PHILOSOPHICAL CONSEQUENCES OF QUANTUM THEORY

Reflections on Bell's Theorem

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HOLISM, SEPARABILITY, AND THE METAPHYSICAL IMPLICATIONS OF THE BELL EXPERIMENTS

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> The real difficulty lies in the fact that physics is a kind of metaphysics; physics describes "reality." But we do not know what "reality" is; we know it only by means of the physical description!
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> —Einstein to Schrödinger, 19 June 1935

Seventeen years ago, just before the first experimental test of Bell's theorem, Howard Stein gave a paper in which he argued that "quantum mechanics poses no special problem of an epistemological kind," but that there is "a cluster of problems" concerning the "meaning" of the theory, problems "of a metaphysical . . . character," which "consist in unanswered questions *about the world*—the physical world" (Stein 1970, 93; see also Stein 1972). Stein was right. The problems that most interested him in 1970, namely, the measurement problem and wave-packet reduction, are not now in the forefront of our interests. But the history of subsequent work inspired by Bell's theorem demonstrates the truth of Stein's main point about the gaps in our understanding of the quantum world. In brief: We know that the quantum-mechanical predictions regarding correlations between previously interacting systems violate the Bell inequalities in certain special cases; we know that these predictions thus differ from those given by what Bell called "local" theories; and we know that the quantum-mechanical predictions are confirmed by the Bell experiments. But we do not understand why—why a theory's being "local," in Bell's sense of the word, leads it to give the wrong predictions, nor why "nonlocal" quantum mechanics gives the right ones. Of course, some technical questions must be answered before we can achieve the desired understanding, but more than that is needed, for the puzzles about "nonlocality" are as much "metaphysical" as they are technical, and this in just the sense intended by Stein, inasmuch as they "lie beyond the present reach of [physics]." Understanding will come, therefore, only if we allow ourselves to indulge in a little metaphysics, only if we ask ourselves what "nonlocal" theories tell us about the world.[1] This is more than a little frightening to those of us who are the metaphysically repressed children and grandchildren of the Viennese diaspora. But duty calls, so sin, if sin we must.

What follows, then, is an attempt to tease out the metaphysical implications of Bell's theorem, its experimental tests, and, most importantly, its recent and revealing rederivation by Jon Jarrett (1983, 1984), all with the aim of understanding what kind of world would evince Bell "nonlocality." I will argue that the source of this "nonlocality" is not necessarily a violation of special relativistic locality constraints (the first-signal principle), but instead, perhaps, a kind of ontological holism or nonseparability (already hinted at in the orthodox quantum-mechanical interaction formalism), in which spatio-temporally separated but previously interacting physical systems lack separate physical states and perhaps also separate physical identities.

More specifically, I will argue that we confront here a possible violation of what I term the *spatio-temporal separability principle,* or just the *separability principle* for short. This is a fundamental ontological principle governing the individuation of physical systems and their associated states, a principle implicit in many classical physical theories. It asserts that the con-

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[1] No sharp distinction of method or content between physics and metaphysics is intended here. I regard physics as aiming, first, to establish general principles (such as the relativity principle, the light principle, the first and second laws of thermodynamics) that function as constraints upon constructive models of the world. Developing the latter is the more properly metaphysical task; it is by the construction of models that we learn in what kind of world the physical principles can be realized. The two types of investigations are complementary, with the elaboration of new principles further constraining and thus guiding the search for models, and the development of new models helping to probe the limits of validity of the principles. If one prefers to view the construction of models as a task for physics itself, so be it; this is, after all, a question of terminology and thus of taste. But then I would insist on describing the constructive enterprise as the metaphysical moment or aspect of physics.

tents of any two regions of space-time separated by a nonvanishing spatio-temporal interval constitute separable physical systems, in the sense that (1) each possesses its own, distinct physical state, and (2) the joint state of the two systems is wholly determined by these separate states.[2] In other words, the separability principle asserts that the presence of a nonvanishing spatio-temporal interval is a *sufficient condition* for the individuation of physical systems and their associated states,[3] and that the states thus individuated exhaust the reality that physics aims to describe, that physical wholes are no more than the "sums" of their parts. In classical, prerelativistic physics, the analogous principle referred to spatial intervals and spatial separation, as opposed to spatio-temporal intervals, and thus should be called the *spatial separability principle*. But I will speak of just the separability principle, with the context indicating which version is intended.

There are two ways to deny the separability principle. The more modest concerns the individuation of states; it is the claim that spatio-temporally separated *systems* do not always possess separable *states*, that under certain circumstances either there are no separate states or the joint state is not completely determined by the separate states. I call this way of denying the separability principle the *nonseparability of states*. The more radical denial may be called the *nonseparability of systems*; it is the claim that spatio-temporal separation is not a sufficient condition for individuating *systems* themselves, that under certain circumstances the contents of two spatio-temporally separated regions of space-time constitute just a single system.

The separability principle must be distinguished from the *locality principle*. In its most general form, the locality principle (which is not to be confused with the Bell "locality" condition)[4] asserts that the state of a system is unaffected by events in regions of the universe so removed from the given system that no signal could connect them. In classical physics, with no theoretical limit on signal velocities, that means any event simultaneous with the momentary state of the given system and separated from it by any finite spatial interval. The relativistic version of the principle asserts that a system's state is unaffected by events in regions of space-time separated from it by a spacelike interval. In either case, the aim of the locality principle is to rule out objectionable kinds of action-at-a-distance. In what follows, I will speak simply of the locality principle, allowing the context to determine whether the classical or the relativistic version is intended.

Locality assumes for its formulation the existence of separate states, but they need not be of the kind assumed by the separability principle; that is to say, they need not be such as to determine completely the joint state of every composite system to which the systems they characterize may belong as parts. Thus, it is possible to have a *local,* but *nonseparable* theory, quantum mechanics being the most important example.[5] The quantum theory is something of an exception, however, for many of our most important physical theories—among them general relativity and classical field theories, such as classical electrodynamics—satisfy both the locality and separability principles.[6] And the fact of their satisfying both principles is significant, for I will argue that all *local, separable* theories, including general relativity, are empirically false when applied to the kinds of microphysical interactions examined in the Bell experiments; or rather, that they would have to be false if one elaborated them into theories capable of describing such microphysical interactions. If one is unwilling to sacrifice locality, the assumption of separability must be recognized as the source of the difficulty. I will also argue that local, separable theories are fundamentally incompatible with quantum mechanics because of

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[2] How the joint state is determined by the separate states depends upon the details of a theory's mathematical formulation. At a minimum, the idea is that no information is contained in the joint state that is not already contained in the separate states, or, alternatively, that no measurement result could be predicted on the basis of the joint state that could not already be predicted on the basis of the separate states. I prefer to think of a physical state not as a cluster of definite properties (like the states of classical mechanics, which are representable by points in a phase space, corresponding to definite values of position and momentum), but more generally as a set of dispositions for the system to manifest certain properties under certain circumstances, which includes, as a special case, states conceived as clusters of definite properties. Accordingly, I define a state, λ, formally, as a conditional probability measure, $p_\lambda(x|m)$, assigning probabilities to measurement results, x, conditional upon the presence of measurement contexts, m. With states thus defined, to say that the joint state is wholly determined by the separate states is to say that the joint probability measure is the product of two separate measures.

[3] The presence of such an interval is also, of course, a necessary condition.

[4] The locality principle and the Bell "locality" condition both aim to express the same intuition about local action, but as I will argue in section 1, the Bell "locality" condition fails to do this in an unambiguous fashion. The terms, 'locality' and 'separability', have each been used in a variety of different ways in the literature on Bell's theorem and on the interpretation of quantum mechanics, so it is important to attend carefully to the definitions being given to them here.

[5] According to the quantum-mechanical interaction formalism, two previously interacting systems possess a joint state not representable as the product of separate states, at least until such time as one of the two systems undergoes a subsequent interaction, such as a measurement. See below, section 1 and section 2, n. 16, for more on the sense in which quantum mechanics is a local theory.

[6] Special relativity can also be given a field-theoretic formulation of the kind we associate with Minkowski, in which case it too would count as a local, separable theory. But for reasons to be elaborated below, I think it a mistake to build separability into special relativity, and so I will not include it among the class of local, separable theories. There are, of course, also some *nonlocal, separable* theories to be found chiefly among the nonlocal hidden variable theories. But they will not be discussed here. And it should be mentioned for the sake of thoroughness that one can imagine theories that are both *nonlocal,* and *nonseparable,* though why one would go to the trouble of constructing such a theory is not clear.

their separable manner of individuating systems and states. This last fact, especially, should be appreciated. For years we have worried that Bell's theorem and the Bell experiments, by exhibiting a kind of "nonlocality" in quantum mechanics, point to a conflict between quantum mechanics and special relativity. Now, however, we find that the conflict lies not there, but between quantum mechanics and general relativity, and that it concerns the fundamental issue of the manner in which the two theories individuate systems and states. This result is pregnant with implications for a variety of problems, not least of which is the quest for a unified fundamental theory incorporating all of the basic forces, including the strong and weak nuclear forces, electromagnetic forces, and gravitation.

