(Draft version – under revision.)

Holism and Nonsupervenience in Quantum Mechanics[1]

Martin Thomson-Jones

1. Introduction

The idea that quantum-mechanical systems display some sort of holism has been around more or less since the creation of the theory, and has attracted increasing attention in recent years, especially in the context of the attempt to understand the failure of the Bell inequalities and the nature of quantum-mechanical nonlocality.[2] The intuitive idea is often expressed by saying that some of the time, in quantum mechanics ('QM'), when we have a composite system, the "whole is greater than the sum of the parts," or the "state of the whole does not reduce to the states of the parts," or there are "facts about the whole which go beyond the facts about the parts."[3] These are the slogans. And the idea is that they are true in some new and interesting sense in QM – that there is a kind of holism in QM which is not to be found in classical physics (or at least rarely found there, or understandably overlooked there).

One crucial task, then, if we wish to understand the metaphysical implications of QM, is to develop a clear account of just what the talk of holism amounts to, and just how we should understand the slogans. In this paper, I will argue that the accounts

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[2] See, for example, Jarrett (1984, 1989), Healey (1991), Howard (1985, 1989), Maudlin (1994, esp. pp. 210-12), Redhead (1987), Shimony (1986, 1987, 1989, 1993), Teller (1986, 1989), and van Fraassen (1991, *passim*). Humphreys (1997) is an interesting, closely related paper, especially pp. 15-16. See also Healey (1991), pp. 394-5, nn. 1-2 for additional references to works by Bohr, Schrödinger, Bohm, and d'Espagnat.

[3] There is thus no obvious connection between the topic of the present paper and discussions of either confirmational or semantic holism.

offered by Paul Teller (1986) and Richard Healey (1991), which share a certain core idea and are, in my view, the most successful to date, fail to capture something important (§§4-5).[4] Along the way, a new argument will emerge to the effect that there *is* some sort of holism in QM (§6). (This argument will make it clear that Teller's and Healey's proposal was certainly heading in the right direction, even if my claim that their accounts miss something is correct.) I will also argue that there is an interesting link between quantum-mechanical holism and the nonlocal correlations (§7); and the discussion as a whole will suggest some constraints that a fully adequate account of quantum-mechanical holism should satisfy (§6, §8).

These issues seem to me to be of fairly broad metaphysical interest, and so I will endeavour not to presuppose much acquaintance with the literature in the philosophy of quantum mechanics, at least in most places, and to structure the discussion in such a way that the more technical material can be laid aside with relative impunity. Those who are well acquainted with the literature, on the other hand, may wish merely to skim the next section.

2. Why holism?

To provide some essential background against which the main arguments can be presented, let me begin by reviewing certain aspects of QM which provide one of the primary sources of the feeling that QM involves some kind of holism. This will involve presenting the standard account of the significance of the Bell inequalities.[5]

Suppose two people are standing at opposite ends of a room, and each of them tosses a coin every five seconds (say). We record one person's tosses for a while and see

[4] The claim that Teller's and Healey's accounts are the most successful to date will not be defended in this paper, except in the respect that I explain what I think is right about their core idea. Critiques of other accounts will have to wait for other occasions.

[5] The outline which follows omits many qualifications and ignores some significant bones of contention. For far more detailed and extensive treatments, and for references to the wider literature, see, e.g., Redhead (1987), Cushing and McMullin (1989), van Fraassen (1989, esp. chs. 4 and 10) and Maudlin (1994, ch. 5).

that the sequence of heads (H) and tails (T) is random, but that over the long run the statistics suggest the probabilities characteristic of a fair coin:[6]

$$p(H) = p(T) = 0.5.$$

Next, we record the other person's tosses for a while, and see the same thing. Imagine, then, our surprise when we begin recording the outcomes at both ends, pairing up the outcomes of simultaneous tosses, and notice that the outcomes are perfectly anticorrelated, so that

