Holism ~~in Physics~~

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1 Introduction

In slogan form, holism is the obscure thesis that the whole is more than the sum of its parts. Physics has been taken to exhibit holism of various kinds, associated with different ways of trying to make this thesis clear. As a first step, consider the claim that a whole has features that cannot be reduced to features of its parts. If we take the features of a physical system to include its behavior, and reduction to involve explanation, then we arrive at a thesis of explanatory or methodological holism. A methodological holist maintains that it is impossible to arrive at an adequate understanding of some physical system's behavior by analyzing that system into its constituent parts and appealing to the laws that apply to them.

Alternatively, reduction may be considered more a matter of metaphysics than epistemology. On a more metaphysical approach, holism is the view that the existence or features of some physical whole are not determined by the existence and features of its constituent parts.[1] Some believe that quantum systems display this kind of holism. After a section discussing methodological holism in physics, the rest of this entry considers whether our physical theories imply such metaphysical holism.

2 Methodological Holism

Methodologically, holism stands opposed to reductionism, somewhat as follows.

> *Methodological Holism*: An understanding of a certain kind of complex system is best sought at the level of principles governing the behavior of the whole system, and not at the level of the structure and behavior of its constituent parts.
>
> *Methodological Reductionism*: An understanding of a complex system is best sought at the level of the structure and behavior of its constituent parts.

Methodological reductionists favor an approach to (say) condensed matter physics which seeks to understand the behavior of a solid or liquid by applying quantum mechanics (say) to its constituent molecules, atoms, ions or electrons. Methodological holists think this approach is misguided: As one condensed matter physicist put it "the most important advances in this area come about by the emergence of qualitatively new concepts at the intermediate or macroscopic

[1] Metaphysical holism may be compatible with the denial of methodological holism: some parts with their features may not determine what whole they compose and so what laws they obey.

levels — concepts which, one hopes, will be compatible with one's information about the microscopic constituents, but which are in no sense logically dependent on it." (Leggett 1987, p.113)

It is surprisingly difficult to find methodological reductionists among physicists. The elementary particle physicist Steven Weinberg, for example, is an avowed reductionist. He believes that by asking any sequence of deeper and deeper why-questions one will arrive ultimately at the same fundamental laws of physics. But this explanatory reductionism is metaphysical in so far as he takes explanation to be an ontic rather than a pragmatic category. On this view, it is not physicists but the fundamental laws themselves that explain why "higher level" scientific principles are the way they are. Weinberg (1992) explicitly distinguishes his view from methodological reductionism by saying that there is no reason to suppose that the convergence of scientific explanations must lead to a convergence of scientific methods.

3 Metaphysical Holism

The metaphysical holist believes that the nature of some wholes is not determined by that of their parts. One may distinguish three varieties of metaphysical holism: ontological, property and nomological holism.

> *Ontological Holism*: Some objects are not wholly composed of basic physical parts.[2]

[2] ~~This is compatible with physicalism if whatever physical entities are considered basic in fact fail to wholly compose such objects.~~

Property Holism: Some objects have properties that are not determined by physical properties of their basic physical parts.

Nomological Holism: Some objects obey laws that are not determined by fundamental physical laws governing the structure and behavior of their basic physical parts.

All three theses require an adequate clarification of the notion of a basic physical part. One way to do this would be to consider objects as basic, relative to a given class of objects subjected only to a certain kind of process, just in case every object in that class continues to be wholly composed of a fixed set of these (basic) objects. Thus, atoms would count as basic parts of hydrogen if it is burnt to form water, but not if it is converted into helium by a thermonuclear reaction. But this way excludes consideration of the metaphysician's time-slices and the physicist's point events (for example) as basic (spatio)temporal parts of an object. What counts as a part, and what parts are basic, are matters best settled in a particular context of enquiry.

