic; in squinting at details it is in danger of failing to grasp what is happening to the whole. It may be said that, for the whole, there is no meaning to "the last state, the present state, and the next state;" that in fact the counterpart to Equation (2) with the Equantum paradigm,

$$S_n = F(S_{n-1}) \tag{5}$$

is preposterous and absurd. To this it might be replied that it is no more so than Equation (2) itself, that any causal law (and therefore Equation (2)) can be expressed in terms of discrete state-transformations by taking readings at stated intervals (i.e. whenever some time-determining transformation takes place), and that even the differential calculus does not need the "infinitesimals" of which Berkeley made so much fun, but can conduct all its business in terms of small but finite differences. A literal interpretation of Equation (5) would, of course, be stretching matters somewhat; there is no reason for all the spots to jump together. Even for medium-sized aggregates equations like (1) might be practically more useful than equations like (3), so that there is no danger of the demise of "law". But what a quantum view of causality would insist upon would be the recognition that such equations rested ultimately on equations like (3). The whole is built up out of its details, and if the principles according to which the whole operates can be satisfactorily accounted for in terms of those according to which the details operate then there is no need for transcendent principles. It is the contention of this paper that time can be accounted for in terms of the behaviour of the ultimate constituents of matter, that continuity can be accounted for in terms of discrete stepwise transformations, and that these accounts remove some of the traditional mystification from the problem of causality.

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