$$p(HT) = p(TH) = 0.5,$$

and therefore

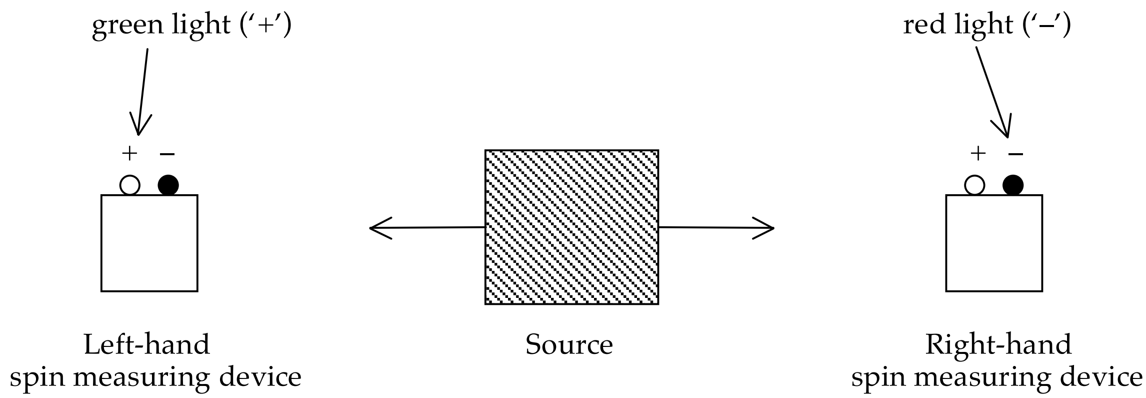
$$p(HH) = p(TT) = 0,$$

(where 'p(XY)' is the probability that the outcome X occurs on the left-hand end of the room and outcome Y occurs on the right). In keeping with what we had earlier noticed about each of the two ends individually, however, the sequence in which 'HT' and 'TH' outcomes occur is quite random.

Striking though such a situation would be, QM seems to tell us that the world frequently behaves in just that way. Electrons, to take the usual example, have spin; the magnitude and orientation of the spin of a particle influence its behaviour in a magnetic field. If we measure the component of an electron's spin in a given direction, there are just two possible outcomes, "+" and "-". Now we can place a source in the middle of the room which will emit pairs of electrons, one after another, in such a way that one electron in each pair flies off to the left-hand end of the laboratory whilst the other flies off to the right. If we then measure, say, the spin in the z-direction of each of the two

[6] These probabilities are treated as absolute for simplicity of exposition – a more cautious presentation would treat them as conditional upon the sort of chance set-up I have described.

electrons in a pair, at opposite ends of the laboratory, and repeat the measurements with each successive pair of electrons, then if we have selected the right sort of source, the outcomes of our measurements are perfectly analogous to the ones in the imaginary coin experiment:



That is, the statistics are:

p(+) = p(-) = 0.5	at each end, in a random sequence
p(+-) = p(- +) = 0.5	(again, in a random sequence)
p(++) = p(- -) = 0.	

The situation I have described, the "EPR-Bohm experiment," is one in which each pair of electrons emerges from the source in a quantum-mechanical state known as the *spin singlet state*, $|\psi_S>$. On the orthodox interpretation of QM, the probabilities in question are objective, and each measurement outcome is the result of an indeterministic process.

Faced with these correlations for the first time, it is natural to suppose that there is a simple explanation for them. One hypothesis which immediately suggests itself is that during the measurement process, events at one end of the room causally influence events at the other. However, apart from the fact that no known type of physical interaction between electrons could do the job, an explanation of that sort is usually taken to fall foul of certain constraints imposed by special relativity (SR). In the terms of that theory, the measurement events can be arranged so that they are *space-like related* to one another; that is, the experiment can be performed in such a way that (whatever reference frame is used) the spatial separation between the events is sufficiently large, and the temporal interval between them sufficiently small, that any signal carrying the causal influence would have to be *superluminal* – it would have to travel faster than the speed of light to connect the two events. This raises at least three difficulties: (a) The idea of a superluminal causal signal is on some views prohibited by the foundational principles of SR itself.[7] (b) The temporal ordering of space-like related events varies across frames of reference. This means that, according to SR as it standardly interpreted, space-like related events do not stand in any absolute temporal order. We are thus faced with a three-fold choice between allowing that in some frames of reference there is causation backwards in time, allowing that causal relations are frame-relative, or turning to a nonstandard interpretation of SR on which all frames of reference are not born equal. (c) Causation between space-like related events at the very least introduces the threat of some well-known causal paradoxes.[8]

Suppose, then, that we give up on the idea of explaining the correlations by positing causation between the two ends of the room. What other form could an explanation take? The only obvious suggestion is that, unbeknownst to QM, each particle emerges from the source already knowing what outcome it will give if its spin in the z direction is measured, and that the predetermined outcomes for the electrons in a

[7] For rejections of this claim (which I agree should be rejected), see Friedman (1983), ch. 4, sec. 6, and Maudlin (1994), ch. 5.

[8] I should stress that I am not here attempting to present a decisive argument that the correlations cannot be explained by positing causal connections between measurement events; nor am I committed to such a view. The point, remember, is simply to rehearse some standard lines of thought so as to set up the motivation for talk of holism in QM.

given pair are somehow coordinated in the source.[9] The coordination event would then be a common cause of the two outcomes at the measuring devices.