Weinberg's (1992) reductionism is opposed to nomological holism in science. He claims, in particular, that thermodynamics has been explained in terms of particles and forces, which could hardly be the case if thermodynamic laws were autonomous. In fact thermodynamics presents a fascinating but complex test case for the theses both of property holism and of nomological holism.

One source of complexity is the variety of distinct concepts of both temperature and entropy that figure in both classical thermodynamics and statistical mechanics. Another is the large number of quite differently constituted systems to which thermodynamics can be applied, including not just gases and electromagnetic radiation but also magnets, chemical reactions, star clusters and black holes. Both sources of complexity require a careful examination of the extent to which thermodynamic properties are determined by the physical properties of the basic parts of thermodynamic systems.

A third difficulty stems from the problematic status of the probability assumptions that are required in addition to the basic mechanical laws in order to recover thermodynamic principles within statistical mechanics. An important example is the assumption that the micro-canonical ensemble is to be assigned the standard, invariant, probability distribution (see the chapters by Frigg and Werndl in this volume.) Since the basic laws of mechanics do not determine the principles of thermodynamics without some such assumptions (however weak), there may well be at least one interesting sense in which thermodynamics establishes nomological holism.

4 Property/Relational Holism

While some form of ontological holism has occasionally been considered (see section 7), the variety of metaphysical holism most clearly at issue in quantum mechanics is property holism. But to see just what the issue is we need a more careful formulation of that thesis.

First the thesis should be contextualized to physical properties of composite physical objects. We are interested here in how far a physical object's *physical* properties are fixed by those of its parts, not in some more general determinationist physicalism. Next, to arrive at an interesting formulation of property holism we must accept that this thesis is not only concerned with monadic properties, and not concerned with all properties. The properties of a whole will typically depend upon relations among its proper parts as well as on properties of the individual parts. But if we are permitted to consider all properties and relations among the parts, then these trivially determine the properties of the whole they compose. For one relation among the parts is what we might call the complete composition relation — that relation among the parts which holds just in case they compose this very whole with all its properties.

Let us call a canonical set of properties and relations of the parts which may or may not determine the properties and relations of the whole the *supervenience basis*.[3] To avoid trivializing the theses we are trying to formulate, only certain properties and relations can be allowed in the supervenience basis. The intuition as to which these are is simple — the supervenience basis is to include just the qualitative intrinsic properties and relations of the parts, i.e., the properties and relations which these bear in and of themselves, without regard to any other objects, and irrespective of any further consequences of their bearing these properties for the properties of any wholes they might compose. Unfortunately, this simple intuition resists precise formulation. It is notoriously difficult to say precisely what is meant either by an intrinsic property or relation, or by a

[3] See, for example, Dean Rickles "Supervenience and Determination", *Internet Encyclopedia of Philosophy* http://www.iep.utm.edu/superven/ .

purely qualitative property or relation.[4] And the other notions appealed to in expressing the simple intuition are hardly less problematic. But, imprecise as it is, this statement serves already to exclude certain unwanted properties and relations, including the complete composition relation, from the supervenience basis.

Finally, we arrive at the following opposing theses:

Physical Property Determination: Every qualitative intrinsic physical property of and relation among some physical objects from any domain D subject only to type P processes supervenes on qualitative intrinsic physical properties and relations in the supervenience basis of their basic physical parts relative to D and P.

Physical Property Holism: There are some physical objects from a domain D subject only to type P processes, not all of whose qualitative intrinsic physical properties and relations supervene on qualitative intrinsic physical properties and relations in the supervenience basis of their basic physical parts (relative to D and P).

If we take the real state of some physical objects to be given by their qualitative intrinsic physical properties and relations, then physical property determination says (while physical property holism denies) that the real state of wholes is determined by the real state of their parts.