All of these results point to the importance of understanding *nonseparability*. We confront here a radical physical holism at odds with our classical intuitions about the individuation of systems and states, and it is precisely this feature of the quantum theory that enables it to provide the correct predictions in the Bell experiments. But the quantum formalism by itself offers neither a deeper explanation of nonseparability nor an account of its larger significance for our understanding of the physical world. This is where physics stops and where metaphysics must show the way, at least until the path is clear enough to allow physics to proceed again.

1. Locality, separability, and the Bell experiments: A nontechnical summary of the formal issues

Bell's theorem (Bell 1964) concerns a simple experiment in which one measures correlations between observables of two spatio-temporally separated, but previously interacting systems, here labeled A and B.[7] At the heart of the theorem is the Bell "locality" condition, which aims to capture the intuition that measurement results in each of the two "wings" of the Bell experiment depend only upon circumstances in the local environment of the measurement-event in that wing. This condition takes the form of a requirement that the joint probability for obtaining one result in the A-wing and another in the B-wing be the product of the separate probabilities for those results, the argument being that if the result in one wing is determined solely by local circumstances in that wing, then it is statistically independent of the result in the other wing, so that the joint probability is calculated according to the ordinary product rule for the compound probability of independent

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[7] For a sketch of Bell's theorem and its experimental tests, see James T. Cushing, "A background essay," this volume, and Clauser and Shimony (1978). A thorough, recent discussion may be found in Redhead (1987b, 82–118).

events.[8] Bell's theorem asserts that the predictions of any theory whose description of the interaction satisfies this "locality" condition must necessarily satisfy, in turn, a certain inequality, the "Bell inequality," which is violated in special cases by the predictions of the quantum theory.[9]

In the experimental tests of Bell's theorem, culminating in the Aspect experiments (Aspect, Dalibard, and Roger 1982), the quantum-mechanical predictions have been consistently confirmed, sometimes with striking precision.[10] These empirical violations of the Bell inequality, taken together with Bell's theorem, thus entail a violation of the Bell "locality" condition by nature itself as well as by quantum mechanics. But here is where the puzzles begin, because as the example of the quantum theory shows, Bell "nonlocality" apparently need not involve a violation of special relativistic locality constraints.

Little progress was made in understanding this state of affairs until Jon Jarrett (1983, 1984) proved that the original Bell "locality" condition is really a conjunction of two logically independent conditions. The first of these requires the stochastic independence of a measurement result in one wing from the selection of an observable to be measured in the other wing. Jarrett calls it "locality," arguing that it is more deserving of the name than the Bell "locality" condition, since, as he claims, it is entailed by the first-signal principle of special relativity. Shimony (1986) recommends the more neutral term, "parameter independence." The other condition, which Jarrett calls "completeness"[11] and Shimony (1986) calls "outcome independence," as-

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[8] In the version relevant to the present discussion, this condition is:

$$p_\lambda^{AB}\,(x, y|i, j) = p_\lambda^{A}(x|i) \cdot p_\lambda^{B}(y|j),$$

where x and y represent measurement outcomes, i and j the observables measured, in the A and B wings, respectively (for the notation, see Cushing, "A background essay,"). Correlations between the two measurement results are not excluded, indeed they are expected, given that the measured observables are assumed to satisfy a conservation principle; one merely assumes that the correlations are the result of prior programming, as it were, from the time of the interaction (an instance of a "common cause"), and not the result of any current distant conspiracy between the two wings.

[9] In this paper, the original Bell "locality" condition and its cousins are all called Bell "locality," deliberately ignoring the differences among them (the quotation marks being employed to distinguish Bell "locality" from the different notion of locality to be defined below). Similarly, the term "Bell inequality" refers, indifferently, to the various different versions of the inequality, and the term "Bell experiments" to all of the experimental tests of Bell's theorem. See Redhead (1987b, 82–118) for a discussion of some of the distinctions that are here suppressed.

[10] For a survey of the experimental results through 1978, see Clauser and Shimony (1978); an up-to-date survey is found in Redhead (1987b, 107–113).

[11] This is not the happiest choice of terminology. As is noted by Shimony (1984a, 226), a theory like quantum mechanics can fail to satisfy this condition and still be "complete" in the

serts the stochastic independence of the measurement result in one wing, not from the observable chosen for measurement in the other wing, but from the result obtained there.[12] On Jarrett's analysis, a violation of the Bell inequality need *not* entail relativistic nonlocality, because it may result *either* from a violation of the Jarrett locality condition, which would perhaps entail relativistic nonlocality, *or* from a violation of his completeness condition. Quantum mechanics, for example, violates completeness but satisfies Jarrett locality.

But while significant progress has thus been achieved, some puzzles remain. For one thing, the connection between Jarrett locality and special relativity is not as clear as it might be. Jarrett's own argument is that violation of his locality condition in the case of spacelike separated measurement events makes possible superluminal signaling, so that special relativistic prohibitions on the latter entail the locality condition. I find it more helpful to note that satisfaction of what is here called the locality *principle* directly entails satisfaction of Jarrett's locality *condition* in such cases, if one assumes that measurement results are completely determined by the state of the measured system and those circumstances in its immediate environment constituting the measurement context.

More troublesome by far, however, is the fact that the *physical* significance of Jarrett's completeness condition and the *physical* significance of its violation in nature and in the quantum theory are not at all clear. What are the physical conditions needed to secure the independence of a measurement outcome in one wing from the outcome in the other? And how would one explain physically the opposite circumstance, the dependence of an outcome in one wing upon the outcome in the other wing?

This is where separability enters the picture, for Jarrett's completeness condition turns out to be equivalent to what I call the *separability condition*, which simply asserts that each of the two previously interacting systems in the Bell experiments possesses its own physical state, the joint state being the product of these separate states (Howard 1987).[13] It should not be surprising

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sense that its description of the joint state of A and B may contain all possible information. It is also not clear that Jarrett's "completeness" is the same as that intended by the Einstein, Podolsky, and Rosen (1935, 777) "completeness condition."

[12] For an outline of the proof of Jarrett's theorem, see Cushing, "A background essay."

[13] The existence of the separate states follows straightforwardly from the identifications:

$$p^A_\alpha(x|i,\ j) = p^A_\lambda(x|i,\ j) \text{ and } p^B_\beta(y|i,\ j) = p^B_\lambda(y|i,\ j),$$

where α and β represent the separate states of the systems in the A and B wings, and λ represents the joint state. (Recall that I define a state as a conditional probability measure assigning probabilities to outcomes conditional upon the presence of global measurement contexts [see above, n. 2]; here the relevant global contexts for the measurements in the A-wing and in the B-

that separability plays a part here, since the most novel, nonclassical feature of the quantum-mechanical interaction formalism is precisely its denial of the separability of the states of the two systems. Nevertheless, in the original proof of Bell's theorem, as in the proof of Jarrett's theorem, a single joint state for the two systems was assumed, in the belief that one thereby achieved a greater generality (see, in particular, Bell 1964, 196). But this generality turns out to be spurious: Any theory whose predictions satisfy the Bell inequality tacitly assigns separate physical states to the two systems, such that the joint state is the product of the separate states, whether or not that fact is explicitly recognized in the formalism of the theory (Howard 1987).[14]

The separability *principle* provides sufficient grounds for the satisfaction of the separability *condition,* just as the locality *principle* provides sufficient grounds for the satisfaction of the Jarrett locality *condition.* Since there is a nonvanishing spatio-temporal separation between the two measuring events in the Bell experiments, the spatio-temporal separability *principle* implies that the systems involved are indeed two, and that they possess separate physical states, the joint state being wholly determined by these separate states. The separability *condition* is a formal statement of the latter circumstance, the existence of separate physical states and a factorizable joint state. Its violation would entail that the two systems do not possess separate

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wing are both determined by the choice of both parameters (i, j).) The essential step consists in noting that Jarrett's completeness condition:

$$p^A_\lambda\ (x|i,\ j,\ y) = p^A_\lambda(x|i,\ j) \text{ and } p^B_\lambda(y|i,\ j,\ x) = p^B_\lambda(y|i,\ j),$$

is equivalent to the factorizability condition (my separability condition):

$$p^{AB}_\lambda\ (x,y|i,j) = p^A_\alpha(x|i,j) \cdot p^B_\beta(y|i,j)$$

(only the definition of conditional probability is required). The separability condition plus the Jarrett locality condition (with α and β, respectively, in place of λ):

$$p^A_\alpha(x|i,j) = p^A_\alpha(x|i) \text{ and } p^B_\beta(y|i,j) = p^B_\beta(y|j),$$

together yield immediately the Bell-type "locality" condition (what Jarrett calls "strong locality") in the form:

$$p^{AB}_\lambda(x,y|i,j) = p^A_\alpha(x|i) \cdot p^B_\beta(y|j).$$

For a critical discussion of this analysis, see French (to appear).