This is where the Bell inequalities come in. Bell is standardly taken to have shown that if the correlations described above are to be explained in terms of such a common cause,[10] without the help of a direct causal interaction between the space-like related measurement events, then the correlations displayed in a slight variation on the experiment described above (one in which we measure *different* spin components of the electrons in a given pair) would have to obey a particular constraint – they would have to satisfy the Bell inequalities. (This is Bell's theorem.) Yet the detailed predictions of QM violate the inequalities, and experiment has repeatedly vindicated those predictions. Thus, it is concluded, no common cause explanation of the correlations can be constructed. The correlations described above thus come to seem deeply puzzling.

Some have then suggested that at least part of the key to understanding the correlations may be the thought that in this sort of situation, the state of the pair of particles is in some new and substantial sense more than just the sum of the states of each particle considered on its own. (After all, the pair, considered as a pair, behaves in a rather striking way, and that behaviour is certainly not captured merely by listing the statistical facts about the behaviour of one particle, and then listing the statistical facts about the behaviour of the other.) Putting this thought in other words, some have invoked the term 'holism' here, and, I will argue, rightly so.

However, it is important to separate two different claims. I am not going to argue that we can *explain* the "spooky" correlations (to echo Einstein's words) by appeal to the notion of holism, as some have suggested. Nonetheless, I think that correlations of this

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[9] QM would on this account be an incomplete theory of the systems in question – and that is essentially the point of the famous "EPR" argument (Einstein *et al*., 1935).

[10] And if there are no "brute" correlations between spatiotemporally separated events, no grand conspiracies on the part of nature to provide us with skewed samples when we collect data, and no backwards causation between events which do have an absolute temporal ordering…. (See the references in n. 5 for elaborations of these complexities.)

sort do point to something nonclassical and surprising in the relation between the states of the parts and the state of the whole. Accordingly, I will argue in this paper that holism of some interesting sort is a predominant feature of the quantum-mechanical world, one that we must come to understand if we are to unravel the metaphysical implications of the theory. Furthermore, my argument will have as a consequence the claim that there is holism involved in the experiment I have just described. It will emerge, in fact, that there is a general and suggestive link between spooky correlations and holism: on at least one class of interpretive approaches to QM, I will argue, such correlations are always produced by holistic states.

We now have a sense of one of the main stimuli to talk of holism in QM, and that will make it easier for us to evaluate Teller's and Healey's proposed explications of such talk. It is important to note, however, that for strategic purposes I will adopt a particular interpretive stance towards QM in what follows. That stance is, first, minimally realist, in the sense that it takes QM to provide descriptions of the states of individual systems in various circumstances, descriptions which are typically (if not always) either true or false, and the truth values of which are determined by the way the systems in question are. Secondly, it also assumes that the state descriptions QM provides are *complete* state descriptions.[11] One interesting and valuable extension of the current discussion will thus involve an investigation of these issues in the context of alternative interpretive approaches.

3. Holism as nonsupervenience

The general idea we are exploring, then, is that in QM the state of a composite system can in some new and interesting sense be greater than the sum of the states of the parts, or can fail to reduce to the states of the parts (again, in some new and interesting sense).

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[11] The interpretive stance I have just outlined leaves open a number of significant interpretive questions; from the point of view of the present project, that is one of its advantages.

Applied to the specific case of the EPR-Bohm experiment, this will mean that the state of the electron pair, $|\psi_S>$, stands in some sort of surprising relation to the states of the electrons taken individually. The next task is thus to say more about the nature of this "surprising relation." Teller and Healey have both proposed that the relation is one of nonsupervenience, and examining this proposal closely is one of my main aims. Before laying out their views more carefully, however, it is worth taking a moment to set aside another contender: emergence.[12]

To see why emergence cannot do the job we need doing, let us remind ourselves of two crucial aspects of the notion. First, in order for a property of a whole to count as emergent relative to the properties of the members of some set of parts, it must be "genuinely novel" – that is, it must be that none of the parts in that set has, or perhaps *could* have, a property of the same type.[13] Second, at least on some accounts, emergent properties of a whole are required to supervene (at least nomologically) on the properties of the parts. Both of the these conditions are plausibly satisfied in what are usually presented as the paradigmatic cases of emergence: consciousness in people who, it is assumed, are composed entirely out of fundamental particles; life in living creatures who are similarly composed; and liquidity in bodies of water, composed entirely of molecules of H_2O (to take three standard examples). There are other criteria which are regularly invoked in characterising emergence – irreducibility, inexplicability, and unpredictability being primary amongst them – but we need only focus on novelty and supervenience to understand why the idea that quantum-mechanical holism is emergence is not a promising one.