There is some residual unclarity in the notion of supervenience that figures in these theses. The idea is familiar enough — that there can be no relevant

[4] See, for example, Weatherson and Marshall (2017).

difference in objects in D without a relevant difference in their basic physical parts. I take it that the modality involved here is not logical but broadly physical or perhaps metaphysical. One might try to explicate the notion of supervenience here in terms of models of a true, descriptively complete, physical theory. At issue is whether such a physical theory has two (kinematically possible) models which agree on the qualitative intrinsic physical properties and relations of the basic parts of one or more objects in D but disagree on some qualitative intrinsic property or relation of these objects.

Teller (1989) has introduced the related idea of what he calls relational holism.

Relational Holism: There are non-supervening relations — that is, relations that do not supervene on the nonrelational properties of the relata. (p. 214)

Within physics, this specializes to a close relative of physical property holism, namely:

Physical Relational Holism: There are physical relations between some physical objects that do not supervene on their qualitative intrinsic physical properties.

Physical property holism entails physical relational holism, but not vice versa. For suppose that F is some qualitative intrinsic physical property or relation of one or more elements of D that fails to supervene on qualitative intrinsic physical properties and relations in the supervenience basis of their basic physical parts. We may define a (non-intrinsic) physical relation R_F to hold of the basic physical parts of elements of D if and only if F holds of these elements.

Clearly R_F does not supervene on the qualitative intrinsic physical properties of these parts. So physical property holism entails physical relational holism. But the converse entailment fails. For let R_G be a physical relation that holds between the basic parts of some elements in D when and only when those elements are in the relation S_G. R_G may fail to supervene on the qualitative intrinsic physical properties of these basic parts, even though all qualitative intrinsic physical properties and relations of elements of D (including S_G) supervene on the qualitative intrinsic physical properties and relations of their basic parts.

Physical relational holism seems at first sight too weak to capture any distinctive feature of quantum phenomena: even in classical physics the spatiotemporal relations between physical objects seem not to supervene on their qualitative intrinsic physical properties. But when he introduced relational holism Teller (1987) maintained a view of space-time as a quantity: On this view spatiotemporal relations do in fact supervene on qualitative intrinsic physical properties of ordinary physical objects, since these include their spatiotemporal properties.

5 Holism in Classical Physics?

At least classically, spatial relations provide the only clear examples of qualitative intrinsic physical relations required in the supervenience basis for physical property determination/holism: other intrinsic physical relations seem to supervene on them. But if one thought a spatially localized object had a determinate value for a magnitude like mass only by virtue of its mass relations to other such objects elsewhere then one might decide to include those relations in the supervenience basis also (see Dasgupta (2013)).

The assumption that all physical processes are completely described by a local assignment of values to magnitudes forms part of the metaphysical background to classical physics. In Newtonian space-time, the kinematical behavior of a system of point particles under the action of finite forces is supervenient upon ascriptions of particular values of position and momentum to the particles along their trajectories. This supervenience on local magnitudes extends also to dynamics if the gravitational or other forces on the particles arise from fields defined at each space-time point.

The boiling of a kettle of water is an example of a more complex physical process. It consists in the increased kinetic energy of its constituent molecules permitting each to overcome the short range attractive forces which otherwise hold it in the liquid. It thus supervenes on the assignment, at each space-time point on the trajectory of each molecule, of physical magnitudes to that molecule (such as its kinetic energy), as well as to the fields that give rise to the attractive force acting on the molecule at that point.[5]

There is no hint of holism in examples like these. Instead, each seems to illustrate classical physics's conformity to physical property determination, insofar as physical properties and relations of the constituent particles or molecules determine the physical properties and relations of the physical system they compose. But these are not the only relevant physical systems here. There is also

[5] Such phase changes present problems when modeled within statistical mechanics (see Bangu's chapter in this volume and Butterfield (2011).

the field that gives rise to the forces to which these constituents are subjected.

A classical field is a physical system in which one or more physical magnitudes take values at points of space-time. Each actual value may be considered a property of that space-time point or of the part of the field that occupies it: in either case, the physical system that bears the property may be considered a basic part of a larger whole, of the field or the whole of space-time, respectively.