[14] The Bell-type "locality" condition entails Jarrett locality if one assumes that the separate probabilities are defined as the marginals of the joint probability, for example:

$$p^A_\alpha(x|i,j) = \Sigma_y\ p^{AB}_\lambda(x,y|i,j)$$

(which definition also yields the existence of separate states, α and β); and then Bell-type "locality" together with Jarrett locality entail in an obvious way that the separate states (probability measures), α and β, satisfy the requisite factorizability condition.

physical states of such kind that the joint state is a product of the separate ones, and thus implies at least what I call the nonseparability of states.[15]

Let me summarize the formal situation. With the help of the Bell and Jarrett theorems, it can be shown that any theory whose account of interactions satisfies both the Jarrett locality condition and the separability condition yields predictions for certain correlation measurements that satisfy the Bell inequality. But in the Bell experiments the Bell inequality is violated in special cases, and in these cases quantum mechanics gives the right predictions. It follows that one (or both) of the locality and separability conditions is violated, which, in turn, implies that one or both of the locality and separability principles must be denied. Quantum mechanics denies the latter.

In the remainder of this paper, I will focus almost exclusively upon the violation of the separability principle. My reasons for leaving the locality principle untouched are partly theoretical, deriving from the special theory of relativity, and partly methodological, deriving, as we shall see, from considerations of the conditions necessary for theory testing. And it is hardly irrelevant that our one correct theory of microphysical interactions, the quantum theory, is a local, nonseparable theory. But most important among my reasons for focusing on nonseparability is simply the fact that I believe it to be the more interesting way out of the Bell experiments, the way more likely to yield new insights that will be useful in our search for a more comprehensive fundamental physical theory.

2. *Field theories and separability*

As far as I can determine, Einstein was the first to point out the fundamental role of the separability principle in field theories. His reflections on the quantum theory led him to distinguish two principles that are essentially the same as the locality and separability principles, and to conclude that their conjunction entails the incompleteness of quantum mechanics. The argument is simple. Consider the kind of physical situation investigated in the Bell experiments, involving measurements upon two previously interacting systems, *A* and *B*. If *A* and *B*, having between them a spacelike interval, are separable, then each possesses its own physical state. If, furthermore, the locality principle is satisfied, if, that is, the state of *B* is unaffected by events in the vicinity of *A*, then the physical state of *B* remains the same regardless of what we choose to do with *A*. But quantum mechanics assigns different ψ-functions to *B*, depending upon the parameter measured on *A* and the result of that measurement.[16] Therefore, if we agree that completeness requires the assignment of one and only one theoretical state (ψ-function) to a system in a given physical state, then quantum mechanics is incomplete.[17]

In the course of what may be his clearest statement of this argument, Einstein (1948) wrote:

> If one asks what is characteristic of the realm of physical ideas independently of the quantum theory, then above all the following attracts our attention: the concepts of physics refer to a real external world, i.e., ideas are posited of things that claim a "real existence" independent of the perceiving subject (bodies, fields, etc.). . . . Moreover, it is characteristic of these physical things that they are conceived of as being arranged in a space-time continuum. Further, it appears to be essential for this arrangement of the things introduced in physics that, at a specific time, these things claim an existence independent of one another, insofar as these things "lie in different parts of space." Without such an assumption of the mutually independent existence (the "being-thus") of spatially distant things, an assumption which originates in everyday thought, physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation. Field theory has carried out this principle to the extreme, in that it localizes within infinitely small (four-dimensional) space-elements the elementary things existing independently of one another that it takes as basic, as well as the elementary laws it postulates for them.

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[15] Whether or not it also drives us to consider the more radical nonseparability of systems themselves is discussed below.

[16] This does not mean that quantum mechanics violates the locality condition. In the sense of "state" defined above (see n. 2), the quantum mechanical "state" of *B*—that is, the probabilities for the possible outcomes of measurements on *B*, given various measurement contexts—depends not upon the choice of the parameter to measure on *A*, which would entail violation of the locality condition (see above, n. 13), but only upon the outcome of the measurement on *A*. Thus, quantum mechanics violates not locality (parameter independence), but separability (outcome independence = Jarrett's "completeness" condition). It may appear, nevertheless, that the state of *B* is changed by "events" in a distant region of the universe, namely, by the outcome of a measurement performed there, so that while no violation of the locality *condition* obtains, the locality *principle*, is violated. But it should be noted, first, that the "separate" states that we assign to *A* and *B* according to the quantum interaction formalism are dependent upon the joint state, which furnishes, in principle, the only correct description of *A* and *B*, and that the "separate" state of *B* is not changed by any "events" in the vicinity of *A* that do not also change the joint state. Second, it should be noted that the outcome of a measurement on *A* is not a "distant event" in the same way that, say, setting the parameter to be measured at *A* is, since this outcome is a function not only of circumstances in the local environment of *A*, but also of the joint state of *A* and *B*, a state that bridges the gap, as it were, between the two systems.

[17] See Howard (1985), where I argue that, in his correspondence with Schrödinger, Einstein repudiated the EPR incompleteness argument in the summer of 1935, a few weeks after its publication, favoring from that time on the incompleteness argument sketched here, an argument differing significantly from the EPR argument.

> For the relative independence of spatially distant things (A and B), this idea is characteristic: an external influence on A has no *immediate* effect on B; this is known as the "principle of local action," which is applied consistently only in field theory. The complete suspension of this basic principle would make impossible the idea of the existence of (quasi-) closed systems and, thereby, the establishment of empirically testable laws in the sense familiar to us. (Einstein 1948, 321–322; author's translation)

Einstein's "principle of local action" and his "assumption of the mutually independent existence of spatially distant things" correspond, respectively, to the locality and separability principles.

Below I will consider the connection that Einstein suggests between these two principles and the possibilities of formulating and testing physical theories. For now I want to consider Einstein's comments about the manner in which field theories express the "assumption of the mutually independent existence of spatially distant things," the separability principle.

A field theory typically assumes as its fundamental ontology a set of points, a manifold in the parlance of the mathematician, together with a topology and a metric defined upon the points of that manifold. Partly for reasons of mathematical convenience, the topology is taken to be identical to that of a corresponding mathematical continuum—three-dimensional (R^3) in the case of classical field theories, four-dimensional (R^4) in the case of general relativity.[18] One does one's physics by first defining upon each of the points of this physical manifold mathematical structures representing the physical structures fundamental to that particular field theory, and then postulating fundamental laws governing the time-evolution of these mathematical structures (at least in the classical case) and the functional dependence of their values at any one point upon the values at other points. Thus, classical electrodynamics postulates a continuous, three-dimensional spatial manifold (once taken to constitute the aether), and defines at each of its points vectors representing the electric and magnetic fields, vectors whose evolution and functional relationships are governed by Maxwell's equations. General relativity postulates a continuous, four-dimensional space-time manifold, and defines upon its points the metric tensor and the stress-energy tensor governed by Einstein's gravitational field equations.[19]

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[18] Or at least the topology of any suitably small piece of the physical manifold is assumed to be identical with that of a piece of the appropriate mathematical continuum.

[19] How much of the structure defined upon the manifold is deemed to have physical content depends upon the particular field theory under consideration. For example, in classical electrodynamics the metrical structure, which determines the geometry of the manifold, is considered nonphysical, part of the *a priori* conceptual background of our physical theory, whereas general relativity invests this metrical structure with physical content. But for our immediate purposes, such differences are inessential.

