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CURIE'S PRINCIPLE

ABSTRACT. A reading is given of Curie's Principle that the symmetry of a cause is always preserved its effects. The truth of the principle is demonstrated and its importance, under the proposed reading, is defended.

> "As far as I see, all *a priori* statements in physics have their origin in symmetry."
> (Weyl, *Symmetry*, p. 126)

1. INTRODUCTION[1]

In 1894 Pierre Curie published a paper in which he stated the principle that the symmetry of a cause is always preserved in its effects. The proof of the principle is simple, yet far from being recognized as an important mathematical truth with wide-ranging applications in physics, when it receives any discussion at all, it is either dismissed out of hand or allotted the status of a mere methodological guide. Even as a methodological guide it is alleged to apply only in deterministic contexts, and hence to hold little interest for today's physics. Here are some pronouncements that are typical of the literature.

> Apart from being logically incorrect, [Curie's Principle] is in obvious contradiction with empirical evidence. (Radicati 1987, 202)

> What is to be said of this fundamental, profound principle that an asymmetry can only come from an asymmetry? The first reply is that *qua* general principle it is most likely false and certainly untenable. (van Fraassen 1989, 240)

> Curie's putative principle (even in my formulation, which did not use causal terms) has no fundamental ontological status ... it betokens only a thirst for hidden variables, for hidden structure that will explain, will answer *why?* – and nature may simply reject the question. (van Fraassen 1991, 24)

Grounds given for rejecting the principle are typically one or more of the following:

(i) the principle purports to be *a priori* but actually rules on an empirical question;

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(ii) the principle is simply false, since nowadays physicists recognize many phenomena which spontaneously break the symmetry of the preceding conditions;
(iii) the principle – even if it is true for deterministic theories – has no application in indeterministic contexts; and finally,
(iv) the principle, if interpreted in such a way as to make it true, is empty.

I will argue *contra omnes murmurantes*:

(i) that the principle, properly understood, is necessarily true;
(ii) that instances of (so-called) 'spontaneous symmetry breaking' are not counterexamples to it;
(iii) that even in the context of indeterminism, it remains a powerful heuristic; and finally,
(iv) that it has important and far-reaching consequences in physics and in the philosophy of science quite generally.

Recognizing the truth of the principle requires properly understanding it, and this in turn requires appreciating Curie's basic insight into the physical significance of the symmetries of a set of laws and the states they relate. It is an insight well worth appreciating, for the physical and philosophical rewards are great, and some of these will be indicated in what follows. Let's turn to the principle to see what all of the fuss is about.

2. THE PRINCIPLE

A physical theory specifies what sorts of objects there are and how they are related to one another, so theories in physics – at least in part – describe structures. Any structure uniquely determines a group of transformations called its symmetry group, and the study of such groups is the mathematical theory of symmetry. It is a particularly elegant theory in that the physically interesting relations between structures receive an exceedingly simple expression in terms of relations between their symmetry groups, and all of the important particular truths about structures can be derived from simple principles relating their symmetries. Curie's Principle is such a principle. Curie states it several times in his paper departing little from the formulation given in the first paragraph:

When certain effects show a certain asymmetry, this asymmetry must be found in the causes which gave rise to them. (Curie 1894, 401)

What the principle says depends crucially on how the terms 'cause' and 'effect' are understood, so bear with me through the definitions; exegetical support for the reading will be given in Section 9. Let A and B be families $\{A_1, A_2 \ldots\}$ and $\{B_1, B_2 \ldots\}$ respectively, of mutually exclusive and jointly exhaustive event types, and let the statement that A is a *Curie-cause* and B its *Curie-effect* mean that the physical laws provide a many-one mapping of A into B, or – more simply – that (relative to the laws) A determines B.[2] A and B may be different aspects of the total state of one system at a single time, or total states of a system at two different times. Curie-causes (and effects) relate to their specifications as physical quantities relate to their values. Consider, for example, the Boyle-Charles law relating the pressure and volume of an ideal gas to its temperature: $PV = kT$. The product of the pressure and volume is, in this instance, the Curie-cause, the temperature is its Curie-effect, and particular values of the two which satisfy the laws are specifications of the same. Similarly, consider the state of an isolated Newtonian system at two different times. The Newtonian dynamical laws are deterministic, so the prior state is the Curie-cause, the later one is its effect, and pairs of particular states which satisfy the equations are specifications. In what follows, I will use subscripts to distinguish Curie-causes and effects from specifications, so $\langle A, B\rangle$ will denote a Curie-cause and -effect, whereas $\langle A_i, B_i\rangle$ will denote one of its specifications.

Now, let us call the symmetries common to all specifications of some Curie-cause its *characteristic symmetries*, and let us call *idiosyncratic* those transformations that are symmetries of some but not all specifications. In the case of the Boyle-Charles law above, transformations under which all specifications of the values of pressure and volume are invariant, e.g., spatial reflections or permutations of the value of some unrelated parameter, are characteristic symmetries of the Curie-cause. By contrast, transformations under which only some specifications are invariant, are idiosyncratic symmetries of those specifications. Exchange of the values of temperature and pressure (in standard units), for example, is an idiosyncratic symmetry only of states for which the two happen to be equal. Likewise, in the case of the Newtonian dynamical laws, transformations under which all states are invariant, e.g., simple spatial displacements, are characteristic symmetries of the Curie-cause, whereas transformations under which only some states are invariant, e.g., exchange of values of mass and acceleration, are idiosyncratic symmetries of those states. I propose that we interpret 'cause' and 'effect' in Curie's statement of his principle as Curie-cause and Curie-effect. The content of the principle, then, is that all characteristic symmetries of a Curie-cause are also characteristic symmetries of its effect.

Equivalently,

if T is an idiosyncractic *asymmetry* of *any* specification of a Curie-effect, then it is also an idiosyncratic asymmetry of some specification of the corresponding Curie-cause.[3]

3. THE PROOF

The proof of the principle follows almost immediately from the definitions in the preceding section. The laws of a deterministic theory enable the Curie-effect B to be derived from the cause A, and can be represented as a mapping of the set of possible specifications of A into the set of possible specifications of B, equivalent to a set (usually infinite) of ordered pairs $\langle A_i, B_i\rangle$ where each $\langle A_i, B_i\rangle$ is a solution to the laws. If $\langle A_i, B_i\rangle$ is such a pair and T is a transformation which acts on A and B, then T takes $\langle A_i, B_i\rangle$ onto $\langle TA_i, TB_i\rangle$. Now, suppose Curie's principle isn't true. Then there is some T, and some pair of solutions of the laws $\langle A_i, B_i\rangle$ and $\langle TA_i, TB_i\rangle$ such that $TA_j = A_j$ but $TB_j \neq B_j$.[4] But the laws are deterministic, so any Curie-cause has only one physically possible effect among the B's and it follows – contrary to the hypothesis – that $TB_j = B_j$, and Curie's Principle is true after all. If A is a Curie-cause of B and T is a characteristic symmetry of A (i.e. if it acts as the identity on each specification A_i of A), it had better act as the identity on each B_i as well.

