A New Look at Relational Holism in Quantum Mechanics

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Teller argued that violations of Bell's inequalities are to be explained by interpreting quantum entangled systems according to 'relational holism', that is, by postulating that they exhibit irreducible ('inherent') relations. Teller also suggested a possible application of this idea to quantum statistics. However, the basic proposal was not explained in detail nor has the additional idea about statistics been articulated in further work. In this article, I reconsider relational holism, amending it and spelling it out as appears necessary for a proper assessment, and application, of the position.

1. Introduction. It is well known that certain quantum-mechanical systems display features that may indicate a conflict with relativity. The traditional example involves two particles in the singlet state. Once the particles are emitted in opposite directions toward spacelike separated measurement apparatuses and spin in a certain direction is measured on one of them, the outcome of a spin measurement in the same direction at the other end is somehow determined. Bell's inequalities, which assume that each quantum object has a well-defined state that accounts for all its measurable properties and that distant objects do not exchange information faster than the speed of light and translate this into simple mathematics, are consequently violated.

The fact that the two outcomes are not independent means that the condition of *factorizability* fails. This condition can be expressed formally as[1]

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

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[1] '*P*' denotes probability; '*x*' and '*y*' denote the outcome at each wing (*A* and *B*, respectively); '*i*' and '*j*' denote the setup of each one of the measuring apparatuses (*A* and *B*, respectively); and λ denotes the pair's state before measurement, which may encode some 'hidden variables'.

Philosophy of Science, 76 (December 2009) pp. 1027–1038. 0031-8248/2009/7605-0022$10.00

Jarrett (1984) notoriously argued that factorizability is, in fact, the sum of two different conditions (using, instead of Jarrett's, the more common terminology): *parameter independence*—the outcome of the measurement at one end of the experimental setup is statistically independent of what is measured at the other end—and *outcome independence*—the outcome of the measurement at one end of the experimental setup is statistically independent of the outcome at the other end. Formally, parameter independence states that

$$P^A(x|i,j,\lambda) = P^A(x|i,\lambda)$$

and

$$P^B(y|i,j,\lambda) = P^B(y|j,\lambda),$$

while outcome independence is the claim that

$$P^A(x|i,j,y,\lambda) = P^A(x|i,j,\lambda)$$

and

$$P^B(y|i,j,x,\lambda) = P^A(y|i,j,\lambda).$$

On the basis of this, Jarrett drew a conclusion that has later become a rather canonical position: in view of the evidence, parameter independence is to be retained, and outcome independence must be given up, as a rejection of the latter would not determine the possibility of superluminal signaling, which is what relativity rules out. Whenever outcome independence fails, in particular, an element of randomness is present that makes superluminal signaling impossible. This is by no means uncontroversial (see Jones and Clifton 1993). More generally, it should be mentioned that the idea that relativity prohibits superluminal signaling has itself been put into doubt (Friedman 1983). Also, Fine (1989) denied that the detected correlations need an explanation, while Winsberg and Fine (2003) suggested that the joint state could be wholly determined, in fact, by the separate states of the two particles, although by a functional relation different from multiplication. The entire Jarrettian approach has even been questioned, for example, by Maudlin (1994). In this article, at any rate, the Jarrettian framework will be taken for granted.

Teller (1986, 1989) proposed a peculiar explanation of the failure of outcome independence. He designated as *particularism* the view that the world is composed of individuals possessing nonrelational properties and relations between which are nothing over and above their nonrelational properties, and claimed that what the violations of Bell's inequalities show is that particularism fails in the quantum domain, and so one has to embrace *relational holism*. The latter is the view that certain properties are 'inherent' relations that are irreducible to the monadic properties of their relata and consequently make—in agreement with the traditional slogan—'the whole (exhibiting the relation) more than the sum of the parts (the related individuals)'. Relational holism, Teller contended (1989, 214–215), makes quantum mechanics compatible with relativity because it allows one to reject the 'ontological locality of values', that is, the idea that all fundamental properties of things are monadic properties localized at space-time points and to which, in virtue of this, 'causal locality' applies. Nothing more specific, however, was added: why and how is it, exactly, that relational holism guarantees the sought 'peaceful coexistence' between quantum mechanics and relativity (if at all)? What is the precise ontology underpinning Teller's proposal?