As an example of a process in Minkowski space-time (the space-time of Einstein's special theory of relativity[6]), consider the propagation of an electromagnetic wave through empty space. This supervenes upon the values of local magnitudes—the components of the electromagnetic field tensor—at each point in space-time. Like the previous examples, this process apparently conforms to the principle of

(*Spatio-temporal) Separability*: Any physical process occupying space-time region R supervenes upon an assignment of qualitative intrinsic physical properties at space-time points in R.[7]

But one may question whether an assignment of values to basic physical magnitudes at space-time points amounts to or results from an assignment of qualitative intrinsic properties at those points. Take instantaneous velocity, for example: this is usually defined as the limit of average velocities over successively smaller temporal neighborhoods of that point. This provides a reason to deny that the instantaneous velocity of a particle at a point supervenes on qualitative intrinsic properties assigned at that point. Similar skeptical doubts can be raised

[6] See section 2 of this volume for more details.

[7] For this and related notions of separability, see Healey (2016a).

about the intrinsic character of other “local” magnitudes such as the density of a fluid, the value of an electromagnetic field, or the metric and curvature of space-time (see Butterfield (2006)).

One response to such doubts is to admit to a minor consequent violation of spatio-temporal separability while introducing a weaker notion, namely

Weak Separability: Any physical process occupying space-time region R supervenes upon an assignment of qualitative intrinsic physical properties at points of R and/or in arbitrarily small neighborhoods of those points; along with a correspondingly strengthened notion of

Strong Nonseparability: Some physical process occupying a region R of space-time is not supervenient upon an assignment of qualitative intrinsic physical properties at points of R and/or in arbitrarily small neighborhoods of those points.

Strong nonseparability implies physical property holism in a physical system, some of whose basic physical parts are or occupy space-time points. But no such holism need be involved in a process that is nonseparable, but not strongly so, as long as the basic parts of the relevant system are themselves taken to be associated with neighborhoods rather than points.

Any physical process fully described by a local space-time theory will be at least weakly separable. For such a theory proceeds by assigning geometric objects (such as vectors or tensors) at each point in space-time to represent physical fields, and then requiring that these satisfy certain field equations. But processes described by theories of other forms will also be separable, including theories of collision which assign magnitudes to particles at each point on their trajectories. Of familiar classical theories, it is only theories involving direct action between spatially separated particles which involve nonseparability in their description of the dynamical histories of individual particles. But such processes are weakly separable within space-time regions that are large enough to include all sources of forces acting on these particles, so that the appearance of strong nonseparability may be attributed to a mistakenly narrow understanding of the space-time region these processes actually occupy.

The propagation of gravitational energy according to general relativity apparently involves strongly nonseparable processes, since gravitational energy cannot be localized (it does not contribute to the stress-energy tensor defined at each point of space-time as do other forms of energy—see section 3 of this volume for further details). But even a non-locally-defined gravitational energy will still be supervenient upon the metric tensor defined at each point of the space-time, and so the process of its propagation will be weakly separable.

The definition of spatio-temporal separability becomes problematic in general relativity, since its application requires that one identify the same region R in possible space-times with different geometries. But while there is no generally applicable algorithm for making a uniquely appropriate identification, some identification may appear salient in a particular case. For example, one can meaningfully discuss whether or not the field is the same everywhere in the region outside the solenoid in the Aharonov-Bohm effect[8] with an increased cur-

[8] See, for example, Feynman's *Lectures on Physics, Volume II* Section 15.5.

rent flowing, even though the size of the current will have a (tiny) influence on the geometry of that region. Note that the definition of nonseparability does not require that one identify the same point in space-times of distinct geometries.