Let me emphasize that the asymmetries in question are characteristic; T is a characteristic symmetry of A *iff* it is a symmetry of each of the A_i's (i.e., *iff* for all A_i, $(TA_i = A_i)$), and it is a characteristic symmetry of B *iff* it is a symmetry of each of the B_i's. If this is not kept in mind, there is a temptation to think that cases like the following provide counterexamples: consider a world consisting of two types of particle, bald and hairy, governed by deterministic dynamical laws which prescribe that all hairy particles decay into bald ones, but bald ones never decay into hairy ones. Take as the Curie-cause partial state-descriptions of the form

$$\langle \text{ \# of hairy particles present, \# of bald particles present} \rangle$$

and consider the transformation T that replaces all bald particles with hairy ones and hairy particles with bald ones

$$T : \langle m, n\rangle \rightarrow \langle n, m\rangle.$$

Now, the state description $A_1 = \langle 3, 3 \rangle$ nomologically determines $B_1 = \langle 0, 6 \rangle$, and T is a symmetry of A but not a symmetry of B.[5] This is correct, but it does not constitute a counterexample to Curie's Principle because T is not a *characteristic* symmetry of A, it is merely an idiosyncratic symmetry of A_1. The A_i's are essentially *ordered* pairs, for they are not all invariant under exchange of bald and hairy particles; having 6 bald and 0 hairy particles is quite different from having 0 bald and 6 hairy ones.

It may still seem that I have pulled a rabbit out of a hat: I have purported to show that it is impossible to write down a set of deterministic equations that carries the state of a system characterized by certain characteristic symmetries onto a state that lacks those symmetries. Even if this is plausible enough with respect to non-geometric transforamtions like the one above, one might expect geometric transformations to provide counterexamples. For the sake of uniformity in talking about geometric transformations, and for reasons that will be given in Section 4, I will restrict attention to the generally covariant formulations of theories and I will assume that the transformations in question are manifold *automorphisms*, i.e. one-one suitably continuous and differentiable mappings of a manifold M into M. A system of equations is *covariant* under a transformation T just in case for any $\langle A, B \rangle$ that is a model of the equations, $\langle TA, TB \rangle$ is a model as well; and a system of equations is *generally covariant* just in case it is covariant under arbitrary manifold automorphisms.[6] No generality is lost because all theories can be given a generally covariant formulation and any transformation can be represented as a manifold automorphism.[7]

Now, imagine a universe which exists for exactly a minute and consists of a sphere which gradually deforms into an ellipse; surely it is possible to write down a deterministic equation describing the evolution of the sphere. Try to do it, however, and you will find that you will need to include a parameter which takes different values for different directions in space, i.e. a parameter whose value is not invariant under arbitrary spatial rotations. You will need to do so because you will need to distinguish the direction along which the sphere elongates. This is precisely to recognize a characteristic asymmetry in the Curie-cause of the elongation of the sphere. Nothing very mysterious is going on here: if A is the Curie-cause of B, then A nomologically determines B. This means that there is a many-one mapping from the set of specifications of A into the set of specifications of B, so different B_i's always (i.e. in all physically possible worlds) 'come from' different A_i's. From this it follows straight-away that the intrinsic asymmetries of B are also intrinsic asymmetries of A.[8]

4. INTERPRETATION OF THE PRINCIPLE

Let me spell this out in a way that brings out the physical significance of the symmetries of a set of equations: instead of thinking of them as automorphisms of the set of solutions, we should think of them as the set of transformations among the values of relevant parameters which preserve their truth. The symmetries of a set of equations determining one among a family B of alternatives, then, correspond physically to either

(i) permutations of the values of B-irrelevant parameters, or
(ii) irrelevant permutations of B-relevant parameters, i.e. transformations which either map them onto themselves or are accompanied by compensating transformations in the values of other parameters in such a way as to preserve the relation described by the law.

The key to understanding Curie's Principle is to focus on the contrapositive; transformations which *aren't* symmetries correspond physically to relevant permutations of the values of relevant parameters. This is easy to see in the case of non-geometric asymmetries, since these correspond to the transformations of values of parameters in the equation expressing the laws in question, but it has not always been so transparent in the case of geometric symmetries. The problem is that if dynamical theories are formulated in their traditional coordinate-dependent manner and geometric transformations are represented as transformations between coordinate-systems, T may be an asymmetry of the laws determining B, even though no T-asymmetric parameter appears in the B-determining equations. This, combined with the historical confusion about the precise nature of the coordinate-dependence, obscured the physical significance of geometric transformations for generations. It is only in hindsight and by concentrating on their coordinate-*in*dependent (i.e. generally covariant) formulations that it becomes clear that geometric asymmetries of a set of B-determining laws can be understood in precisely the same manner as their non-geometric asymmetries, viz. as relevant permutations of the values of B-relevant parameters. And this is because it is only in the generally covariant formulations that the geometric asymmetries of the laws change the value of some parameter in the B-determining equations.