Teller himself seems to acknowledge the need for further work when he claims that "the step we may need to take to advance our physical theory and our conceptual scheme for the physical world may be to come to terms with inherent relations and *to understand how they give rise to (or come to be seen as) the nonrelational* properties which have so far formed the basis of our physical world view" (1986, 81; emphasis added).

In the concluding section of his 1986 article, moreover, Teller formulated another hypothesis that he didn't pursue further. His claim there is that "the work to be done includes a closer examination of whether we have a specifiable and acceptable account of [particles as] *individuals*. . . . One worry I have in mind here concerns possible problems with *quantum statistics for identical particles*. It is possible that *these quantum statistics can themselves be clarified by applying the idea of inherent relations*" (1986, 80; emphasis added).

It seems worthwhile, therefore, to examine Teller's proposal in more detail, trying to articulate it further. Three desiderata can be formulated as

1. a detailed ontological explanation of why relational holism, or something close to it, makes sense of the failure of outcome independence;
2. an account of how, in quantum systems, inherent properties of composite systems give rise to the nonrelational properties of individual particles composing them;
3. an application of Teller's suggestion for an account of quantum statistics in a framework in which particles are individuals.

2. The Ontological Nature of Emergent Quantum Properties. The main thing that must be done in order to make progress with respect to Teller's original formulation of relational holism is to say something more precise about the properties taken to play a crucial role. First of all, Teller intends quantum holism as a form of *nonsupervenience*. Nonsupervenience is, obviously enough, the negation of supervenience, that is, the sort of dependence relation given which two things sharing a set of properties, A, necessarily also share a set of certain other properties, B, acting as the supervenience basis for A. But while this, when applied to quantum systems, allows for particles being in exactly the same state as entangled particles without actually being entangled and for identical entangled systems having component particles in different states, it doesn't, strictly speaking, explain the peculiar nature of entangled systems in themselves. The important fact is, rather, that entangled systems are *holistic* systems that possess new features that didn't exist at the level of their separate components; that is, *emergent* properties. Although this is clearly related to nonsupervenience, it is equally clearly something different, as it individuates the *cause* of the failure of supervenience. In what follows, I will therefore focus on emergence. I will conceive of it as a form of *mereological* irreducibility, that is, as the view that the emergent properties of entangled systems are full-blown physical constituents of those systems.

Having said this, one first element that must be emphasized is, to my mind, that the properties that emerge in quantum entangled systems have an essential *dispositional* component. This appears clear from the simple consideration of the fact that it is relations *between measurement outcomes* that we aim to get a better grasp on. A fermionic system in the singlet state, for example, has total spin zero, *plus* a 'propensity' or 'tendency' to give rise to anticorrelated spin values for the component particles upon measurement.[2] And it is this latter tendency and the dynamics of its realization that we want to understand. Generalizing, all correlations exhibited by entangled systems (in fact, all quantum properties) have the same characteristic: they encode information that has to do exclusively with what will be true of their bearers *under certain conditions, that is, when certain measurements will take place*. Without this entailing a commitment to any specific view of dispositions[3] and, in fact, only committing to dispositional properties in a very minimal sense,[4] I will assume this fact to be uncontroversial and, indeed, vital for a proper understanding of the theory and the domain it describes.

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[2] Teller himself, considering systems of this type, speaks of a 'partially effective disposition' or 'correlation-propensity' that is an objective property of the pair of objects (1989, 221–222).

[3] For example, I will leave it open whether the correlations that emerge in quantum systems should be regarded as irreducible 'bare dispositions' (see, e.g., McKitrick 2003), or are instead reducible to certain properties of the physical systems exhibiting them, which act as their categorical bases.