While strictly outside the domain of classical physics, quantum phenomena such as the Aharonov-Bohm effect may be thought to manifest holism due to the failure of spatio-temporal separability even in *classical* electromagnetism. What lies behind this thought is that a satisfactory explanation of the effect apparently requires attribution of intrinsic electromagnetic properties to *loops* in space-time (see Healey (2016a), section 10). But electromagnetism is still weakly separable here, since one can take these loops to be arbitrarily small. So classical electromagnetism manifests no physical property holism, even in phenomena like the Aharonov-Bohm effect.

Separability would be a trivial notion if no qualitative intrinsic physical properties were ever assigned at space-time points or in their neighborhoods. But this would require a thorough-going relationism that took not just geometric but all local features to be irreducibly relational (cf. Esfeld (2004)).

6 Quantum Holism?

The main reason to believe quantum systems exhibit holism is quantum entanglement. In the first instance entanglement is a relation between not physical but mathematical objects representing the states of quantum systems. Different forms of quantum theory represent quantum states of various systems by different kinds of mathematical object. So the concept of quantum entanglement has been expressed by a family of definitions, each appropriate to a specific form and application of quantum theory (see Earman (2015)). The first definition (Schrödinger (1935)) was developed in the context of applications of ordinary non-relativistic quantum mechanics to pairs of distinguishable particles that have interacted, such as an electron and proton.

A hydrogen atom may be represented in ordinary non-relativistic quantum mechanics as a quantum system composed of two subsystems: an electron e and a nuclear proton p. When isolated, its quantum state may be represented by a vector Ψ in a vector space H constructed as a tensor product of spaces H_p and H_e used to represent states of e,p respectively. The states of e,p are then defined as entangled if and only if

$$\Psi \neq \Psi_p \otimes \Psi_e$$

for every pair of vectors Ψ_p, Ψ_e, in H_p and H_e respectively. This definition naturally generalizes to systems composed of n distinguishable particles. But alternative definitions seem preferable for a collection of indistinguishable particles—of electrons or of photons for example (see Ghirardi et al. (2002), Ladyman et al. (2013), Ladyman (this volume)).

It follows that the states of the electron and proton in an isolated hydrogen atom are entangled. But one may also represent the hydrogen atom as composed of a center-of-mass subsystem C and a relative subsystem R represented by vector states Ψ_C, Ψ_R in H_C, H_R respectively such that

$$\Psi = \Psi_C \otimes \Psi_R$$

If the state of the hydrogen atom is represented by Ψ then the states of quantum subsystems C,R are not entangled but the states of quantum subsystems p,e are entangled. This illustrates the important point that one cannot draw metaphysical conclusions from a mathematical condition of quantum entanglement without first deciding which quantum systems are physical parts composing some physical whole. It may seem natural to take the physical parts of a hydrogen atom to be an electron and a proton. But note that the state of an isolated hydrogen atom is usually represented by Ψ_R, and not by Ψ or Ψ_e.

Viewed as basic physical parts of a hydrogen atom represented by state Ψ, its electron and proton may be considered entangled component subsystems since Ψ cannot be expressed as a product of vectors representing the state of each. The electron and the proton may each be assigned a mixed state, but this pair of states does not uniquely determine the state Ψ: these quantum state assignments violate the following condition.

> *State Separability:* The state assigned to a compound physical system at any time is supervenient on the states then assigned to its component subsystems.

This may occasion no surprise if a system's quantum state merely specifies its chances of exhibiting various possible properties on measurement. But it may have metaphysical significance if its quantum state plays a role in specifying a system's categorical properties—its real state, so that the real state separability principle is threatened.[9]

[9] ~~See Maroney (this volume) for more on these alternative readings of the quantum state.~~

> *Real State Separability Principle*:The real state of the pair AB consists precisely of the real state of A and the real state of B, which states have nothing to do with one another.[10]

His commitment to this last principle is one reason why Einstein denied that a physical system's real state is given by its quantum state (though it's not clear what he thought its real state consisted in). But according to (one variant of) the rival Copenhagen interpretation, the quantum state gives a physical system's real dynamical state by specifying that it contains just those qualitative intrinsic quantum dynamical properties to which it assigns probability 1. On this last interpretation, violation of state separability in quantum mechanics leads to physical property holism: it implies, for example, that a pair of fundamental particles may have the intrinsic property of being spinless even though this is not determined by the intrinsic properties and relations of its component particles.