A slightly more detailed discussion is given in the appendix, but a quick example will help to illustrate the kind of confusion encouraged by the coordinate-dependent style of formulation. Consider an isolated Newtonian system consisting of a ball at rest on a frictionless surface. Let A_1 be the coordinate description of the state of the ball at a time t_1 and B_1 its state one minute later at t_2 relative to a coordinate system with respect to which the ball is at rest. Suppose that the ball remains isolated in the interim. $\langle A_1, B_1 \rangle$ is a solution to Newton's laws, and since the laws are deterministic, A_1 is the Curie-cause of B_1. Now, consider the coordinate transformation T which takes every point (x, y, z, t) onto the corresponding point $(x, y, z + at^2, t)$. T carries $\langle A_1, B_1 \rangle$ onto $\langle TA_1, TB_1 \rangle$ which has the ball spontaneously accelerating in the z direction with no force acting on it, so although $\langle A_1, B_1 \rangle$ is a solution to the laws, $\langle TA_1, TB_1 \rangle$ is not. The situation is usually described by saying that Newton's laws hold 'relative to' the first coordinate system but not 'relative to' the second, and hence are not covariant with respect to transformations between the two. A better way to describe it is to say that there is some dynamically relevant difference between $\langle A_1, B_1 \rangle$ and $\langle TA_1, TB_1 \rangle$, a difference which is obscured by the fact that they get the same coordinate-description, simply relative to different coordinate systems. For surely, one is inclined to think, it doesn't matter which coordinate system one describes a given system in terms of. The difference shows up much more clearly on their coordinate-independent representations where there is no relativity to a coordinate system and the difference between $\langle A_1, B_1 \rangle$ and $\langle TA_1, TB_1 \rangle$ is explicitly represented.

This might be a good place to pause and say a word about the relation of Curie-causes and -effects to what we ordinarily call initial and final conditions. On the one hand, we think of the initial conditions relevant to some effect as the set of conditions which – by the lights of our theory – are sufficient to ensure its appearance, in the sense that in all models of the theory in which the initial conditions obtain, the effect obtains also (and which are such that, moreover, this is not true of any proper subset of them). On the other hand, we don't typically include among the initial conditions relevant to an effect B everything that goes into the specification of its Curie-cause, A. In particular, we don't include the intrinsic spatiotemporal structures which distinguish systems related by a geometric transformation that is *not* a symmetry of the laws. With respect to the Newtonian ball above, for example, something which fixes the inertial or non-inertial character of the system's motion must be included in A, but there is nothing in what we usually regard as the relevant initial conditions which does that, so these cannot be identified with the Curie-cause of B.[9] I think this is a real tension in our use of the notion of initial conditions. Whether we want to revise it by giving up the gloss, or by extending the notion of initial conditions so that they include everything that goes into the specification of the Curie-cause, is up for grabs.

5. HOW ONE COULD DOUBT THE PRINCIPLE

Curie's Principle appears so simple and obvious on the reading I have given that some explanation is needed for why people have doubted it. There are a lot of ways one might go wrong: one reason, surely, is the general confusion surrounding the physical significance of geometric transformations, but there are others. Among them is the fact that Curie seems to have assumed that the world is governed by deterministic laws and so he often speaks as though we can infer simply from the existence of an asymmetry in the state of a system at a time, that there was an asymmetry in the state which preceded or that asymmetric causes intervened from the outside. This is a mistake; the world might be – and according to our current theories *is* – riddled throughout with indeterministic events. We should keep the assumption of determinism separate from Curie's Principle and allow for indeterminism by reformulating the principle to say that we can infer from the existence of the asymmetry in some individual effect *either* that there was an asymmetry in the Curie-cause *or* that there was no Curie-cause. This is not to suggest, however, that the principle is useless in indeterministic contexts; far from it, but I will leave its application in such contexts to Section 6.

Another way to doubt the principle is to restrict what counts as a cause in such a way as to rule out some of the conditions which go into the specification of the Curie-cause. Return again to the Newtonian ball of the last section; I said that something which fixes whether the system is moving inertially or accelerating must be included in the Curie-cause. One might insist that no such thing could be included in the *cause* because the state of motion of a system is not one of its intrinsic features and only intrinsic features can be counted among the causes of its behavior. I don't think there is much to be said for such a position; it is clear from the examples Curie uses in his paper to illustrate the principle that he had no such restricted notion of cause in mind, nor is it consistent with our usage in either scientific or non-scientific contexts. We count the speed at which the car was traveling among the causes of the accident, and the differences in the velocity of light in different media among the causes of refraction.

Yet another way to doubt the principle, and a particularly prevalent one, stems from a faulty definition of symmetry. It is related to the confusions encouraged by the coordinate-dependent style of formulation mentioned in the last section, and is illustrated by A.F. Chalmers in a 1970 paper. Chalmers writes:

> In a deterministic theory, Curie's Principle will be satisfied for a transformation T if the laws of the theory are invariant under T, for if neither a cause *nor the appropriate laws change under* T, the derivation of the corresponding effect will take an identical form

for the transformed and untransformed system and will yield identical expressions for the effect. (Chalmers 1970, 133)

Chalmers restricts the application of the principle to transformations which are symmetries of the laws, because he thinks it would otherwise be violated by situations of the following kind: a law which is asymmetric with respect to T takes initial conditions symmetric with respect to T onto final conditions *not* so symmetric. For example, dynamical laws asymmetric under spatial reflection will evolve an experimental set-up which is symmetric under reflection onto one that is not. Suppose, we place a bit of cobalt-60 in a magnetic field created by a ring current in a wire, and two feet away, the mirror image of the (cobalt + ring) set-up. The combined system [(cobalt + ring)$_r$ + (cobalt + ring)$_l$] is symmetric with respect to reflection through the plane P separating the right system from the left, but the laws predict that in both subsystems the cobalt-60 atoms will decay significantly more often on the right side. This means that the evolution of the combined system will not be symmetric with respect to reflection through P, for the reflection of the right system should show a prevalence of decay on the left, instead of the right.

Is this a situation in which Curie's Principle is violated? No. A moment of thought should convince one that insofar as the laws predict the lopsided result, the initial experimental set-up cannot be symmetric under reflection. The theoretical description of the (cobalt + ring)$_r$ and (cobalt + ring)$_l$ cannot be the same because the two will evolve differently and the differences in the evolution are predicted by the laws (prevalence of decay *in* the direction of the field for one, and *against* the direction of the field for the other). Chalmers' confusion is the result of his definition of symmetry. Immediately preceding the passage quoted above he writes:

Any transformation of the co-ordinate system that leaves the mathematical form of a law unchanged is a symmetry (or invariance transformation) for this law. (Chalmers 1970, 144)

He is falling prey here to a mistake that has a long and venerable history. Since it has been clearly discussed and diagnosed by others, and since I discuss it in detail elsewhere, I will be short with it.[10] Chalmers' definition identifies the symmetries of a law with the transformations in its covariance group, i.e. the group of those transformations which preserve its truth. I mentioned above that there are two ways of formulating dynamical theories:

(i) in the traditional style which makes use of coordinate systems and with respect to geometric transformations are expressed as transformations between coordinate systems, and

(ii) in a coordinate independent-style in which geometric transformations take the form of manifold automorphisms, one-one, suitably continuous and differentiable mappings of neighborhoods of M into M.