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[12] Useful brief overviews of the literature on emergence can be found in Kim (1996, pp. 226-29) and (1994, pp. 576-77), and Teller (1995).

[13] Two explanatory comments concerning this formulation of the criterion of novelty: (i) Whether a property of a composite system counts as novel or not is relativised to a set of parts of the system. That seems right: Consciousness is a novel property of a normal living human body if we start with a large collection of electrons, protons, and neutrons, but not if we start with, say, an kidney and the rest of the body minus the kidney. (ii) The novelty of a property in the intended sense is clearly more than a matter of not being shared by any of the parts – weighing 300 lbs. is surely not a novel property of my desk, relative to its top and the four legs, in the relevant sense. Hence the talk of *types* of property.

First, there is at least the danger that emergence turns out to be a plainly commonplace phenomenon in the world of classical physics and elsewhere, as the mention of liquidity just now suggests. A host of similar properties readily suggest themselves as candidates for emergence: transparency, solidity, redness, high reproductive fitness (relative to a certain sort of environment), electrical conductivity, acidity, and being mammalian, say. Yet we are searching for an understanding of some sort of holism which is peculiar to QM – or at least, not obviously ubiquitous in our conceptions of the world.[14] Secondly, and most decisively, a pair of electrons in the state $|\psi_S>$ does not seem to have novel properties in the relevant sense, as compared to the properties of the two electrons taken individually. (Of course, the criterion of novelty has not been fully explicated here, because no systematic story has been given about how properties are to be sorted into types in the right way. My claim, nonetheless, is that it is unlikely that a systematic story of types could be given which would both deliver the judgements of novelty we need to capture the intuitive notion of emergence elsewhere, and yield the result that an electron pair in $|\psi_S>$ has novel properties in the relevant sense.) The pair of electrons has various spin-related properties, and these are manifested in the experiment, but clearly the individual electrons which compose the pair have spin-related properties of their own. Thus the suggestion that quantum-mechanical holism is emergence fails to capture precisely the intuitions which led to talk of holism in the first place.[15] Finally, if holism in the present sense is emergence, and if emergence requires supervenience, then we again get the result that there is no holism in the EPR-Bohm experiment, for as Teller and Healey have both emphasised, and as we

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[14] Healey makes essentially this point (1991, pp. 396-97).

[15] It might be suggested that the pair does have properties of a kind which the individual electrons could not have, namely, dispositions to produce joint outcomes with certain statistical properties on joint measurement. The problem with this suggestion can best be appreciated at the end of the next section; it is that the suggestion would yield too much holism, as the same could seemingly be said of a pair in the state $P_1 \otimes P_2$.

are about to see, the properties of a pair of electrons in the state $|\psi_S>$ do not supervene on the properties of the individual electrons.

If there is some new and interesting sort of holism present in the EPR-Bohm experiment, then, it would seem not to boil down to emergence. So let us turn now to consider an alternative proposal. Paul Teller and Richard Healey have both turned to the notion of supervenience – or, more specifically, *non*supervenience – in their attempts to limn the nature of quantum-mechanical holism, and in my view their accounts are the most successful accounts offered to date.[16]

Supervenience is by now a familiar notion in the philosophical literature – perhaps an excessively familiar one in some areas. Although a veritable zoo of supervenience relations have been given precise formulation in one place or another,[17] the following broad characterisation will serve for our purposes:[18]

> If the *A*'s and the *B*'s form two sets of properties, then the *A*'s supervene on the *B*'s if, and only if, whenever matters are the same with respect to the *B*'s for two individuals, they are the same with respect to the *A*'s.

This characterisation is to be interpreted in such a way that the *A*'s might be properties of composite systems (the "individuals"), and the *B*'s properties of their parts. Furthermore, the term 'properties' should be understood as applying, when necessary, to relations between individuals, in addition to monadic properties of individuals (whether intrinsic or relational). Qualifications can always be added when we make specific supervenience claims. So, for example, we might make the claim that the

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[16] See primarily Teller (1986) and Healey (1991). Although I am arguing against Teller's and Healey's main proposal, it will be quite apparent how much the present discussion owes to their work on this difficult issue.

[17] See, for example, Kim (1994) and references therein, and Savellos and Yalçin (1995).

[18] Note then that we are interested here in local, rather than global, supervenience. Note also that for the sake of generality the phrase 'two individuals' can be understood to encompass "pairs" of individuals made up of a single individual at two different times. As for the modal force of the 'whenever,' see the end of this section.

intrinsic physical properties of composite systems of some particular sort supervene on the intrinsic physical properties of their parts.

