with the usual connectives and quantifiers. Such a hope, however, is vain.

Suppose the domain of some discourse is infinite and that the Gs it contains are exactly the Fs together with one individual *a*. Then if most things are G, most things are F, because in the *infinite* case the addition or deletion of just one G cannot make a difference. Analogously, in any infinite domain if most things other than *b* are F then most things are F. For example any set containing most of the nonzero integers contains most of the integers. None of this need be true in finite domains, however: if there are just seven things three of which are F and four, the three Fs and *a*, are G, then most things are G but it is false that most things are F. Now as is well known, we can easily find a set of formulae with no finite model but each of whose *finite* subsets has a finite model. For instance, where n is any finite number, let A_n be a formula asserting the existence of more than n things:

$$\forall x_1 \ldots \forall x_n \exists y(x_1 \neq y \ \& \ldots \& \ x_n \neq y).$$

Then the denumerable set of formulae

$$\{A_1, \ldots A_n, \ldots\}$$

is such a set, and entails the conditional

$$(Mx)(Fx \vee x = a) \longrightarrow (Mx)Fx$$

although clearly no finite subset does. It follows that the classical logic of 'most' cannot be captured in any standard system in which consequence is compact (e.g. because all proofs in it are finite).

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THE CHAOLOGY OF MIND

By Adam Morton

> When an infinitely small variation in the present state may bring about a finite difference in the state of the system in a finite time, the condition of the system is said to be unstable.... the existence of unstable conditions renders impossible the prediction of future events, if our knowledge of the present state is only approximate... It is a metaphysical doctrine that from the same antecedents follow the same consequents.... But it is not much use in a world like this, in which the same antecedents never again concur. James Clerk Maxwell, 1873

MAXWELL's point is that although identical causes have identical effects (in a deterministic world), it does not follow that even very similar causes have even roughly similar effects. Determinism therefore does not entail predictability. His remarks anticipate a flourishing branch of contemporary physics, which has been called Chaology. Moreover, as Maxwell goes on to point out, his remarks apply in a general way to the special case of the relation between mental and physical states of a person. And when one combines the observation that very similar causes may have very different effects with the realization that similarity is relative to a language one is led to see that though two states of the nervous system may be very similar when described neurologically, the differences in their effects may make them very different when described as states of mind. This is in effect a formulation of minimal materialism, or the token identity theory of mind-brain identity.

My aim is to show that the resemblance between unpredictability in deterministic physical systems and token identity theories in the philosophy of mind is no accident. I first show that chaology provides a model for the relation between two vocabularies postulated in token identity theories, and then I argue for the more speculative claim that deterministic unpredictability may be the reason why token identity theories are true.

I Models of Token Identity

Theories such as those of Lewis and Davidson, which postulate that tokens of mental and physical types are tokens of physical, particularly neural, types, can be characterized in terms of three central claims and two less central claims about the relations between two vocabularies, ϕ and ψ, meant to be our stock of physical and mental words respectively. I shall take the tokens which are described by these vocabularies to be states of mind and brain. Similar claims could be made for physical and mental events and properties.

(i) Token identity: Every ψ state is a ϕ state.
(ii) Type non-identity: Classes of states as picked out by the ϕ vocabulary need not coincide with classes picked out by the ψ vocabulary, and vice versa.
(iii) Maxwell's point: Arbitrarily similar ϕ (ψ) states can be very different ψ (ϕ) states.

To these I shall add two more claims. The first is meant to capture part of what Davidson calls the anomalous nature of the mental. And the second gives a constraint on too extravagant formulations of anomalousness.

(iv) Anomalousness: There are no statable laws which reduce all ψ descriptions to ϕ descriptions.
(v) Qualified correlation: In a number of limiting cases one can deduce the ϕ description from the ψ description.

I shall say that vocabularies satisfying these conditions are 'S-related'. (S for supervenience.) The attractions of talking this way in the philosophy of mind are familiar. It would be rather disturbing, though, if mental and physical vocabularies were the only example of vocabularies related in this way.

Analogies of the first two conditions above are satisfied by the standard example, that of symbol-tokens classified in various ways. But even for these two conditions the analogy to mental and neural processes is not very good, for the objects of the descriptions are objects rather than states or events. And the example does not satisfy the remaining three conditions in any very clear way.