Any theory whatsoever can be formulated in the latter style, and – so formulated – is covariant under arbitrary transformations. If we accept Chalmers' identification of the symmetries of a set of laws with its covariance group, we will have to say that any law can be written in a form in which it is symmetric with respect to arbitrary transformations. Moreover, we will have to admit that the symmetries of a given law are not invariant under translation from one formulation into a mathematically equivalent one: formulated in a coordinate-independent manner its symmetries will be the group G of all one-one sufficiently continuous and differentiable transformations, and formulated in coordinate-dependent but mathematically equivalent manner its symmetries will form a proper subgroup of G. Clearly this isn't right. The symmetries of a set of equations are the automorphisms of its set of solutions only when that set is well defined, i.e., when it is the same independent of its relation to any coordinate system, and this is so only when it is given a generally covariant formulation. If Chalmers had been thinking in terms of such a formulation, his mistake would have been clear to him because the left and right subsystems would have been distinguished by the value of some parameter which is not invariant under reflection. This, again, is why I suggested we restrict our attention to the generally covariant formulations of theories, in the hope that we can avoid some of the confusions encouraged by the coordinate-dependent style.

6. THE PRINCIPLE IN INDETERMINISTIC CONTEXTS

I have suggested that we read Curie's Principle as an observation about how the symmetries of some effect are related to those of the conditions which determine it, if such there be. The 'if such there be' expresses a significant restriction, for the deterministic theories which ruled physics in Curie's day have been superseded by quantum mechanics together with its notorious indeterminism. So the question arises: does Curie's Principle have any application where the laws in question are *in*deterministic, and in particular, does it have any application in the context of quantum phenomena?

The answer is, in both cases, yes. The difference between deterministic and indeterministic laws is that the former map state-descriptions onto state-descriptions whereas the latter map state-descriptions onto *probability functions which define a distribution over the set of possible state-*

descriptions.[11] The Curie-effect of an indeterministic law is just the resulting function, and its asymmetries are defined as follows: T is an asymmetry of a probability function p just in case there is some B_i such that $p(B_i) \neq p(TB_i)$. In the last section, I described experiments in which atoms of cobalt-60 placed in a magnetic field show a prevalence of decay on the left over the right. Experiments like these were first carried out by Wu at Columbia in 1956, and prompted the recognition of the asymmetry of the laws with respect to spatial reflection. The context is an indeterministic one, and the recognition of the asymmetry of the laws involves an application of Curie's Principle: the direction of decay is in each case regarded as undetermined, but the laws are assumed to entail a probability distribution over possible directions of decay which explains the relative frequency of directions in a long run of tests. The left/right asymmetric effect which requires explanation, then, is not the direction of any individual decay event but the probability distribution which favors left over right directions of decay. The significantly greater frequency of left-side decays makes for a left/right asymmetry in the Curie-effect, and hence by Curie's Principle, the Curie-cause A of B cannot be intrinsically symmetric under exchange of left and right.

The principle has another role in indeterministic contexts, for it suggests a precise criterion for separating the chancy from the law-governed aspects of a system. Define the *coarse-state* of a system governed by an indeterministic law as the most complete state-description B_c such that $p(B_c) = 1$. If we call the state-descriptions over which the distribution is given the *fine-states*, the coarse-state determined by a given probability function is the incomplete state-description which includes all and only those features common to all of the fine-states which get a non-zero probability. Now we can say that *transformations which are symmetries of the coarse state but not symmetries of the fine states will in general be permutations of chancy features of the system.* Consider, for instance, the indeterministic process in which an alpha-particle is emitted from a radioactive nucleus and suppose that the state of the nucleus is such that the particle is no more likely to be emitted in any one direction than another. The coarse state of the nucleus is in this case spherically symmetrical but the fine-states are not, since each of them specifies a particular direction for emission. Those aspects of the fine-states which break the spherical symmetry of the coarse state, i.e., the direction in which the particle is actually emitted, are just its unpredictable aspects.

So let it no longer be said that Curie's Principle doesn't apply in indeterministic contexts; it has all the force it does in deterministic contexts, and more. Not only does it relate the asymmetries of the probability distribution over possible final states which acts as the Curie-cause in indeterminisitic contexts to those of the initial state, but it provides a precise criterion for separating the chancy from the law-governed features of the final state.

Showing how it applies specifically to quantum mechanics is somewhat complicated because of interpretive disputes about the theory; the best we can do is to divide interpretations into two classes and say how Curie's Principle applies to the interpretations in each class. On interpretations which incorporate a so-called 'collapse postulate', the state of an isolated system evolves deterministically except during 'measurement' when it 'collapses' into a state probabilistically determined by its state before the interaction.[12] So on interpretations of quantum mechanics which incorporate a collapse postulate, the law which determines the probability distribution over the outcomes of measurement interactions for systems given the state of the system before interaction, i.e., Born's rule, is treated as an indeterministic dynamical law. On interpretations of quantum mechanics which incorporate no collapse postulate, by contrast, Born's rule is treated as a law of coexistence relating *partial* state descriptions to a probability distribution over fuller state descriptions. The former include only the values of observables of which the system is in an eigenstate, the latter include the values of additional observables.[13] In either case, i.e., whether the Born probability of a value **a** for an observable **A** for a system in a state Ψ is interpreted as the probability that if we measure **A** it *will evolve* into an eigenstate of **A** with eigenvalue **a** or as the probability that the system in fact *possesses* value **a** for **A**, Born's rule is treated as an indeterministic law which maps the state-descriptions onto a probability distribution over state-descriptions. And in either case, the former is the Curie-cause of the latter, and Curie's Principle applies to them just as it does in deterministic contexts.

As to separating the chancy from the law-governed aspects of a quantum-mechanical system; a system's coarse-state includes values for all observables of which it is in an eigenstate and is symmetric under permutations of the values of observables of which it is not. Its fine-states, on the other hand, include values for observables of which it is not in an eigenstate and hence are not symmetric under permutations of those values. Moreover, there are no other transformations which are asymmetries of the fine-states and are not asymmetries of the coarse-state. Applying our criterion for separating the chancy from the law-governed aspects to quantum mechanical systems, then, we get that the values which a system possesses (or comes to possess after a measurement of the right sort) for observables of which it is not in an eigenstate are chancy, and are – moreover – the *only* chancy features of its state. This is just the right result.