[4] That is, in a sense that doesn't contradict, e.g., Strawson's (2008) claim that there are no dispositions, as everything that is real is categorical. (See Blackburn 1990 and Holton 1999 for the opposite idea that reality is essentially dispositional.)

A question that is intimately related to this is whether the emergent properties of entangled wholes, irreducible to the monadic properties of their component particles, truly are—as Teller believes—relations. While Teller takes this for granted and even to be entailed by the failure of outcome independence, this is by no means necessary. For example, it might instead be the case that the monadic properties of certain particles, when the latter become entangled, give rise to other monadic properties, although emergent and only belonging to the total system, and that it is these latter properties that invariably evolve into the correlated properties that we observe when we perform actual measurements. In this setting, the correlations wouldn't, in fact, correspond to genuine relations but, rather, derive from monadic properties of the total system and their dispositional element. It follows that holism can be separated from the view that there must be fundamental, irreducible relations; that is, one can have quantum holism without quantum relational holism. (It is worth pointing out that, as a matter of fact, if the emergent properties in question are not relations, then particularism as it is defined by Teller holds in the quantum domain—as it requires only the reducibility of relations to nonrelational properties.) Be this as it may, the 'relational' label that Teller uses for his form of holism will be put into parentheses in what follows.[5]

2.1. How Is the Failure of Outcome Independence Explained? On the basis of the above, I maintain that, when measurements of the state-dependent properties of entangled particles are performed, they affect the emergent properties exhibited by the entire system *directly*, so 'triggering' their dispositional element. In virtue of this, these properties *subsequently* turn into separate, categorical, nonrelational properties, that is, the correlated properties of the particles after measurement. Crucially, this event of property creation, as well as the 'content' of the created properties, is fully determined by the information encoded in the initial property, exactly in the same way as every other disposition 'encodes' its own manifestation(s).[6] In other words, a measurement on an entangled system, commonly understood as an event E_1 localized where one of the particles is

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[5] The approach that gives priority to relations seems endorsed in Muller and Saunders 2008. My view is, to the contrary, that the second perspective is more convincing. In any case, this is immaterial for present purposes.

[6] For the spin of two fermions, e.g., one has a property, exhibited by the whole, 'encoding' the information that

$$P^{AB}(x = y \mid i, j, \lambda) = 0.$$

That is, the two particles have opposite spin when a measurement takes place. It is clear that this alone suffices for making the equalities defining outcome independence (see above) false.

and determining another event E_2 localized where the other particle is in fact an event E_1 located everywhere the total system is (in particular, at the locations of *both* component particles) that determines events E_2 and E_3 localized at different places and yet in physical and spatiotemporal continuity with their cause, E_1. This means that one has a process that is *entirely local* at each stage. For, since the emergent property is exhibited by the system as a whole, it can be regarded as 'extending' over the entire system in such a way that its effect on (i.e., its evolution into separate properties of) the particles is not at a distance (and yet determines a correlation between spatiotemporally separate spin values).

A similar view seems mirrored in the words of Gisin, according to whom "a quantum correlation is not a correlation between 2 events, but a single event that manifests itself at 2 locations" (2008, 5), and in those of Lange: "This is weird. However, because the weirdness pertains to the character of the events themselves rather than to their causal relations, spatiotemporal locality is satisfied. . . . Locality . . . fails to require that an event serving as a cause or effect occupy a continuous region in space. . . . If some cause . . . is confined to one of . . . two . . . volumes, then the effect's occurrence in the other volume will have something of the weirdness of action at a distance. But, strictly speaking, it will not count as violating locality" (2002, 294–295).

The idea is, then, that the being 'spread out' of the system and of its emergent properties entails that the relevant causal processes are physically continuous and, therefore, not at a distance after all, hence not problematic. Strange as it may seem, such a possibility should certainly not be ruled out a priori.