Here is a better example. The two vocabularies describe the states of a physical system and the laws which govern its evolution. The "ϕ" vocabulary describes the system at particular times and the laws of its evolution, attributing to it particular precise states ('positions in phase space') and simple classes of states ('geometrically simple regions of phase space'), and also formulating the laws by which one precise state evolves to another. I shall call this the vocabulary of momentary states. The "ψ" vocabulary describes possible patterns of evolution of the system through time, attributing to it geometrically simple trajectories through actual or phase space. A description of the system as following a straight or a cyclic path belongs to the ψ vocabulary. So does a description of it as tracing a path depicting the Eiffel tower or as having a prime number of left-hand turns. I shall call this the vocabulary of trajectories.

It is important to see that the contrast between these two vocabularies is not simply that between states-at-a-time and laws, on the one hand, and trajectories on the other hand. For the distinction is one of descriptive vocabularies rather than of states described, and some states-at-a-time may be defined in terms of trajectories. For example a description of the form 'will begin in n seconds time to follow a trajectory of kind T' or 'might in n seconds follow a trajectory of kind T if . . .', describes a state-at-a-time, but in ψ vocabulary terms. And, similarly, a trajectory-based description of the form 'the path followed according to laws L from initial state S' gives in the ϕ-vocabulary a description of a trajectory.

In the cases I am concerned with the system is deterministic but chaotic. That is, the laws governing the evolution of the system are stated by a theory T and a function D with two features. (a) Determinism: T entails that $D(S, t, t')$ is the exact state of the system at any time t, given as a function of its state S at any earlier time t'. (b) Chaos: with increasing t D takes simple sets of precise states ('geometrically simple regions of phase space') to complex sets which cannot be described by the ϕ vocabulary ('geometrically complex regions of phase space: in the limit regions with fractal boundaries'). In effect, as time goes on sets of arbitrarily similar initial states evolve to more and more diffuse sets of very dissimilar states.

There are many such systems. A simple pendulum swinging from a very slightly oscillated support shows chaotic motion: an infinitesimal alteration of its initial conditions can cause it to follow an entirely different trajectory. The flow of a fluid in a container or around an obstacle is chaotic as soon as any degree of turbulence enters the picture. The motion of colliding billiard balls, those models of determinism, is chaotic given even the slightest gravitational influence from beyond the table.

Given such a system, the descriptions of its states in terms of the vocabulary of momentary states and that of trajectories are S-related. The five conditions are satisfied, as follows:

(i) Token identity: The system at any given time is in a particular token state (a particular point in phase space), which though sometimes definable in terms of trajectories always has a definition as a momentary state.

(ii) Type non-identity: Many geometrically simple classes of trajectories define geometrically complex classes of initial states, and vice versa.

(iii) Maxwell: States which are very similar when described in momentary state terms can be very different when described in terms of the trajectories they lead to.

(iv) Anomalousness: The laws that govern the evolution of the system do not entail laws relating classes of trajectories to classes of initial states.

(v) Qualified correlation: Some classes of trajectories are definable in terms of initial conditions, so some descriptions in terms of trajectories can be unpacked into momentary descriptions.

Exactly similar remarks could be made about trajectories defined in terms of the two vocabularies.

II Dispositions, Tracking States

The relation between initial conditions and trajectories can thus model the relation between physical and mental states postulated by token identity theories. The model is more interesting than that of types and tokens of written characters, for it concerns physical states and their causal properties. As a result it may be of use in exploring the ways in which mental life and neurological functioning may be related. In particular, it seems a good model to use when trying to make precise the ideas of token states and events — essential to most sophisticated materialisms.

But, still, the model may be just a model, whose details reveal nothing about what is modelled. I cannot show conclusively that it is not. But this section and the next are meant to describe a more interesting possibility, that the model may have its roots in some deep and characteristic facts about mind.

To begin, is there any reason to believe that those states of the nervous system which we describe in mental terms have any relation to trajectory-based descriptions of physical systems? I think the case can be made for two kinds of psychological state: dispositions and tracking states.