If an entangled vector state of a pair of quantum systems violates state separability then there are measurements of dynamical variables (one on each subsystem) whose joint quantum probability distribution cannot be expressed as a product of probability distributions for separate measurements of each variable. Quantum theory predicts such a probability distribution for various types of spatially separated measurements of variables including spin and polarization components on a pair of entangled physical entities assigned such a state, and many of these distributions have been experimentally verified.[11]

[10] This principle was stated (in German) by Einstein in a letter to Schrödinger dated June 19th, 1935.

[11] See, for example, Aspect *et al.* (1981, 1982), Henson *et al.* (2015), Giustina *et al.* (2015).

Bell (1964, [2004]) considered a class of theories that introduce additional (so-called) hidden variables λ and so permit a more complete description of such systems than that provided by their entangled quantum state. He reasoned that in order to reproduce all quantum predictions for the possible outcomes of spatially separated measurements on such an entangled pair, any such theory must yield a probability of 0 or 1 (conditional on the value of λ) in order to satisfy the locality condition that neither outcome depends on the choice of distant measurement. He then proved that the probabilistic predictions of any such local hidden variable theory must satisfy particular (Bell) inequalities violated by predictions of quantum theory for certain entangled state assignments.

In later work Bell (1990, [2004]) generalized this result to any theory of a certain type meeting a condition he called Local Causality which, he argued, quantum mechanics does not meet. He motivated this condition by appeal to an intuitive principle closely related to Einstein's (1948) principle of

> *Local Action*: If A and B are spatially distant things, then an external influence on A has no immediate effect on B.

Howard and Teller sought to defend Local Action against Bell's argument. Teller (1989) took violation of Bell's inequalities to be a manifestation of Relational Holism. Howard (1989) instead blamed their violation on the failure of the following separability condition:

> *Howard Separability*: The contents of any two regions of space-time separated by a nonvanishing spatiotemporal interval constitute sep-

> arable 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.

Henson (2013) and others have questioned this line of reasoning, including the conclusion that its appeal to holism or nonseparability helps one to understand how these correlations involving entangled systems come about without any action at a distance that violates relativity theory, Local Causality or Einstein's principle of Local Action.

While diverging from the Copenhagen prescription mentioned above, some modal interpretations[12] take real states of systems to be closely enough related to quantum states that entangled systems' violation of (quantum) state separability implies some kind of holism or nonseparability. Van Fraassen (1991, p. 294), for example, sees his modal interpretation as committed to "a strange holism" because it entails that a compound system may fail to have a property corresponding to a tensor product projection operator $P \otimes I$ even though its first component has a property corresponding to P. In fact, a clearer case of holism would arise in a modal interpretation that implied that the component lacked P while the compound had $P \otimes I$: *ceteris paribus*, that would provide an instance of physical property holism.

Healey (1989,1994) offered a modal interpretation and used it to present a model account of Bell's puzzling correlations which portrays them as resulting from the operation of a process that violates both spatial and spatiotemporal

[12] See Lombardi and Dieks (2017), especially section 6.

separability. He argued that, on this interpretation, the nonseparability of the process is a consequence of physical property holism; and that the resulting account yields genuine understanding of how the correlations come about without any violation of relativity theory or Local Action. But subsequent work by Clifton and Dickson (1998) and Myrvold (2001) cast doubt on whether the account can be squared with relativity theory's requirement of Lorentz invariance. More recently Healey (2016b) has given a different account of how quantum theory may be used to explain violations of Bell inequalities consistent with Lorentz invariance and Local Action. This account involves no metaphysical holism or nonseparability.