7. SPONTANEOUS SYMMETRY BREAKING

Having given an argument to the effect that spontaneous symmetry breaking is impossible, I had better consider the actual phenomena physicists call by that name and show that they do not provide counterexamples. The most striking example of abrupt symmetry change, and also one of the first to be discovered, is Euler's load: if we take a vertical column and load it from the top with a perfectly symmetrical distribution of weight, when the load reaches a critical value, the rod will buckle breaking the symmetry of the initial conditions. Other examples include the change of symmetry that occurs in a liquid uniformly heated from below when the vertical temperature gradient reaches a critical value, an effect demonstrated quite indisputably in experiments performed by Benard – a colleague of Curie in Paris – in 1900. Poincare – also a Paris colleague of Curie's – discovered asymmetric pear-shapes of fast rotating fluid masses in self-gravitating equilibrium . . . just to mention a couple of instances which were around and available to Curie long before the instances of spontaneous symmetry breaking (usually in the contexts of superconductivity and quantum field theory) which occupy physicists nowadays. In these cases, as with the buckling rod, the symmetry breaks down when a scalar parameter reaches a critical value, without the intervention of visibly asymmetric causes, and the symmetry of the initial state is larger than that of the resulting state. But in light of what preceded, unless these are indeterministic phenomena, Curie's Principle is violated. What is going on?

The clue to the explanation lies in the phrase 'without the intervention of visibly asymmetrical causes'. The case of Euler's load, though striking, is somewhat different than the others. Here, the buckling of the rod in a particular direction appears to be a genuinely indeterministic phenomenon. When the load reaches a particular weight, the differential equations which express the functional dependence of the behavior of the column on the load simply break down. The column buckles, and – so long as the situation is perfectly rotationally symmetric – there is no predicting beforehand the direction in which it will go. The other cases are more interesting, and result from the non-linearity of the dynamics.[14] With respect to actual physical systems, the symmetry of both causes and effects is seldom exact: in part because of the impossibility of completely decoupling a system from its surroundings, in part because of the inevitable presence of experimental error, and in part because of the presence of fluctuations (whether thermal or quantum mechanical). Where the dynamics are governed by non-linear equations, it is *not* true that nearly symmetric causes produce nearly symmetric effects or *vice versa.* On the contrary, not only can large asymmetrical causes produce small (even undetectable) effects, but large asymmetric effects may arise from seemingly symmetrical causes. Seemingly symmetrical, but not entirely so; there are always the fluctuations. What happens in every case of so-called spontaneous symmetry breaking in current physics is that when some (usually scalar) parameter reaches a critical value, the symmetric solutions cease to be stable under small external chance perturbations, and so pushing the parameter past the critical value will make the system vulnerable to perturbations that carry it into an asymmetrical state. The symmetrical solution always exists but is not always stable for all values of the parameters that enter the equations of motion. Where it is not, asymmetrical solutions may appear that *are* stable, thus precipitating a change in the symmetry of the system that appears to be occasioned solely by the change of a scalar parameter. In general, if a system is non-linear and possesses bifurcation points where a set of stable solutions of lower symmetry branch off from the original symmetrical solution and the system is subject to external chance perturbations, a very small chance perturbation may switch the solution to an asymmetrical one.

It should be clear that there is nothing in this which violates Curie's Principle. These are not cases of systems governed by deterministic equations in which all symmetries of causally relevant factors are not preserved in the effect, but rather cases in which the effect of certain causally relevant factors (the external perturbations) appear only under certain conditions, viz. when some other parameter reaches a critical value. The situation is commonplace but particularly striking in non-linear contexts where the causes are so small and the effects so large; in such cases, the cause is so apparently symmetrical and the effect so evidently not so, but the asymmetries in the effects are still present in the causes.

8. THE PRINCIPLE AND HIDDEN VARIABLES

No discussion of Curie's Principle would be complete without saying something about its connection with hidden variables. If A is the Curie-cause of B, A is fixed (up to a constant) by the values of the parameters on the left-hand side of the B-determining equations in a generally covariant formulation. Curie's Principle entails that if T is a characteristic asymmetry of B, at least one of the parameters which characterizes A is characteristically asymmetric with respect to T. Call T a *hidden characteristic asymmetry* of A just in case T is an asymmetry of A, but the specifications A_i and TA_i are not all distinguishable by unimplemented sight, i.e. in case, for all A_i, we cannot commonly distinguish A_i from TA_i 'just by looking'.[15] And call T an *apparent characteristic asymmetry* just in case it is an asymmetry which is not hidden. It is certainly possible for apparently T-

symmetric states to evolve deterministically into apparently T-*a*symmetric states, but Curie's Principle entails that in every such case T is a hidden characteristic asymmetry of the initial state. Hence, if an isolated system in an apparently symmetric state evolves into a state that is evidently T-asymmetric, so long as the evolution is deterministic we can conclude that the symmetric facade of the initial state was a dupe: it concealed all of the characteristic asymmetries revealed in the final state. Molecular biology is replete with particularly impressive instances of apparently T-symmetric conditions giving rise, by evidently deterministic processes, to apparently T-asymmetric effects. Frog zygotes, for example, start out as spherical cells suspended in an homogenous seeming fluid and develop into highly structured organisms; almost every stage in their development introduces asymmetries not apparently present in the preceding stage. By Curie's Principle, if the process is deterministic, the initial state is – despite appearances – at least as asymmetric as the final.[16]

If we combine Curie's Principle with a methodological principle to the effect that the only theoretical reason for postulating a hidden characteristic asymmetry is as the nomological determinant of some apparent asymmetry, we can derive a great deal about how the apparent structure of the physical world relates to the underlying physical structure postulated by our theories. For together they entail that the hidden causes postulated by our theories should collectively conceal as much asymmetry as is revealed in their collective effects and *only* so much asymmetry as is revealed in their collective effects.[17] This narrows the class of theories quite drastically, but doesn't come close to picking out a unique one. A theory will typically regard a single hidden parameter as causally implicated in a wide range of distinct effects while being only partially responsible for any given one. So even if we know that the asymmetries in any effect are present in its Curie-cause and we require that Curie-causes have no hidden asymmetries that are not asymmetries of their effects, there is still room for differences in theory in the way in which the asymmetries get divided up and distributed among the individual parameters. There are better ways of doing the dividing up, of course, but what they are is a question to which neither Curie's Principle nor the above methodological principle, answers.