I shall take dispositions to be states of mind definable in terms of what an agent would do and experience in various possible circumstances. Dispositional descriptions of states of mind are defined in terms of possible patterns of development of actions and experiences-at-a-time, and so they are clearly "trajectories" in relation to instantaneous states of mind. By 'tracking states' I mean those states of mind which represent particular physical objects and facts in such a way that the state may be said to 'track' the object or fact: if the object or fact were to change in specific respects, so would the state. Various tracking states have been studied by Grice, Unger, Goldman, Morton, and Peacocke. Tracking states are also in an obvious way 'horizontal' to momentary states of mind. That is, they are a kind of counterfactual disposition: if the environment [or intention] were different in respect *X* then the state of mind [or action] would be different in respect *Y*. They too are thus trajectory-based. But there is an important difference: the relevant causal influences derive as much from the environment as from the mind or nervous system itself. These are only two of the many kinds of mental state that are plausibly seen as trajectory-like. For states of mind usually concern not what is going on in the person at an instant but what pattern of action, feeling, or thought is being played out over a span of time.

At this point I must assume a limited token identity of mind and brain, in effect assumptions (i) and (iv) above. Given these, it follows that each state of mind at a time can be identified with a state of the nervous system. *Then* dispositions, related to them as trajectories to momentary states, are in fact trajectory-based states of a physical system, the brain. And tracking states are trajectory-based on momentary patterns of firing of neurons we see that the states of the nervous system studied by neurophysiology are based on momentary patterns of firing of neuros we see that neurological and psychological descriptions are ϕ and ψ vocabulary descriptions of a physical system as described in the previous section. And therefore *if* the system is deterministic but chaotic, the token identity is accompanied by a type non-identity.

Is the system chaotic? Most sufficiently complex physical systems are, and the complexity of the nervous system is astounding. And when we consider systems consisting of the nervous system and parts of the environment, chaotic evolution becomes inevitable. The appearance of chaotic evolution in the working of the nervous system is so safe an assumption, in fact, that what needs explanation is its stability, the extent to which later states of mind and brain *are* predictable in terms of earlier ones. People remember much of what they experience, carry out chains of reasoning in a determinate way, and so on. Not without exception, but regularly enough for it to be remarkable that a system of so many parts interacting in so many ways and subject to so many forces should be even to this degree predictable.

Now the really interesting questions open up, and the answers to them are not at all obvious. What kinds of chaos do neural systems exhibit? Which of these kinds are relevant to states of mind? Answering these would take us a small way towards answering the most basic and important question about mind and body: which neural kinds are mental kinds?

III Chaotic Explanation

There are many ways in which a physical system can be unpredictable. One easily imagined way is illustrated by a sphere falling onto a sharp spike and being deflected to right or left until it meets another spike further down, and so on. Here although the system is deterministic the dependence on the exact point of impact between sphere and spike is so delicate that the system evolves as if it made a random choice at each impact. This is one kind of deterministic unpredictability. Many other physical systems although physically very different have just this kind of unpredictability. But it is fairly clear that it is not this kind of unpredictability that we can expect to find in the psychologically relevant functioning of the nervous system. It doesn't capture the mix of stability and chaos typical of mind, either in its internal evolution or in its response to the enviroment.

To make things a bit more definite, suppose that one was trying to give necessary conditions for a state of the nervous system to be a tracking state of mind. The first thing to note is that tracking states exhibit to a high degree the paradoxical predictability-within-chaos of mind-bearing brains: as the state of some external object changes (for example) the perceptual state of the observer changes accordingly, but between the external object and the perceptual state there is no direct linkage but a complicated, unpredictable and easily diverted network of causal paths. This seems to me to fit very naturally ito what is becoming the standard typology of chaotic systems. They are usually classified in terms of the connections between their 'control parameters' and their 'attractors'. Control parameters describe causal influences from outside the system and quantifiable differences from physically similar systems exhibiting different patterns of evolution. Attractors are regions of phase space into which all sufficiently near states of the system eventually evolve. The system is classified in terms of the way in which the values of the control parameters affect the resulting set of attractors.