But while different field theories may postulate different structures, what is essential to all field theories is that *some* structure is postulated and that this structure is assumed to be well defined at every point of the manifold. It is also an essential characteristic of field theories that the structure thus defined is taken to exhaust the physical reality that the theory aims to describe. To know the strength of the electric and magnetic fields (or the corresponding potentials) at every point of space in a given region is to know all there is to know about the electromagnetic field within that entire region. Similarly, to know the values of the ten components of the metric tensor at every point within a given region of the space-time manifold is to know all there is to know about the gravitational field in that region. In this sense, field theories are radically reductionistic: the whole reality of a field in a given region is contained in its parts, that is to say, its points.[20]

One consequence of this last characteristic of field theories will emerge with special significance. It is that when one sets about describing physical interactions within the framework of a field theory, the only way to do it is in terms of functional relationships among the structures separately well defined at each of the points involved in the interaction. Thus, the value of the electric field at point A may be changed by virtue of an interaction between the field at this point and the field at point B (typically a point immediately adjacent to A, the field at B itself interacting with one of its immediate neighbors, C, and so on); but the interaction can consist in nothing more than such a change in the value of the field *here* because of the value of the field *there*.

Einstein's point about separability and field theories is now twofold. First, in taking the field, understood as a continuous manifold of points, as the basic reality described by a theory, we tacitly assume that each point of the manifold constitutes a separate physical system. Thus my reading of Einstein's comment about "localiz[ing] within infinitely small . . . space-elements the elementary things existing independently of one another that it takes as basic." Second, by assuming that the fundamental structures defined on the manifold (like the vectors representing electric and magnetic fields, or the metrical and stress-energy tensors) are well defined at every point and that they exhaust the reality described by the theory, we tacitly assume that a separate physical state is assigned to each of the point-systems and that the joint state of any set of such point-systems is wholly determined by the states of its constituents. Thus, my reading of Einstein's remark about "localiz[ing] . . . the elementary laws it postulates for them [the point-systems]," since the fundamental structures (states) are what the fundamental laws govern.

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[20] This is not to deny that the value of a field at one point may be functionally dependent upon the values at other points. But even in such a case the value of the field is well defined at each point of the underlying manifold, and that is the property essential to a field theory.

Putting these two remarks together, we can now understand the larger point Einstein intended to make about field theories. It is that by modeling a physical ontology upon the ontology of the mathematical manifold, we take over as a criterion for the individuation of *physical* systems and states within field theories the mathematician's criterion for the individuation of *mathematical* points. This criterion is the existence between two points of a nonvanishing interval, which gets interpreted as a three-dimensional spatial interval in classical electrodynamics, and as a four-dimensional spatio-temporal or metrical interval in general relativity. In this way, field theories—as understood by Einstein—necessarily satisfy the separability principle.[21]

Einstein also remarked that field theories carry out the separability principle "to the extreme." What he means is simply that the field-theoretic criteria of individuation yield an ontology of infinitesimal point-systems. But this extreme is not required by the separability principle, which demands only that the presence of a nonvanishing spatio-temporal interval be a sufficient condition for the individuation of systems and states. One way to avoid the field-theoretic extreme is to admit physical systems only of finite magnitude in one's ontology. Thus, in classical mechanics, where the three-dimensional spatial manifold plays the role of a container, a background against which physical events are played out, and where the systems described may be of any finite size whatsoever, spatial separation is still, implicitly, a sufficient condition for individuation. Another way to avoid the field-theoretic extreme is to assume that there is a minimum finite spatial or spatio-temporal interval, as one does in "finite" or "discrete geometries." As long, however, as one takes the presence of intervals of this size or larger as a sufficient condition for individuation, the separability principle is still respected.[22]

A crucial assumption necessary to secure the possibility of the field-theoretic way of implementing the separability principle (or, for that matter, the possibility of *any* way of implementing it) is that the spatial or spatio-temporal intervals whose presence is taken to be a sufficient condition for individuation are in some sense *objective*. This is no problem in classical field theories, where the full Euclidean structure is taken for granted, and with it the objectivity of all spatial intervals. In general relativity, however, matters are more complicated, because here the metrical structure of space-time is incorporated into the physics of gravitation, with the consequence that spatial intervals lose the objectivity they possessed classically. But the spatio-temporal or metrical interval: $ds^2 = g_{ij}dx_idx_j$, is objective in general relativity, since it is invariant under arbitrary continuous coordinate transformations; this is why it takes the place of the spatial interval in the general relativistic version of separability. Indeed, one who demands separability in a physical theory may see in this circumstance an argument for covariance with respect to the group of continuous transformations as at least a minimum necessary condition on a physical theory, because enlargement of the transformation group threatens to deprive ds^2 of its invariant status.

One can, of course, employ the field-theoretic apparatus for the sake of its mathematical covenience, without thereby assuming that physical reality is represented by an ontology of separable point-systems. For the field can be regarded as an approximation to the physical reality being described, as in hydrodynamics, where the discontinuous molecular microstructure of a fluid is ignored for reasons of mathematical convenience. But in order to adopt this attitude—regarding the continuous field as approximating a reality with a different microstructure—it is necessary that one have in reserve an alternative criterion for the individuation of microsystems. In hydrodynamics, this criterion is provided by the atomic-molecular theory of the constitution of matter. The problem takes on a different aspect, however, in the case of field theories regarded as fundamental theories, where there is, by hypothesis, no other level of structure that could provide alternative criteria of individuation. Lacking such, it is hard to imagine any criterion other than that implicit in the structure of the mathematical manifold. This is not to say that there can be no alternative criteria of individuation; the point is rather that the criteria offered by the mathematical manifold seem more natural for lack of an evident alternative.[23]

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[21] The conception of field theories outlined here is similar in most respects to what is called in recent literature a "space-time theory"; see, for example, Friedman (1983, 32–70). The one important difference is that I do not insist that the states assigned to each point of the field correspond to a set of wholly definite properties. The historically important field theories, like classical electrodynamics and general relativity, have that form, but the basic field-theoretic structure is more general, allowing for states incorporating intrinsically indefinite properties (such as propensities), as long as the states themselves are definite, in the sense of being mathematically well defined. What is important is not the definiteness or indefiniteness of the properties, but the criteria whereby the systems and states are individuated. I should also note that my conception of field theories has even more in common with, indeed it is very nearly identical with the point of view that Paul Teller calls "particularism" (see Teller, this volume).

[22] This last observation implies that one does not deny the separability principle merely by assuming a discrete as opposed to a continuous manifold, as in theories postulating the existence of smallest possible "atoms" or "quanta" of space and time. Questions about separability cut deeper than the questions raised in the old debate over continuous versus discrete space and time.

[23] Notice that the ontology of field theories does not exclude the possibility of composite systems made up of sets of point-systems. But it does imply, first, that the state of any such composite system is completely determined by the separate states of its constituent point-systems, and, second, that under all circumstances the composite system is decomposable, in theory, into spatially (or spatio-temporally) individuated parts that are separable in the sense of possessing their own separate states that determine collectively the state of the whole, there being no theoretical limit to this decomposition excepting the ideal limit represented by the fundamental point-systems themselves.

Against the background furnished by the field-theoretic embodiment of the separability principle, the locality principle—Einstein's "principle of local action"—takes its traditional place, asserting that the state assigned to any point-system will be unaffected by events in "distant" regions, meaning, in the principle's relativistic versions, any events separated from the given point-system by a spacelike interval. The locality principle is thus an essential supplement to the separability principle, necessary to secure the traditional aim of field theories: elimination of action-at-a-distance, and with it the kind of ghostly conspiracies between events in different regions of the universe that could give rise to causal anomalies.

We commonly regard locality constraints as deriving from the first-signal principle of special relativity. Should the latter therefore be included among the theories whose employment of the typical field theoretic ontology convicts them also of endorsement of the separability principle? Special relativity can be formulated as a field theory; Minkowski was the first to do it in a formally satisfactory way. In this version, special relativity is necessarily a separable theory, the basic difference between special and general relativity being then simply that the former assumes a flat, quasi-Euclidean metric, and the latter a non-flat, variable metric. But the Minkowski formulation is only one version of special relativity, and it is an historical accident that we associate this formulation with the theory itself.

For our purposes, it is better to think of special relativity as an instance of what Einstein (1919) called a "theory of principle," consisting not of a constructive model—the manifold and metric of the Minkowski formulation—but of a set of regulative principles providing constraints on any possible constructive model. In the case of special relativity, these regulative principles are (1) the principle of (special) relativity itself, which asserts, in one version, the kinematic equivalence of all inertial reference frames, or that physical laws take the same form in all inertial frames, and (2) the light principle, which asserts that in an inertial frame the velocity of light is a constant, independent of the velocity of the source relative to that inertial frame. The first-signal principle and, thus, the locality principle, are arguably implied by (1) and (2), whereas the separability principle is not.