It could be objected that the problem with nonlocality remains, because it is still true that two distinct locations can be individuated in the process, and what happens in one of them is mysteriously connected to what happens in the other. The right reply to this is that (and this is perhaps the key point that needs to be understood about quantum mechanics) in quantum mechanics certain 'things' exist that are 'basic units' regardless of the fact that they are 'extended' in regions larger than single points in space. These basic units should not be examined from the perspective of the individual spatial points they 'transcend', especially when it comes to causal events. The evidence related to Einstein-Podolsky-Rosen (EPR) and the violation of the Bell inequalities, that is, points to a sort of unity and fundamentality different from the one we usually assume, which takes space-time points as minimal elements determining a universally applicable frame of reference. Howard's words apply here: "The mistake is in 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" (1989, 249).

At most, the evidence requires one to put into doubt what, following Jones (1991, 131–135), one may call 'causal separability', that is, the requirement that an event A can be the cause of another event B only if A has a part entirely in the past light cone of B that entirely causes B. Indeed, if the emergent property of the whole system is such that it is affected in its entirety by a measurement localized where one particle is and, as a consequence of this, determines a new categorical property of another particle at a different location, it is clear that causal separability fails. But this, as explained, is not in itself a violation of locality.

What about the process seemingly being *instantaneous* or, at least, faster than light, as it takes place at two locations at the same time? Using an example offered by Einstein in 1927 at the Fifth Solvay Conference, Chang and Cartwright (1993, 183) ask the reader to consider an electron that has just passed a narrow slit and is about to be recorded on a photographic plate. When the electron is recorded, in fact, the exact position measurement that is obtained is perfectly anticorrelated with a negative result for localization at every other point in which it could have been detected. Isn't this analogous to what happens when a measurement is performed on an entangled system? If so, then what we have is, in the end, nothing but the familiar dynamics of the collapse of the wave function. While Einstein's conclusion, as is well known, was to reject quantum mechanics, in view of the ubiquitousness of wave function collapses one might prefer taking another route and, at least in the specific case of holistic systems, follow Chang and Cartwright in their suggestion "to reject the finite-speed propagation requirement for these special kinds of quantum measurement processes" (1993, 183).

We have seen how this rejection might be plausibly connected to the existence of systems and properties that, although extended in space and time, are not analyzable in terms of basic space-time units. This, it can be claimed, is the key intuition underlying the holist position. If this is correct, then, to the extent that the primary aim of this article was to shed some light on Teller's holism, it seems that this has been accomplished. Whether or not the emerging view is acceptable (and, if so, whether or not it is useful) is, I guess, something on which opinions will differ. At any rate, it surely is a possible viewpoint as to the true nature of the quantum domain.

2.2. Common Causes. The above is also relevant with respect to the question about common causes. A canonical assumption, to the effect that for EPR correlations a common cause is excluded because all possible causes are considered in the form of hidden variables, can be questioned, in fact, as it appears to take for granted exactly the classical particularist perspective that Teller urges us to do away with. Of course, no common cause can be found in λ as long as the latter includes information about (*a*) the separate particles and their nonrelational properties and (*b*) localized elements of reality in the particles' past light cones *and nothing else*. But shouldn't the emergent property determining the correlation among the particles be considered a relevant factor in itself and, in fact, exactly the common cause being looked for? According to the view just put forward, measurements on entangled particles act on emergent properties of the whole and consequently *influence* the system's components by determining their monadic properties as manifestations of a holistic disposition; surely this means that the emergent properties are causes in the required sense!

3. Quantum Statistics. As is well known, quantum statistics represents a threat for those wishing to interpret the quantum domain in terms of individual particles, as it is quite different from the classical statistics obeyed by what we take to be paradigmatic individual objects. This is, no doubt, what Teller had in mind in his remark, mentioned above, in which he considered the possible relevance of relational holism for an understanding of quantum statistics in an ontological setting based on individuals.