In the context of unitary (Everettian) quantum theory, Wallace and Timpson (2010) advocate a form of spacetime state realism according to which the properties of a region of spacetime composed of two or more disjoint subregions fail to be determined by the properties of those subregions. Noting the implied physical property holism and failure of spatiotemporal separability, they defend this possibility against possible objections and argue for its positive advantages in the relativistic domain.

Esfeld (2001) takes holism, in the quantum domain and elsewhere, to involve more than just a failure of supervenience. He maintains that a compound system is holistic in that its subsystems themselves count as quantum systems only by virtue of their relations to other subsystems together with which they compose the whole.

7 Ontological Holism in Quantum Theory?

As applied to physics, ontological holism is the thesis that there are physical objects that are not wholly composed of basic physical parts. Views of Bohr, Bohm and others may be interpreted as endorsing some version of this thesis. In no case is it claimed that any physical object has nonphysical parts. The idea is rather that some physical entities that we take to be wholly composed of a particular set of basic physical parts are in fact not so composed: This may be because these do not exhaust their parts or because the entities actually *have* no independently existing proper parts.

According to Bohr's version of the Copenhagen interpretation[13], one can meaningfully ascribe properties such as position or momentum to a quantum system only in the context of some well-defined experimental arrangement suitable for measuring the corresponding property. He used the expression 'quantum phenomenon' to describe what happens in such an arrangement. In his view, then, although a quantum phenomenon is purely physical, it is not composed of distinct happenings involving independently characterizable physical objects—the quantum system on the one hand, and the classical apparatus on the other. And even if the quantum system may be taken to exist outside the context of a quantum phenomenon, little or nothing can then be meaningfully said about its properties. It would therefore be a mistake to consider a quantum object to be an independently existing constituent of the apparatus-object whole.

Bohm's reflections on quantum mechanics (Bohm [1980], Bohm and Hiley

[13]See the essays in Bohr (1934).

[1993]) led him to adopt a more general holism. He believed that not just quantum object and apparatus, but any collection of quantum objects by themselves, constitute an indivisible whole. This may be made precise in the context of Bohm's (1952) interpretation of quantum mechanics (see Tumulka (this volume)) by noting that a complete specification of the state of the "undivided universe" requires not only a listing of all its constituent particles and their positions, but also of a field associated with the wave-function that guides their trajectories. If one assumes that the basic physical parts of the universe are just the particles it contains, then this establishes ontological holism in the context of Bohm's interpretation. But on an alternative view of the ontology of the Bohm theory the wave function does not represent a physical field but merely specifies the dynamical law obeyed by the particles.

Some (Howard 1989; Dickson 1998) have connected the failure of a principle of separability to ontological holism in the context of violations of Bell inequalities. Howard considers his own Howard Separability principle to be a natural transposition of Einstein's Real State Separability to field theory, maintaining that Einstein uses this as a principle of individuation of physical systems, without which physical thought "in the sense familiar to us" would not be possible. Howard himself contemplates the possible failure of this principle for entangled quantum systems, with the consequence that these could no longer be taken to be wholly composed of what are typically regarded as their subsystems. Dickson (1998), on the other hand, uses these same concerns expressed by Einstein (1948) to argue that such holism is not "a tenable scientific doctrine, much less an explanatory one" (p. 156).

One may try to avoid the conclusion that experimental violations of Bell inequalities manifest a failure of Local Action by invoking ontological holism for events. The idea would be to deny that these experiments involve distinct, spatiotemporally separate, measurement events, and to maintain instead that what we usually describe as separate measurements involving an entangled system in fact constitute one indivisible, spatiotemporally disconnected, event with no spatiotemporal parts.[14] But such ontological holism conflicts with the criteria of individuation of events inherent in both quantum theory and experimental practice.

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