Now that we have a better understanding of how general relativity and other field theories satisfy the separability principle, let us reconsider more carefully the strong claims made above to the effect that (1) the Bell experiments imply the falsity of any fundamental microtheory based upon general relativity, and that (2) any such microtheory would be incompatible with quantum mechanics. My point is really a very simple one. To take general relativity—in its field theoretic formulation—as a basis for a fundamental microtheory is to take the ontology of general relativity as the starting point for the ontology of one's microtheory. It is to assume that, at root, the only reality is the space-time manifold and the mathematical structures (metric tensor, stress-energy tensor, etc.) defined upon the points of that manifold. And that means, most importantly, respecting the criteria of individuation for systems and states implicit in general relativity. In short, it means that one's microtheory will satisfy the separability principle.

One may want to define additional structures upon the points of the space-time manifold, say in order to explain interactions other than those mediated by gravitational and electromagnetic forces, but as long as these structures are well defined for every point of the manifold, and are understood as determining completely the relevant properties of any composite system, the separability principle will be satisfied. If one then employs this microtheory to explain the interactions investigated in the Bell experiments, one will, of necessity, assign separate states to the two interacting systems, of such a kind that the joint state is wholly determined by those separate states, and thus, one's description of the interaction will satisfy the separability condition. This already implies a fundamental incompatibility between such a theory and the quantum mechanical explanation of the interaction in question.

If, in addition to the assumption of the criteria of individuation inherited from general relativity—which entails satisfaction of the separability principle—one assumes locality, then the microtheory's account of the Bell interaction will necessarily give the wrong predictions for the correlation measurements in the Bell experiments, since it necessarily satisfies both the separability and the locality conditions. Thus, any fundamental microtheory built in this fashion upon the foundation of the field-theoretic space-time structure embodied in general relativity will be both empirically false and incompatible with quantum mechanics.

It might be argued that quantum field theories represent a counterexample to the point just made, inasmuch as they seem to combine the basic ontology of the space-time manifold with a typically nonseparable structure of quantum mechanical states. But if what I have argued up until now is correct, this is an impossible combination. And, in fact, the ontological picture of quantum field theories is not at all that clear, precisely because of its attempt to marry the field and particle ontologies at a fundamental level. The enterprise seems to succeed, after a fashion, for the quantum theory of free fields, the various states of which (aside from the vacuum state) can be identified with systems of noninteracting particles. But as soon as one attempts to describe interactions in the context of quantum field theory, the many notorious difficulties that have beset the program from its inception in the 1930s (e.g., the infinite self-energy of the electron, arising from its interaction with its own electromagnetic field) begin to set in, difficulties that can be remedied only by *ad hoc* expedients like renormalization. That the difficulties start here should come as no surprise, however, given the foregoing analysis; for it is precisely in the context of interactions that nonseparability rears its head.

3. *Arguments for separability (and for locality)*

In the long quotation above, Einstein argued that the separability principle is necessary because "without such an assumption of the mutually independent existence (the "being-thus") of spatially distant things . . . physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation" (Einstein 1948, 321). He followed this with an argument for the necessity of the locality principle, an argument that tied locality to the possibility of "establish[ing] . . . empirically testable laws in the sense familiar to us" (322).

But before looking into these arguments more closely, I want to consider another comment of Einstein's. It dates from March 1948, around the time when Einstein wrote the article containing the previous quotation. The occasion was Max Born's having sent to Einstein the manuscript of his Waynflete lectures (Born 1949), seeking Einstein's reaction to his discussion of Einstein's attitude toward quantum mechanics. Einstein responded with a number of what he himself characterized as "caustic marginal comments" (quoted in Born 1969, 221), and at the end of the manuscript he wrote the following:

> I just want to explain what I mean when I say that we should try to hold on to physical reality. We are, to be sure, all of us aware of the situation regarding what will turn out to be the basic foundational concepts in physics: the point-mass or the particle is surely not among them; the field, in the Faraday-Maxwell sense, might be, but not with certainty. But that which we conceive as existing ("actual") should somehow be localized in time and space. That is, the real in one part of space, *A*, should (in theory) somehow "exist" independently of that which is thought of as real in another part of space, *B*. If a physical system stretches over the parts of space *A and B*, then what is present in *B* should somehow have an existence independent of what is present in *A*. What is actually present in *B* should thus not depend upon the type of measurement carried out in the part of space, *A*; it should also be independent of whether or not, after all, a measurement is made in *A*.
>
> If one adheres to this program, then one can hardly view the quantum-theoretical description as a *complete* representation of the physically real. If one attempts, nevertheless, so to view it, then one must assume that the physically real in *B* undergoes a sudden change because of a measurement in *A*. My physical instincts bristle at that suggestion.
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> However, if one renounces the assumption that what is present in different parts of space has an independent, real existence, then I do not at all see what physics is supposed to describe. For what is thought to be a "system" is, after all, just conventional, and I do not see how one is supposed to divide up the world objectively so that one can make statements about the parts. (Einstein to Born, 24 March 1948, in Born 1969, 223–224; author's translation)

Part of this passage recapitulates in abbreviated form the argument that I earlier attributed to Einstein, in which the incompleteness of quantum mechanics is said to follow from the conjunction of the locality and separability principles. And the second paragraph evaluates the prospects for escaping this conclusion by denying locality. What most interests me, however, is the last paragraph, where Einstein considers the denial of separability.

Einstein's assertion that if separability is denied "then I do not at all see what physics is supposed to describe" echoes his previously quoted remark to the effect that the separability principle is a necessary condition for the possibility of formulating a physical theory. But now he adds a supporting argument. He says, first, that the concept of a "system" is conventional, by which I take him to mean that a criterion of individuation is, logically, a convention, dictated neither by empirical considerations, nor by *a priori* principles. Since we must therefore choose a criterion of individuation, so Einstein implies, we must at least choose an *objective* one. And, concluding, he suggests that the separability principle provides the only imaginable or conceivable objective criterion. Einstein is thus giving a *methodological* justification for the *physical* principle of separability—some scheme of individuation is needed if we are to formulate our theories—but the methodological argument rests upon a further *physical* assumption, namely, that spatio-temporal separation is the only conceivable objective criterion of individuation.

No one will deny the need for objective criteria of individuation. But there may be debate about Einstein's claim that the choice of a criterion is conventional, and there should be debate about the claim that separability is the only imaginable or conceivable objective criterion. What lies behind these two claims? Since Einstein himself offers no further explanation, let me offer a hypothetical reconstruction of his reasoning.

The thesis of the conventionality of criteria of individuation has both a global and a local context in Einstein's thinking. The global context is Einstein's articulation and defense, for at least the previous thirty years, of a conventionalist philosophy of science, conventionalist in roughly the holistic, Duhemian sense, similar in its essentials to the view that we now associate with the Quine of "Two Dogmas of Empiricism" (Quine 1951).[24] From this point of view, any assertion in a larger body of theory may be adjusted so as to secure the accommodation of the whole theory to the available evidence, since it is only the whole theory that stands the test of experience. That is to say, no part of a theory is granted immunity from revision on such grounds as its alleged *a priori* necessity, nor is the choice of the features to be revised forced upon us by experience. In short, every individual proposition belonging to a theory has the status of a convention.

This version of conventionalism must be contrasted with the Schlick-Reichenbach version, which confines the conventions to the coordinating definitions or bridge-principles—deeming these devoid of physical or empirical content—and maintains that the remaining genuinely empirical assertions each meet the test of experience individually (see, e.g., Schlick 1936, and Reichenbach 1924, 1–9). For our purposes, the point of the contrast between the two kinds of conventionalism is that the Duhem-Einstein-Quine variety accords the status of a convention not only to definitions, but also to assertions possessing physical content.[25] Thus, it is possible for Einstein to regard the choice of a criterion of individuation, a choice with abundant implications for the way we do physics, as a matter of convention.

The local context for Einstein's ascription of conventional status to criteria of individuation is his commitment to field theories. Ignore for the moment the implicit criterion of individuation that field theories borrow from the continuous mathematical manifold, and think of the "field" as an undifferentiated "stuff" filling space (or space-time). To do physics at all, we must somehow divide this undifferentiated "stuff" into distinct physical systems that will serve as the subjects of predication for our physics. But if this "field of stuff" is the fundamental physical reality, if, that is, no extrinsic criteria for the individuation of systems and states are found in another layer of structure, then the "field" does not of itself fall apart, as it were, along any inherent lines of division. Neither logic, nor *a priori* principle, nor experience compel us to partition the field in a given way.