The problem with quantum statistics is, in particular, that in quantum mechanics only (anti)symmetric states are possible. This means that, for quantum systems, particle exchanges do not make a difference: simply put, there is only one way for two 'quantum coins' to fall with different faces up. Moreover, since nonsymmetric states are excluded in the quantum case, it is, in effect, altogether impossible for two quantum coins to be *one* determinately heads and the *other* determinately tails, and there is a fact of the matter only concerning whether they will be in the same state or not. This evidence, a traditional argument goes, is sufficient for concluding in favor of the nonindividuality of quantum particles, as if it is denied that quantum particles possess definite identities, then their statistical behavior is readily explained.

However, an application of holism can avoid this conclusion. To do this, one has to maintain that *quantum holism concerns not only entangled systems but also nonentangled ones*. This entails that *all* state-dependent properties of all many-particle systems of quantum identical particles are emergent properties of the total system, not reducible to separate properties of the component identical particles. Why is this useful with respect to the problem at hand? Because if quantum statistics exclusively describes what will be true of a multiparticle whole by expressing the 'dispositional content' of emergent properties it exhibits, then the identities of the component particles become statistically irrelevant. For, as we have seen, such emergent properties describe only correlations between measurement outcomes for the separate particles, without also containing any information about the specific particles. From this it follows that they are 'indifferent' to which particle is which. If this is the case, it clearly becomes possible to think of the particles as individuals in spite of the peculiar features of quantum statistics. For the emergent properties (relational or not, dispositional or otherwise) may not say anything about any specific particles, and yet the particles be individual objects. In other words, the correspondence between classical state descriptions, such as, say, 'both coins heads', and quantum ones, such as, for example, 'both particles spin up', is broken (only the former describes two separate nonrelational properties), and this allows one to explain why there are no state descriptions of the form 'particle 1 spin up and particle 2 spin down' (such a description requires two distinct nonrelational properties) without putting into doubt the particles' individuality.

It must be emphasized that the claim that holism also applies to nonentangled many-particle systems does not entail that the mere *description* of several independent particles as a unitary whole via the tensor product formalism—which would be identical to the description of a genuine many-particle system composed by those particles—is sufficient for drawing conclusions about the relevant properties (from monadic properties of the particles to emergent properties of the whole). This would clearly be absurd. As for entangled systems, for nonentangled ones too holism is manifested only once interaction gives rise to actual wholes. The need for a more precise definition of such interactions doesn't imply that sense cannot be made of the distinction between genuine and merely formal wholes.

4. Are Emergent Properties Encoding Correlations Ontologically Robust?

Before closing, the reformulation of Teller's relational holism suggested in this article must be evaluated, if briefly, against the background of a related debate. In his 1999 article and other papers, David Mermin contended that only correlations are ontologically significant in quantum mechanics. His argument in favor of this conclusion (the so-called Ithaca interpretation of quantum mechanics) is that all the theory's counterintuitive features can be eliminated by simply denying that there are any intrinsic properties of individual entities over and above correlations among quantum systems. Mermin's proposal thus amounts to the hypothesis that only the correlations between subsystems of individual isolated composite quantum systems are real and objective properties of those systems. This suggestion is clearly relevant with respect to the holist viewpoint just articulated, according to which, although they are not the only components of physical reality, quantum properties encoding correlations certainly are genuine emergent properties not reducible to more basic physical elements.

Cabello (1999b) and Jordan (1999) objected that correlations cannot be considered objective and unproblematic either. For correlations themselves appear to be influenced at a distance in the way that is normally considered to be challenging, or even paradoxical, and that essentially motivated Mermin's enterprise. Hence, the suggested interpretation doesn't help in making sense of the quantum domain as Mermin intends it. For example, taking the four-particle state,

$$|\psi\rangle_{1234} = (|\uparrow\rangle_1 |\downarrow\rangle_{2-} |\downarrow\rangle_1 |\uparrow\rangle_2 \otimes |\uparrow\rangle_3 |\downarrow\rangle_{4-} |\downarrow\rangle_3 |\uparrow\rangle_4),$$

one may measure a component of spin on particles 2 and 3, projecting them in one of four available factorizable states,

$$|\uparrow\rangle_2 |\uparrow\rangle_3;\ |\uparrow\rangle_2 |\downarrow\rangle_3;\ |\downarrow\rangle_2 |\uparrow\rangle_3;\ |\downarrow\rangle_2 |\downarrow\rangle_3.$$