9. EXEGETICAL SUPPORT

There is some unfinished business; I need to address the question of whether the reading of Curie's Principle that I have given captures Curie's own intentions. Curie writes that "when certain causes produce certain effects, the symmetry elements of the causes must be found in the produced effects". This raises two exegetical questions: (i) what is meant by 'cause' and 'effect'? and (ii) how do we define the symmetries of the causes and effects, so construed? I have read the principle as asserting that the characteristic symmetries of a Curie-cause are also characteristic symmetries of its effect, i.e., as asserting that if the laws provide a many-one mapping of a family $A = \{A_1, A_2, A_3, \ldots\}$ of alternative events into a family $B = \{B_1, B_2, B_3, \ldots\}$, then the transformations which are symmetries of all of the A_i's are also symmetries of all of the B_i's. So far as I can see, no other reading of the principle is compatible with the examples with which Curie illustrates it and the application which he makes of it in his paper.

The paper is quite beautiful; in it Curie does much more than simply state his principle, he uses it to derive the intrinsic symmetries of the electric and magnetic field quantities from the description of certain carefully chosen experimental phenomena. The application he makes of the principle in these arguments leaves little doubt as to how he intends it to be understood. All have the same form: the set of symmetries of a quantity **q** is shown to coincide with a group **G** by application of Curie's Principle to experimental situations in which **q** figures as part of the effect of some phenomenon and the cause of some other. The first is used to establish that the symmetries of **q** include all of the transformations in **G**, the second is used to establish that the symmetries of q include no transformations *not* in **G**. The conclusion is that the group of intrinsic symmetries of **q** is exactly **G**.

The argument deriving the intrinsic symmetry of the electric field at a point, for example, goes like this. Consider the groups of symmetries associated, respectively, with

(A) a cylinder at rest,
(B) a system consisting of two coaxial cylinders rotating in opposite directions,
(C) an arrow, and
(D) a cylinder rotating about its axis.

Assume that mass is a scalar quantity, that linear momentum has the symmetry of (C), and that angular momentum has the symmetry of (D). Now, consider the electric field at the center of a parallel plate condenser made up of two oppositely charged discs. The cause of the field has the symmetry of (C), with the line through the center of the disks as the isotropic axis. From Curie's Principle it follows that the symmetry group of the field at the center of the condenser must include the transformations in (C). Next, consider a point charge placed at a point p in space where there is an electric field. The charge will experience a force which has symmetry (C), and so – again from Curie's Principle – it follows that the symmetry

(C), and so – again from Curie's Principle – it follows that the symmetry group of the field at p includes *only* transformations in (C). These together entail that the intrinsic symmetry group of the electric field at a point is just (C).

The argument that the intrinsic symmetry of an electric current is also (C) follows the same pattern. Curie considers two situations, one in which a current is the effect of an electric field and another in which a current is the cause of chemical decomposition in electrolysis. Application of Curie's Principle to the former establishes that the symmetry of the current is *at most* (C), application of Curie's Principle to the latter establishes that the symmetry of the current is *at least* (C), and it follows that the symmetry of an electric current is exactly (C). So, also, goes the argument that the magnetic field at a point has the intrinsic symmetry of (D); the relevant experimental situations in this case are those in which a magnetic field is caused by a current in a circular coil and causes electromagnetic induction, respectively.

In all of these arguments, and in every example Curie discusses in other sections of the paper, Curie's Principle is applied to conditions related only as Curie-cause to Curie-effect. Curie is quite explicit that this is what he intends; he writes "whenever a physical phenomenon is expressed as an equation, there is a causal relation between the quantities appearing in both terms". Moreover, it is clear that this is all that is required for the validity of the arguments. There remains the question of whether the symmetries in question are symmetries of particular specifications of Curie-causes and -effects or characteristic symmetries of the families as wholes, i.e. symmetries of *each* specification in the two families, respectively. There are two reasons for thinking that Curie intends the latter. The first is interpretive charity; if we read him as meaning the former, the principle is false. Indeed, quite obviously so; the example of bald and hairy particles given in Section 2 is a clear counterexample and it is easy to generate others. The second reason is that in the above arguments, the existence of *any* specification of A that is T-asymmetric is sufficient to establish the T-asymmetry of A, the existence of *any* specification of B that is T-asymmetric is sufficient to establish the T-asymmetry of B, and Curie's Principle is taken to entail that the asymmetries of B (so established), are also asymmetries of A (so established). Curie finds one among the possible specifications A_j of A which is T-asymmetric and one among the possible specifications B_k of B that is T-asymmetric, and concludes that A and B are both T-asymmetric. He does not require that the particular T-asymmetric specifications invoked be related as individual cause and effect, i.e. he does not require that $\langle A_j, B_k \rangle$ is itself a solution to the laws.

Curie's Principle is often read as though it did, i.e. as though it states that the symmetries (idiosyncratic and characteristic alike) of each particular specification of a Curie-cause must also be present in the specifications of its corresponding effect. And indeed, the principle - separated from its context – is ambiguous between such a reading and the reading I have given, but a look at Curie's examples and his own application of the principle in the paper is quite enough to clear up the ambiguity. There can be little serious doubt as to his real intentions.

10. IS THE PRINCIPLE TRIVIAL?

I will take a moment before concluding to fend off the objection that Curie's Principle – as I've interpreted it – is trivial. There is one sense in which it *is* trivial, namely that it follows from the definitions of the terms in which it is stated. This sort of triviality, however, does not render it insignificant, for it must be granted that there are mathematical theorems which both follow from the definitions of their terms and have a great degree of physical import. A more serious worry is that the Principle is not only trivial but too *obvious* to be interesting. It doesn't require a long proof or reveal subtle and unexpected connections; one scarcely needs to unpack the definitions to see that it is true. The right way to answer this, I think, is to reply that therein lies its beauty. Here is an analogy: any plane figure can be represented in either of two ways, by a line diagram on a page or by the function which generates it. Some truths about the relations between such figures require complicated algebraic proofs but are conspicuously true if we look at the corresponding line diagrams, e.g., the fact that figure A is embeddable in figure B. Other truths about relations between figures are almost impossible to discern from their line drawings but are easy to see with a quick peek at the functions which describe them, e.g., the fact that A results from the composition of functions which generate B and C. One has an elegant way of representing a type of object when the most *important* truths about those objects appear obvious when they are so represented. It is nothing more than a recommendation of conceiving of physical laws as a function from one set into another and attending to the characteristic symmetries of the elements in the two sets, that Curie's Principle appears obvious when one does. The substance of the principle derives from the fact that the simple relation it expresses between the symmetries of the domain and range of a function can often be used to draw conclusions *about* the former which cannot be gleaned directly from observation, *from* information about the latter which can. It lies not in seeing that the principle is true, but in recognizing phenomena in the physical world which are related as Curie-cause to -effect, and applying Curie's Principle to draw conclusions from the *observed* asymmetries of the latter about the often hidden asymmetries of the former.