Our choice of a partition has, therefore, the logical status of a convention, determined only by considerations of mathematical and physical convenience. Mathematical convenience is achieved by a partitioning that permits the employment of familiar tools, like the differential calculus. Physical convenience is achieved by one that conduces to the overall simplicity of our physical laws. The only conceivable *a priori* constraint upon the choice of a partitioning, or a criterion of individuation, is that the criterion be objective.

What then of Einstein's claim that the separability principle represents the only imaginable objective criterion of individuation? Since I will argue below that there are other objective criteria, it is important to understand how Einstein reached this conclusion. Notice, first, that he did not say that separability is the only *possible* objective criterion, but that it is the only *imaginable* or *conceivable* one, arguing that if separability is given up, then "I do not *see* how one is supposed to divide up the world objectively so that one can make statements about the parts." Imaginability or conceivability are subjective matters; we are each endowed with different powers. But *Einstein* did not suffer from a weak imagination. These capacities, though subjective, are conditioned by objective historical factors—to a large extent, what we can imagine or conceive depends upon how our imaginings and conceivings have been schooled, and most importantly upon the models with which we have been outfitted. So to understand what Einstein could or could not imagine or conceive, we must look to the relevant history.

And there is an interesting history, going back at least to the beginnings of atomism among the Greeks. There is an inherent logic of atomism that drives one, inevitably, regardless of where one begins, to three conclusions. The first of what I might call these "lines of force" in atomism leads through the distinction between primary and secondary qualities, to the Cartesian and Newtonian conclusion that only the "numerical" or "mathematical" properties of physical bodies count as objective, primary qualities. And even these are gradually pared away until one is left with a purely spatial property, such as *position*, as the sole objective criterion for distinguishing physical systems.

The second line of force leads through the doctrine of the divisibility of matter to the conclusion that no finite physical structures can be ultimate or fundamental, that any finite system must have concealed within it a deeper structure, more basic parts that can be taken apart, at least in theory, so that nothing short of the infinitesimal point-particle can be fundamental. And the third line of force leads through the impossibility of explaining interaction in terms of contact action between perfectly elastic ("hard") finite atoms, to the conclusion that the "spaces" between atoms must be filled continuously by something capable of mediating interactions.

All three conclusions met with criticism in their day. Leibniz was the most forceful critic of the first, arguing from the relational doctrine of space to the conclusion that position has no absolute significance and thus cannot serve as the ground for distinguishing physical systems. He stated this conclusion most clearly in a fragment from around 1696: "All things which are different must be distinguished in some way, and in the case of real things position

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[24] For further development and documentation of this theme, see Howard (1984, 1988).

[25] In casting doubt upon the analytic-synthetic distinction, this variety of conventionalism questions also the legitimacy of a principled distinction between definitions and empirical propositions. For Einstein's questioning of the latter distinction, see Einstein (1936, 316) and Howard (1988).

alone is not a sufficient means of distinction. This overthrows the whole of purely corpuscularian philosophy."[26] But none of the criticisms prevailed at the time, and with the emergence of the field-theoretic point of view in the late eighteenth and nineteenth centuries, in the work of Boscovich, Faraday, and Maxwell, the three lines of force of classical atomism found their ultimate expression.[27]

Einstein inherited this tradition, and his remarks about the separability principle as the only objective criterion of individuation must be seen against that background. His one major departure from the tradition, of course, was his siding with Leibniz in favor of the relational theory of space (or space-time). But he did not follow Leibniz all the way to the conclusion that adoption of the relational point of view deprives us of our last possible objective criterion of individuation. For while position loses its absolute, objective status from the relational point of view, Einstein saw where Leibniz did not that a frankly *relational* property, namely, spatial or spatio-temporal separation, in the guise of the metrical interval, can take the place of position as an objective ground for individuation, since it is a relativistic invariant.

Nevertheless, Einstein's way of seeing the world was shaped by this tradition, so much so that the *only* alternative he could find to position as a ground of individuation was another spatial (or, again, spatio-temporal) property. This constraint was made even more severe by Einstein's having collapsed the distinction between matter and space-time, between matter and geometry. For Einstein, all physical properties are, from a fundamental point of view, geometrical properties. The metrical interval being the only invariant among the geometrical properties, and hence the only objective property, means that it is the only candidate as a ground for individuation.

Thus Einstein's argument for the claim that the separability principle provides the only conceivable objective criterion of individuation, and that it is therefore necessary for the possibility of *formulating* physical theories. What about his related argument concerning both the separability and locality principles, to the effect that each is necessary for the possibility of *testing* physical theories—again a *methodological* argument? Recall his exact words. First, regarding separability: "Nor does one see how physical laws could be formulated *and tested* without such a clean separation." And then, regarding locality: "The complete suspension of this basic principle would make impossible the idea of the existence of (quasi-) closed systems and, thereby, the establishment of empirically testable laws in the sense familiar to us." Einstein gives us here again no further explanation of his reasoning, so we have to do more reconstruction.

Think about testing from an abstract point of view. We do physics by first dividing the world into parts that we call systems, then ascribing states to these systems, and then, finally, postulating laws governing the evolution of these states and their functional relationships. When we test, we look for some property thought to belong to a system in a given state because our laws imply the presence of that property—say a value of spin, position, or linear momentum—as the result of the system's evolution from an earlier state to the present one. We seek such properties through measurement, or more generally, observation. And if we are realistic in our attitude toward measurement, we assume that the result of a measurement is determined by the state of the measured system, at least to an extent sufficient to license inferences from measurement results to the presence or absence of the property sought.

Why would the separability principle be necessary for testing, understood thus? Einstein's answer is, I think, a simple one. Some method for individuating systems is necessary, for if one did not individuate, if one did not divide the world into parts, then the reference of any claims we might make about the world would be indefinite, or rather, the reference would comprehend the whole universe. One might make measurements, but *to what* would one ascribe the properties thought to be revealed by those measurements? Thus, some scheme of individuation is necessary. Believing that the presence of a spatio-temporal interval is the *only* objective basis for individuation, Einstein concludes that the separability principle is necessary to secure the possibility of testing as well as formulating theories.

What then about Einstein's claim that the locality principle is also necessary? The locality principle says that a system's state is not influenced by events in "distant" regions of space (or space-time). Suppose that we have suspended the locality principle, allowing such influences; suppose furthermore that we perform a measurement to test a claim about a system's being in a specific state, its possessing a specific property; and suppose finally that we

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[26] G. W. Leibniz, "[Sur le principe des indiscernables]" (1696), in *Opuscules et fragments inédits de Leibniz*, ed. L. Couturat (Paris: Alcan, 1903), p. 8; English translation "On the principle of indiscernibles," in *Leibniz: Philosophical Writings*, ed. G. H. R. Parkinson (London: Dent, 1973), p. 133. Berkeley was perhaps the most famous critic of the second line of thought, that leading to the existence of infinitesimals, though, of course, this criticism was directed primarily against infinitesimals in mathematics. He contended, among other things, that a composite whole could not contain an infinite number of parts (*The Analyst* [Dublin and London, 1734], reprinted in *The Works of George Berkeley*, vol. 3, ed. A. C. Fraser [Oxford: Clarendon Press, 1901], pp. 1–60; see especially Queries 5 and 19). The essential arguments in this controversy are preserved in Kant's second antinomy (*Kritik der reinen Vernunft* [Riga: Hartknoch, 1781], pp. 434–443), and they survive to this day in debates over continuous versus discrete geometries.

[27] I mean quite deliberately to deny the common representation of the difference between atomistic theories and field theories as a fundamental metaphysical difference. I see in field theories the inevitable culmination of the inherent logic of atomism; they represent atomism carried to its logical extreme—a sea of infinitesimal atoms, any two atoms having between them a continuum of other atoms.

get a result other than the predicted one. Does this mean that our claim about that system's being in that state was wrong? Not at all. It could always be the case that the measurement result was affected in some unforeseen fashion by one of these "distant" influences. Unless they are screened off, we cannot trust the measurement results to give us reliable information about the state of the observed system. Thus, Einstein says that the locality principle is necessary in order to secure the existence of closed systems, and *therefore* also to secure the possibility of testing theories.