Tracking states fit easily into this style of analysis. The control parameters are set (in part) by the states of the environment, e.g. by the location of a perceived object. The attractors of the system are stable perceptual states, for example those registering the locations of perceived objects. Thus each perceptual state corresponds to a large class of neural states — the attractor — whose boundaries are often very complex. Given a specific value of the control parameters and a nervous system in a wide but not universal set of initial states — e.g. an object perceived under normal conditions by an observer — the system will settle down to a state within the corresponding attractor — e.g. the appropriate perceptual state will result.

Putting things this way does not give any laws connecting perceptual situation and perceptual state, or help determine which neural states are perceptual tracking states. What it does is to reveal that the explanatory strategy employed in chaology subsumes as a special case differential explanation, the pattern of explanation appropriate to tracking states. And this does suggest — only suggest — that the vocabulary and methods being developed to classify and understand chaotic systems may be part of what we need to understand how states of the nervous system can be states of mind. For one thing, in producing explanations and something like predictions within a context of essential unpredictability chaology wrestles with some of the problems facing psychological explanation. And faced with the general problem of relating patterns of activity over time — as many psychological states surely are — to instantaneous states, in the presence of a combination of rough overall predictability and small-scale chaos, the study of the behaviour of essentially unpredictable physical systems is too promising a tool to ignore.[1]

[1] The Maxwell quotation is from a lecture reprinted in Campbell and Garnett [1]. It was brought to my attention by Professor Michael Berry, the coiner of the term chaology, whose writings and conversation introduced me to the subject. Tritton [8] and Crutchfield and others [3] explain the main points of chaology. For a thorough exposition see Schuster [7], and for a suggestion of its importance to philosophy see Hunt [6]. The definition of determinism should really be vastly more involved: see Earman [4]. The possible use of my model to clarify the ideas of a state and an event was suggested to me by Chris Allman's PhD thesis (Bristol 1987). Ideas like those of my last section are found in Harth [5], pp. 208–14. For more on neural states as points in a phase space see Churchland [2]. I owe the term 'minimal materialism' to Pascal Engel. David Hirschmann has given me much advice and encouragement, Marie McGinn caused some last-minute revisions, and the Editor pointed out a serious mistake.

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References

[1] Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell*, London: Macmillan, 1882.
[2] Paul Churchland, 'Phase-Space Representation and Coordinate Transformation', *Behavioral and Brain Sciences* 9 (1986) 93–4.
[3] James P. Crutchfield, J. Doyne Farmer, Norman H. Packard, and Robert S. Shaw, 'Chaos', *Scientific American* 255 (1986) 46–57.
[4] John Earman *A Primer on Determinism*, Dordrecht: Reidel, 1987.
[5] Erich Harth *Windows on the Mind*, Brighton: Harvester, 1982.
[6] G. M. K. Hunt 'Determinism, Probability and Chaos', *Analysis* 47.3 (June 1987) 129–33.
[7] Heinz Georg Schuster, *Deterministic Chaos*, Weinheim: Physik-Verlag, 1984.
[8] David Tritton 'Chaos in the swing of a pendulum', *New Scientist* 111 (1986) 37–40.

THE WATERFALL ILLUSION

By Tim Crane

IF you stare for a period of time at a scene which contains movement in one direction, and then turn your attention to an object in a scene which contains no movement, this object will appear to move in the opposite direction to that of the original movement. The effect can be easily achieved by attaching a piece of paper with a spiral drawn on it to the spinning turntable of a record player, and then turning the turntable off while continuing to look at the spiral (see Frisby 1979, pp. 100–101 for a detailed description of how to bring this about). But the illusion of movement can also occur when looking at a waterfall, for instance, and turning one's attention away from the waterfall to a stationary object such as a stone; hence its name — the 'Waterfall Illusion'.

The effect is quite striking, and not difficult to achieve. But the above description is not quite right. For although the stationary object *does* appear to move, it does not appear to move relative to the background of the scene. That is, there is a clear sense in which it also *appears to stay still* (see Blakemore 1973, p. 36). There is a distinct appearance of lack of motion as well as motion. Understandably enough, many find this aspect of the illusion quite extraordinary; John Frisby writes that

> although the after-effect gives a very clear illusion of movement, the apparently moving features nevertheless seem to stay still! That is, we are still aware of features remaining in their 'proper' locations even though they are seen as moving. What we see is logically impossible! (Frisby 1979, p. 101)