Some instances of such applications that I have mentioned are these:

(i) the case of the development of frog zygotes described in Section 8 in which the apparent determinism of the process, combined with information about the evident geometric asymmetries of the final stage, tells us a great deal about the hidden structure of the apparently spherically symmetric early stages,

(ii) Curie's arguments, described in Section 9, deriving the characteristic symmetries of the electromagnetic field quantities, and finally,

(iii) also touched on in Section 9, the characteristic asymmetries of the appearances, represented by the empirical substructures of a theory's models, must also be characteristic asymmetries of the underlying physical structure postulated by theories and represented by their higher-level structure. This expresses the only *a priori* constraint that the appearances place on the higher level theoretical structure of our models.

11. CONCLUSION

In the year before Curie's paper was published in the *Journal de Physique*, Sophus Lie published the third and final volume of his *Theorie der Transformationsgruppen* in the preface to which he urged deliberate attention to the symmetries of physical laws. Though Lie and Curie were contemporaries, their emphases were quite different; Lie focused on the symmetries as mathematical properties of the laws, whereas Curie concentrated on the characteristic symmetries of the physical states themselves. In the century separating us from the years in which those seminal works came out, physicists have followed Lie's mathematical emphasis and Curie's basic physical insight has been all but lost.

The insight, as I've suggested, was beautifully simple and quite obvious once one adopted Curie's perspective: a physical law can be identified with a function from one set of physical states into another. If the law is a dynamical law, the states in question are the states of a system at two different times; if it is a law of coexistence, they are partial state descriptions of a system at a single time. Curie's Principle follows just from the notion of such a function; it says that all transformations which are characteristic symmetries of the former are also characteristic symmetries of the latter. More intuitively, it says that transformations which leave the values of all relevant parameters unchanged also leave unchanged their effects. We have seen physical applications of the principle ranging from guiding the postulation of hidden variables in theorizing to providing a criterion for separating out the chancy aspects of a system's evolution. I have not said much about its broader philosophical import, but it should be clear that the way symmetries operate in physics suggests an understanding of the scientific applications of some philosophically important notions. It suggests, in particular, that A is *causally relevant* to B just in case the B-determining laws are not symmetric with respect to arbitrary permutations of the values of A, and that *if (counterfactually)* A_i had occurred, *then* B_i would have occurred as well; moreover, if A_i had occurred, then no *other* B_i would have. In sum, echoing the first sentence of Curie's paper, I think that there is much interest in introducing into philosophy the symmetry considerations familiar to physicists, and Curie's Principle is a very good place to start.

APPENDIX: NON-GENERALLY COVARIANT FORMULATIONS AND GEOMETRIC TRANSFORMATIONS

A dynamical theory is typically presented as a state space together with a set of laws; if the laws are deterministic, they pick out a group (or semi-group) of evolution operators $\{U_d\}$ such that if the state at t is Ψ, then the state at $t + d$ is $U_d(\Psi\}$. A trajectory through the state space $\Psi(t)$ satisfies the laws just in case for all t and d, $\Psi(t + d) = U_d\Psi(t)$. If T is a transformation defined on the state space,

(i) T is a symmetry of state Ψ *iff* $T\Psi = \Psi$
(ii) T is a symmetry of a set $\sum$ of states *iff* $T \sum =_{\text{def}} \{T\Psi\ :\ \Psi \text{ in } \sum\}$
(iii) T is a symmetry of the laws *iff* for all d, $TU_d = U_dT$, i.e. $V\Psi T(U_d\Psi) = U_d(T\Psi)$. Equivalently, iff $U_d = T^{-1}U_dT$ for all d.

Now, clearly if $\Psi = T\Psi$ then $T(U_d\Psi) = TT^{-1}U_dT(\Psi) = U_dT\Psi$, so if T is a symmetry of the initial state and the laws, then it is a symmetry of the final state. What is harder to see, but is nevertheless true, is that *if T is not a symmetry of the laws then it is not a symmetry of the set $\sum$ of possible initial states.* Let A be the state at some initial time, and let B be the state at a final time, and suppose T is an asymmetry of the laws. If there exist two physically possible trajectories $\langle A_i, B_i\rangle$ and $T\langle A_i, B_i\rangle$ where $B_i \neq TB_i$, it must also be the case that $A_i \neq TA_i$. But if there is some A_i such that $A_i \neq TA_i$, then T is not an characteristic symmetry of A, notwithstanding the fact that in the traditional formulation, A_i and TA_i

have the same coordinate-dependent description. For those descriptions are given relative to different coordinate systems and there are dynamically relevant differences between the manifolds they represent.

Consider the example I gave in Section 4 of an isolated Newtonian system consisting of a ball at rest on a frictionless surface. A_1 is the state of the ball at a time t_1, B_1 is its state one minute later at t_2 both in their coordinate-dependent form relative to a coordinate system with respect to which the ball is at rest; and suppose that the ball remains isolated in the interim. $\langle A_1, B_1 \rangle$ is a solution to Newton's laws, and A_1 is the Curie-cause of B_1. Now, consider the coordinate transformation **T** which takes every point (x, y, z, t) onto the corresponding point $(x, y, z + at^2, t)$; **T** carries $\langle A_1, B_1 \rangle$ onto $\langle \mathbf{T}A_1, \mathbf{T}B_1 \rangle$ which has the ball spontaneously accelerating in the z direction with no force acting on it. Newton's laws in their traditional coordinate-dependent representation are not covariant with respect to **T**, and it is evident in this case that the description of the ball's trajectory relative to a coordinate system obtained from the original by **T** does not satisfy them.