Such an argument for the necessity of the locality principle does not aim to establish any particular upper bound on signal velocities as a necessary condition for theory testing. Instead, what it requires is a kind of theoretical closure. The project of physical science could withstand the discovery of super-luminal signals, for example, as long as a theory were developed to account for them. What Einstein's argument requires is that current physical theory establish *some* upper bound on signal velocities in order to secure the possibility of its own testing, recognizing full well that one possible—and not at all unreasonable—response to results inconsistent with the theory is to raise this upper bound. Testing becomes impossible only if the theory in question establishes *no* upper bound, for then one cannot define the concept of a "closed system."[28]

With Einstein's claim that the locality principle is a necessary condition for theory testing, I am in complete agreement, for exactly the reasons that Einstein gives. I agree as well with his claim that some scheme for individuating systems is necessary in order to formulate and test scientific theories. But I disagree with the more specific claim that the spatio-temporal separability principle is necessary, because I doubt Einstein's claim that it provides the only imaginable objective criterion of individuation. Agreeing with him on this last point would entail one's declaring the quantum theory, which violates the separability principle, to be, in effect, a fundamentally incoherent theory (and I suspect that such a worry lay behind Einstein's reservations regarding the quantum theory's candidacy as an acceptable fundamental theory). But this is a step that I do not feel compelled to take.

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[28] Notice the kind of argument that Einstein does not use to justify the locality principle. Historically, the concept of local action, a stepchild of the concept of contact action in the mechanistic worldview, was preferred because the alternative was thought to be inconceivable. Thus, both Hume and Berkeley argued that there is no clear idea corresponding to the concept of a force of gravity. But we now understand that the argument was really circular. Nonlocal action is inconceivable because we cannot conceive—what?—a mechanism that would explain it by the mediation of local effects. But this circularity was not so obvious to earlier generations of thinkers. And thus the felt need for aethers and other metaphysical anesthetics to dull the pain of a broken worldview. No—Einstein's argument is not that nonlocal action is inconceivable. It is easy to imagine such effects. The problem is that their existence would make hash of physical science.

4. The possibilities for a nonseparable ontology

Where do we stand now? To begin with, the empirical evidence of the Bell experiments forces us to give up either the separability principle or the locality principle. But there are good theoretical and methodological reasons for retaining the latter, since the locality principle is arguably entailed by special relativistic constraints on action-at-a-distance, and since it is also arguably a necessary condition for securing the testability of our theories. Let me now add two more reasons. First, Aspect's sophisticated version of the Bell experiment (Aspect, Dalibard, and Roger 1982), in which the orientations of the analyzers and thus the observables to be measured are switched while the particles are in flight, provides us with a lower bound on the speed of the superluminal signals whose existence would be entailed by denial of the locality principle. In theory, one could raise that lower bound arbitrarily, either by increasing the distance between the analyzers in the two wings of the experiment, or by increasing the frequency with which the analyzer orientations are switched. There is, however, no *a priori* reason to expect that the troublesome quantum correlations leading to violations of the Bell inequalities will disappear at any specific value of this lower bound, and so the strategy of denying the locality principle threatens to turn into what Lakatos called a degenerating research program.

Second, the locality principle partakes more of the character of those high-level principles, like the conservation of energy, the second law of thermodynamics, and the light principle—I like to call them regulative principles—that Einstein (1919) said should serve as constraints in the search for constructive theories, whereas the separability principle partakes more of the character of a constructive hypothesis. Like Einstein, I believe that ultimate understanding is provided only by a constructive theory; but, also like Einstein, I believe that any particular constructive hypothesis should bow to the authority of regulative principles that, like the locality principle, enjoy considerable empirical substantiation. And so I would argue that the locality principle ought to be given the benefit of the doubt. The burden of proof should fall upon those who prefer nonlocality to nonseparability.

That leaves repudiation of the spatio-temporal separability principle as the only alternative. But some criterion for individuating systems and states seems to be necessary if we are to formulate and test physical theories. So the question becomes, what are the alternatives to the separability principle, which means, more specifically, what kinds of comprehensive, fundamental nonseparable theories can we imagine?

Some constraints control our imaginings. Most importantly, the pattern of correlations revealed by the Bell experiments and predicted by the quantum theory must be reproduced by any acceptable fundamental theory, these correlations themselves playing the role of a kind of regulative principle guiding the search for constructive fundamental theories. And some features of general relativity should probably be preserved, if only in the macroscopic limit, such as the principle of general covariance (which may prove to be an extremely weak constraint) and the insight into the connection between geometry and gravitation. On the other hand, the field-theoretic criterion of individuation cannot play a fundamental role—at least not for the individuation of states. But within these constraints, we should give imagination free rein.

One might first ask whether or not quantum mechanics itself could serve as the starting point for a fundamental theory, since it is a local, nonseparable theory. What is more, it seems to supply an objective criterion of individuation alternative to the one provided by the spatio-temporal separability principle. For it appears that at least an operational criterion of individuation is available precisely in the *nonexistence* of the troubling kinds of quantum correlations that lead to violations of the Bell inequalities. Thus, any two regions of space-time between which such correlations did not exist would be accounted separate systems possessing their own separate states that wholly determine the joint state.

But there is a problem, because in theory any two regions of space-time between which there is a timelike separation have to be regarded as being in interaction with one another, owing to the pervasiveness of gravitational and electromagnetic forces. So there ought to be quantum correlations between *any* two such regions of space-time, however weak those correlations might be and however difficult they might be to detect experimentally. In many cases the correlations will be so weak as to be practically negligible, and thus we may have here a practical criterion of individuation. But at the level of fundamental theory, the proposed criterion of individuation—the nonexistence of quantum correlations—is almost no criterion at all, since the correlations are so widespread.

In fact, this problem is not merely an objection to regarding quantum mechanics as a satisfactory fundamental theory, it raises questions about the very coherence of quantum mechanics as it is ordinarily employed. Strictly speaking, the quantum theory of interactions implies that we should write down one grand nonfactorizable state function for the whole of the forward light cone of any event. Of course we do not do this, but we have *no* fundamental principle that justifies our ignoring this radical nonseparability of quantum states. As a practical matter, we say that the correlations are negligible in most cases, the fundamental theoretical problem being swept under the rug.

Another reason why quantum mechanics itself cannot serve as a model for a satisfactory fundamental theory is that while it individuates *states* in a nonseparable fashion, it nevertheless implicitly individuates *systems* according to the criterion assumed in the spatio-temporal separability principle. Will this work? My answer is, first, that I do not see the point of individuating systems and states differently. What is a system if it has *no* set of properties that it can call its own? In what sense can we even talk of a system if we cannot predicate anything of it alone? One might reply that systems individuated after the fashion of the separability principle still do have their own properties, such as mass or charge. But these properties are not sufficient to distinguish two otherwise identical systems in the same way that spatio-temporal separation is thought, classically, to be adequate for individuation. Moreover, it would be unwise to distinguish systems on the basis of properties like charge and mass when we lack a fundamental theory of those very properties, at least a fundamental microtheory for them.

There is, however, a still more serious objection to the reactionary strategy of clinging to spatio-temporal separation as a criterion of individuation for systems when it has been abandoned as a criterion of individuation for states. It is that quantum nonseparability infects even the spatio-temporal location of interacting systems, so that there is no objective basis for asserting, in the case of two interacting systems, A and B, that system A is at position x^A and system B at position x^B. At best, one can assign definite probabilities to the possible values of the *relative* separation between the two, but even then one cannot say which particle is which.

From one vantage point, this should not be surprising. In a fundamental theory of the kind sought by Einstein, at least, the aim—not yet achieved in general relativity—is to absorb *all* of the physical properties of systems into the geometry and topology of the universe; or, from another point of view, to absorb the geometry and (at least some of) the topology of the universe into the physics of the systems inhabiting that universe. We should expect that in such a fundamental theory *all* of the defining features of the space-time manifold would be candidates for inclusion among the properties determined by the physical states of our systems, just as the metrical structure of space-time is determined by the distribution of mass-energy in general relativity. But then, if the nonseparable manner of individuating states is to be the norm for all physical properties, it should affect also the spatio-temporal location of systems. The mistake is thinking that the structure of the space-time manifold can be insulated from the nonseparability that affects the rest of our physics, so that this manifold stands alone as a ground of individuation. And this is an objection not only to regarding quantum mechanics as a fundamental theory; it is objection to any attempt to retain the spatio-temporal separability of systems after having abandoned it for states.[29]

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[29] There are additional unsolved problems of interpretation in quantum mechanics to which one might also point as objections to according fundamental status to the quantum theory, such as the measurement problem and wave-packet reduction. But I do not cite them here, because I do

If quantum mechanics itself is not a candidate for the kind of fundamental nonseparable theory that we seek, what other possibilities exist? In particular, what are the possibilities for a theory that would be nonseparable both in the way it individuates states and in the way it individuates systems? We might, of course, be driven back to the tacit quantum-mechanical strategy of a nonseparable scheme for individuating states combined with a more classical field-theoretic scheme for individuating systems. But let us try the more radical program, if only to see how far it can be pressed before it fails.