This also projects the combined state of particles 1 and 4, *previously not interacting*, in one of the correlated states,

$$|\downarrow\rangle_1 |\downarrow\rangle_4;\ |\downarrow\rangle_1 |\uparrow\rangle_4;\ |\uparrow\rangle_1 |\downarrow\rangle_4;\ |\uparrow\rangle_1 |\uparrow\rangle_4.$$

Given the same initial system, however, one can equally measure the so-called Bell operator on particles 2 and 3, and this projects their combined state in one of the four 'Bell states',

$$|\psi\rangle^{\pm}_{23} = 1/\sqrt{2}(|\uparrow\rangle_2 |\downarrow\rangle_3 \pm |\downarrow\rangle_2 |\uparrow\rangle_3),$$

and the combined state of particles 1 and 4 in a correlated Bell state,

$$|\varphi\rangle^{\pm}_{14} = 1/\sqrt{2}(|\uparrow\rangle_1 |\uparrow\rangle_4 \pm |\downarrow\rangle_1 |\downarrow\rangle_4).$$

Since Bell states are maximally entangled, this latter situation is clearly different from the previous one for what concerns noninteracting particles 1 and 4, and yet the initial scenario is the same, and only the type of measurement made on particles 2 and 3 changes. Therefore, it seems that quantum correlations are at least partly not amenable to a description in terms of objective local elements of reality as desired by Mermin—at least once a criterion of objectivity as 'no change without interaction' (which is Mermin's criterion) is applied.[7] What can the holist reply to this?

Not much, but something. The main indication of the failure of what Seevinck (2006) called 'ontological robustness' for quantum correlations, we have just seen, consists of the supposed possibility of creating correlations without interaction. However, it is the fact that *particles* that never

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[7] Seevinck (2006) expressed the same point in terms of Bell-like inequalities, and Cabello (1999a) added that it is also impossible to think of all quantum correlations as being already present in the initial state before measurement.

interacted enter into a joint state upon interaction among other particles (and in a way that is determined by the specific features of that interaction) that, allegedly, makes realism about correlations unworkable. But one may (should?) regard the *emergent properties encoding the correlations*, and not the particles, as the basic 'unit of significance' for physical interaction here.[8] If one does this, then the alleged problems may, after all, disappear. In the above example, particles 1 and 4 surely never interact, *but properties encoding correlations involving them do*. And by the same mechanism that we invoked with respect to explaining the observed outcome dependence in EPR-like settings by denying causal separability, it can be claimed here that interactions among the emergent properties can give rise to new properties involving any of the particles these properties are *about*, as it were, in spite of the prima facie violation of locality; because such properties are fundamental causal 'actors', spread out across the entire system, that (can) act (locally) on seemingly mutually independent particles (particles, that is, whose monadic properties are not directly interrelated and never get to interact during the process). In general, it is possible to conjecture that the evolution of emergent properties into other properties takes place via events that—no doubt—involve individual particles but is by no means limited to what can be the case for individual particles and their monadic intrinsic properties. For the ontological features of and, consequently, the possibilities available to such emergent properties are simply different.

A closer examination of these properties and their interactions is certainly in order and might reveal the implausibility of the whole proposal. However, it could also lead to a better understanding of the quantum world via the further articulation of the holist approach to quantum physical systems first explicitly formulated by Teller.

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[8] Without this being taken to mean, à la Mermin, that there are no particles with monadic properties, of course, but just that the properties of the whole have a sort of 'causal priority' with respect to the components and their properties when it comes to certain types of processes.

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