What is going on can be described crudely (though well enough for our purposes) as follows. There are dynamically relevant differences between manifolds represented by Cartesian coordinate-systems moving non-inertially with respect to one another. Hence, in moving from the manifold represented by the first coordinate system to the manifold represented by the second, something on which the dynamical behavior of Newtonian systems depends is changed, so the relativity to a coordinate system expresses a dependence on parameters which must be explicitly included if one is to formulate laws which hold 'absolutely', i.e. relative to all coordinate systems. This is what is done in the generally covariant, or 'coordinate-independent', representation. Whereas in traditional formulations one states dynamical laws which hold only 'relative to' manifolds with particular intrinsic structures and which are hence covariant only under automorphisms which preserve those structures, in the generally covariant formulations one states laws which explicitly relate dynamical behavior to the relevant intrinsic structures. The new laws hold 'relative to' all manifolds and are consequently covariant with respect to all transformations between them. This is why it is true only of the generally covariant formulation of a theory that if T is a geometric asymmetry of its laws, there is a parameter in the B-determining equations which is not invariant under T. In the same way, if we have laws which hold only 'relative to' systems of one or another mass, in order to formulate laws which hold for systems of any mass, we have to relate the behavior of a system to its mass and a new parameter representing mass (i.e., not invariant under changes in mass) will appear in the equations.

NOTES

[1] Many, many thanks are due to David Z. Albert, Paul Benacerraf, and Bas van Fraassen; and to Elijah Millgram, and Gideon Rosen.

[2] I'll suppress the relativity from here on, though talk of A being the Curie-cause of some effect B is always to be understood as tacitly relativized to the laws of a theory.

[3] It follows from the definition of a characteristic symmetry that T is an idiosyncratic asymmetry of (i.e. is not a characteristic symmetry of) some specification of a A (or B) *iff* it is *not* a characteristic symmetry of A (or B). We get the second formulation of Curie's Principle by taking the contrapositive of the first (i.e., if T is not a characteristic symmetry of a Curie-effect B, then it is not a characteristic symmetry of its Curie-cause, A), and replacing the antecedent and conclusion with their equivalents under the definition of characteristic symmetry.

[4] Notice that the fact that we can write down pairs of specifications $\langle A_i, B_i\rangle$ and $\langle TA_i, TB_i\rangle$, where $TA_j = A_j$ but $TB_j \neq B_j$ (as, for example, is the case if A and B are far enough apart that T operates on B but not on A) is unimportant. What is ruled out by Curie's Principle is the existence of pairs of *solutions to the laws* $\langle A_i, B_i\rangle$ and $\langle TA_i, TB_i\rangle$, such that $TA_j = A_j$ but $TB_j \neq B_j$.

[5] Thanks to an anonymous referee for *Philosophy of Science* for the example.

[6] Here, as above, where a definition is given, the defined term is indicated by bold type.

[7] Let me emphasize that the covariance group and the symmetry group of a theory are two different things. The covariance group is the set of coordinate transformations which preserve the truth of the laws. The symmetry group of a theory is the set of automorphisms of its solution set, the transformations which never take you from a solution onto a non-solution, or *vice versa*.

[8] Since it is not necessarily the case that the A's can be represented as a function of the B's (i.e. that the mapping is one-one), it doesn't follow that differences in the A's are always accompanied by differences in the B's, and hence it doesn't follow that the asymmetries of the A's are also asymmetries of the B's. I will come back to this in Section 8.

[9] We usually regard the positions and momenta of the particles which constitute the ball as the relevant initial conditions, without any specification of whether the coordinate system with respect to which they are given, is an inertial one.

[10] See J. L. Anderson, *Principles of Relativity Physics*, New York: Academic Press, (1967), pp. 75–83; and M. Friedman, *Foundations of Space-time Theories*, Princeton, NJ: Princeton University Press (1983), pp. 46–62.

[11] Indeterministic laws which pick out a range of possible states without assigning probabilities, are conceivable, so this is a special case. But it is a case which covers all indeterministic laws of which we have actual examples in science, and so it is the important one.

[12] It is a notoriously hard problem for all of the interpretations in this class to characterize measurement interactions precisely, but for the purposes of the discussion, we can assume the problem has a solution.

[13] Here is how this characterization applies to some of the more familiar no-collapse interpretations: on the Kochen/Healey/Dieks interpretations, the set of observables for which a composite (measured system + measuring apparatus) system has values, over and above

those of which it is in an eigenstate, is determined by the unique biorthogonal decomposition of the system's state (if such there be, i.e., if there is no degeneracy), and the values the system has for those observables is probabilistically determined by applying Born's rule to its Ψ-function. On the modal interpretation of van Fraassen, the additional observables are determined by the history of the combined system (whether they have just engaged in a measurement interaction and which observable was measured, under some precise physical characterization of the conditions under which these obtain), and – as above – the value those observables have are probabilistically determined by applying Born's rule to its Ψ-function.

[14] The role of non-linearity explains why all of the early examples come from fluid dynamics. It is an interesting historical fact that although they were being investigated in close proximity to Curie, and close to the time he wrote the symmetry paper, neither he nor his colleagues appear to have considered them in the light of their symmetry properties.

[15] 'Commonly', here, means something like 'in normal circumstances, with normal vision, with due attention and training, etc.'.

[16] We can think of physical evolution, in fact, as precisely a process wherein hidden structure is made apparent. The distinction between hidden and apparent asymmetry is – as I understand it, and in terms more familiar than his own – David Bohm's distinction between explicate and implicate order, and conceiving of evolution in these terms is to hin of it as what he refers to as explication of implicate order.

[17] If T is not a symmetry of B, then according to Curie's Principle, there is some parameter P which is not invariant under T, and is such that $A_1 \rightarrow B_1$, $A_2 \rightarrow TB_1$, and A and A' are distinguished by different values of P. If A and A' are not observationally distinguishable, P is a 'hidden variable'. Whenever we postulate hidden variables as the causes of differences in observable behavior, we assume that there exists a Curie-cause for some family of alternative events and derive the characteristic asymmetries of the postulated cause from those of the effect. It is generally accepted that postulated hidden parameters must be measurable, i.e. must have observable effects beyond the effect it is introduced to explain (e.g., on a measuring apparatus). Without such a constraint, the distinction between deterministic and indeterministically evolving systems becomes empirically empty, for we can postulate hidden differences *wherever* we observe hidden behavior.

All of this suggests that the specifically theoretical aspect of scientific theorizing (insofar as it consists in choosing between models which embed the same empirical substructures but differ in their higher level theoretical structure) is just an application of Curie's Principle on a cosmic scale, for it is entirely a matter of deriving intrinsic asymmetries in a postulated Curie-cause (the underlying physical structure of the world) from asymmetries in its effect (the appearances), on the assumption that the former determines the latter.

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