Notice that we pass here from the realm of analytical metaphysics—where we try to uncover and assess the metaphysical implications of existing physical theory—into the realm of speculative metaphysics—where we try to extend existing physical theory, guided by the insights gained through the earlier analysis. Such speculations make no pretense to being themselves adequate physical theories. They are, instead, just the philosopher's hints and suggestions, there for the physicist to do with as he or she sees fit.

One possibility that comes quickly to mind involves a reconsideration of the nature and role of the metrical interval in field theories modeled upon general relativity. What enabled Einstein to regard the existence of a nonvanishing metrical or spatio-temporal interval as a criterion of individuation for systems and states is the fact that, within general relativity, the metrical interval is invariant under arbitrary continuous coordinate transformations. But what if we could construct a theory within which what appears from one point of view to be a non-null metrical interval separating two regions of space-time appears to be a null interval from another point of view? By ''point of view'' I mean here neither a reference frame nor a coordinatization, but something more like the kind of interaction between the two regions.

The result would be a *contextual* criterion of individuation—two systems distinguished from the point of view of one kind of interaction, say a gravitational one, may count as but one system from the point of view of another kind of interaction, say one governed by the strong nuclear force. Only if the two regions were separable from all points of view would they be considered totally separable, constituting two genuinely distinct physical systems.

How might this idea be realized mathematically? Perhaps we need a structure like the ordinary four-dimensional space-time manifold upon which we construct several overlapping geometries, a gravitational geometry, an electromagnetic geometry, and so forth, each with its own metric. I am tempted to suggest that gravity would be responsible for the macrogeometry of the universe, the other forces giving rise to microgeometries on ever smaller scales, geometries responsible for tiny ''wrinkles'' in the macrogeometry. But, of course, there cannot be such a simple hierarchy of scales, for quantum mechanics implies that the nonseparability arising from electromagnetic or weak nuclear interactions can affect regions of space-time ''separated'' in the sense of the gravitational geometry by intervals of arbitrary magnitude.

Another way to realize the idea of individuations relative to different kinds of interactions involves a higher-dimensional theory, say one in which gravity is responsible for the geometry of the ordinary four dimensions of space and time, with other forces being responsible for the geometries of the higher dimensions. Thus two systems might be separable within the first four dimensions, that is to say, separated by a nonvanishing metrical interval that is invariant under arbitrary continuous four-dimensional transformations, but nonseparable in some of the higher dimensions. A third realization might involve the introduction of different manifolds, each with its own metric, for the different interactions.

Proceeding in any of these ways, we might find that from the point of view of the geometry of gravitation all regions of space-time are in fact separable, nonseparability being confined to the microgeometry or to the geometries of other dimensions. My guess, however, is that nonseparability arises from gravitational interactions as well, but that the resulting quantum-gravitational correlations are so weak as not to be evident in most situations.

The second to the last of the just-mentioned alternatives, that involving higher-dimensional geometries, would present to us the aspect of what might be termed ''backdoor'' connections, higher-dimensional connections between systems that appear distinct within the ordinary four dimensions. One can imagine yet another, far more unusual way to realize ''backdoor'' connections. This would involve just a four-dimensional manifold, but one with a topology different from that assumed in general relativity. And it would involve identifying the physical systems not with pieces of the manifold, but with various kinds of holes in the manifold. What I have in mind may be represented by a two-dimensional model of a sheet with two ''holes'' in it that are connected by a ''tube.'' Let the ''holes'' represent two apparently distinct systems, the apparent ''distance'' between them over the sheet being relatively large, and let the ''tube'' represent the connection between them engendered by a previous interaction. What appear to be two distinct ''holes'' from

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not believe that they are the deep problems they are frequently taken to be. It is not often enough stressed that both problems concern interactions, this being, again, the context in which quantum nonseparability is evinced. The problem of measurement arises only because the nonfactorizability of the post-measurement joint object-apparatus state leads to the apparatus's being afflicted by the same indefiniteness that originally afflicted the object. For its part, wave-packet reduction is held to occur only when we perform an observation, which is to say only when the system in question interacts with another system. Neither of these problems will find a satisfactory solution until we have a better understanding of nonseparability.

within the sheet, appear to be merely the "ends" of just a single tubular "channel" from within the "tube." Moreover, the "distance" through the "tube," that is to say the "length" of the "tube," may be made as small as we wish, depending upon the strength of the interaction, by manipulating the metric within the "tube." We can even imagine "tubes" that grow "longer" and "thinner" as the correlations engendered by an interaction grow weaker. And we can also imagine new "tubes" growing as new interactions arise, growing perhaps out of "pipettes"—extremely "thin" "tubes" that we may assume always to connect any two regions of the sheet.

The limit case, perhaps corresponding to such phenomena as pair-creation, may be represented by a "thread"—an infinitely "thin" and sometimes infinitely "short" "pipette"—blossoming into a "tube." There is even room here for deeper layers of structure, for we may imagine both "intratubes" connecting two regions of the wall of a single "tube," and "intertubes" connecting regions of the walls of different "tubes." There is no limit to the depth of structure achievable in this way. And the resulting picture of an infinitely complex "tubular" lattice is really quite a beautiful one. Notice that this suggestion requires our making not only the geometry of the universe dependent upon dynamical considerations, but also the fine details of topological structure as well. I actually find this an attractive feature of the model, because I have long been puzzled as to why in general relativity there is in some respects an *a priori* topological structure, whereas the geometry is merged with the physics. If one can entertain a geometrodynamics, why not also a topodynamics?

Allow me to describe now one final possibility that I can imagine for a fundamental nonseparable theory, the one that is the most radical from an ontological point of view. Earlier, I conceded that some criterion, at least, for the individuation of systems is necessary in order for us even to formulate a physical theory. Perhaps that was too hasty a concession. Perhaps it is possible to adopt a kind of radical ontological holism in which the whole of the forward light cone of any event is regarded as one nonseparable whole because of the pervasiveness of physical interactions, and yet to do this without lapsing into the silence of scientific nirvana. That is to say, maybe we can opt for radical ontological holism and still do some physics.

The possibility of this approach is suggested by a feature of the quantum-mechanical interaction formalism that is too often not emphasized. For while it is true that quantum mechanics assigns to previously interacting systems a single, nonfactorizable joint state, it is also true that once one specifies a "measurement-context," that is to say a set of co-measurable observables for both systems, one can then always construct a factorizable joint state (strictly speaking, a mixture over factorizable joint states) that will give the same predictions for measurements of those observables that would otherwise be given by the nonfactorizable joint state.[30] Of course, this factorizable joint state will always give the wrong predictions for at least one observable not belonging to the set that defines the original context, but this circumstance, which is but a symptom of the underlying nonseparability, does not detract from the fact that, for the observables associated with the specified context, the factorizable state gives all of the right predictions. And one may even pretend, if one wishes, that the separate factors of this joint state are associated with physically separate systems, as long as one remembers that this is really not the case.

The application of contextual factorizability or contextual separability in a fundamental theory should be obvious. The contents of the forward light cone of any event would constitute a single, nonseparable whole, and this single "system" would be assigned a single, nonfactorizable joint state for all properties, including spatio-temporal location. But in any given context, that is, given a specification of the observables we wish to investigate, we can always find a factorizable state description giving us all of the information we need. This factorizable state description would not be the whole truth, but it would represent all of the truth that is accessible in the given context. Or to put the idea differently, the universe is "really" one, but once we put a specific question to it, it falls apart quite naturally into apparent parts.

There you have it. If these metaphysical speculations are a bit woolly-headed, so be it. As I said, it is up to the physicist to decide what to do with them. But there is a limit to my woolly-headedness. About two things I am quite serious. The first is that the problem of nonseparability must be faced squarely. Quantum mechanics is nonseparable, at least when it comes to the individuation of states, but it is not a fundamental theory. At the same time, the nonseparability evinced by quantum mechanics and confirmed by the Bell experiments (assuming that we retain locality) suggests that the route to a satisfactory fundamental theory does not lie through traditional field theories, like general relativity, owing to their manner of individuating systems and states according to the spatio-temporal separability principle. We are thus a long way from finding the kind of fundamental theory that we need.

The second point about which I am serious is that the construction of a satisfactory fundamental theory will require creative imagination of a kind all too rare among contemporary physicists and philosophers of science. What I am talking about is the need for speculative metaphysics, a kind of imagining that by definition carries us beyond the bounds of current physical theory. Here is one place where the philosopher, who should be less inhibited than the physicist, can help to show the way.

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[30] The relevant theorem is proved in Howard (1979, 382–386).