The accounts Teller and Healey offer of holism in QM differ in a number respects, but they share a common core, and it is that common core which I am concerned to examine here. The central agreement I have in mind in this: for both Teller and Healey, holism *is* nonsupervenience of one precise sort or another. For Teller, the crucial phenomenon is that of the relations between the parts of a composite system (and so the relational properties of those parts) failing to supervene on their intrinsic, or nonrelational, properties:[19]

> By *relational holism* I will mean the claim that objects which at least in some circumstances we can identify as separate individuals have *inherent relations*, that is, relations which do not supervene on the non-relational properties of the distinct individuals.[20]

(Teller takes position to be a non-relational property, an assumption he discusses elsewhere in the paper.[21] Given that, spatial relations between objects will of course supervene on their non-relational properties – otherwise classical physics would be replete with relational holism so defined. One who regards position as a relational property can simply modify Teller's definition so as to include spatial relations in the (non)supervenience base.) The notion of relational holism is said to provide "a reading which we can give to holism which analytic philosophers ought to find relatively clear,"[22] and more specifically, to enable us to make sense of talk of holism in QM:

> The strange ways in which things seem interdependent in quantum mechanics has often suggested holism to interpreters, but they have been reluctant or uneasy about embracing the holism because of its obscurity. The

[19] I will leave the twin notions of the relationality and the intrinsicality of properties unanalysed, in the not atypical hope that either a satisfactory analysis can be (or has already been) found, or no analysis is needed.
[20] Teller (1986), p. 73.
[21] See also Teller (1987).
[22] Teller (1986), p. 73.

suggestion of applying relational holism to this problem gives a proposal for further clarification and critical examination.[23]

For Healey, on the other hand, the account is formulated in terms of the quantum-mechanical failure of the intrinsic properties of and relations amongst composite systems to supervene on the intrinsic properties of their components, and the spatial relations between those components:

> **Pure Spatial Holism**
> There is some set of physical objects from a domain **D** subject only to processes of type **P**, not all of whose qualitative, intrinsic physical properties and relations are supervenient upon the qualitative, intrinsic physical properties and the spatial relations of their basic physical parts (relative to **D** and **P**).[24]

The differences here are unimportant in the present context. I will frame my discussion in terms closer to Healey's, but my points will apply equally, *mutatis mutandis*, to Teller's account.

A point of terminology: by the "state" of a system (composite or not), I will mean simply the collection of its intrinsic properties. Thus there is always more to the state of a system, in this sense, than is specified by its quantum-mechanical wavefunction (or, more generally, its density operator), regardless of one's preferred interpretation of QM – consider, for example, the mass of the system, or its charge, or spin, or isospin. The wavefunction instead specifies one part of the state of the system, namely, its dynamical state, understood as a collection of dynamical properties. I should also point out that I mean to include any dispositions a system may have in its state, as I take it that

[23] Ibid., p. 80. Teller also makes it clear that he takes relational holism to be essentially peculiar to QM: "A massive reentry of inherent relations provides one mark of the sharply non-classical nature of quantum mechanics. Inherent relationality infects classical mechanics and special relativity at worst in the relationality of space-time, if space-time is inherently relational. But inherently relational properties inundate quantum mechanics, at least if we take the state function to attribute properties to individual micro systems" (ibid., p. 76).

[24] Healey (1991), p. 409. For a discussion of the advantages and disadvantages of this definition as compared to Healey's definition of "pure physical holism," see pp. 408-9 of the paper, and for the definition of a basic physical part (relative to domain **D** and process of type **P**), see p. 399. These details can be omitted for the purposes of our inquiry.

dispositional properties are intrinsic properties. There is a somewhat subtle issue here, however, and if we should ultimately decide that some or even all dispositional properties are relational, then we can simply redefine the term 'state' so as to include all the dispositional properties of the system in question.

There is one important issue concerning Teller's and Healey's proposal which must be addressed before we proceed. Teller and Healey claim that the way to understand talk of holism in QM is by interpreting it as talk about failures of supervenience. What is being *denied*, then, when we talk about such failures of supervenience, is that in QM, whenever two composite systems of the same type[25] have parts in the same states, standing in the same spatial relations, the states of the whole systems are the same. But what is the sense of this 'whenever'? That is, what is the modal force of the supervenience claim which is being denied when we assert that there is holism present?

One possible answer is that it is merely a claim of metaphysical supervenience which is being denied – that "whenever two composite systems…" should be read "whenever two composite systems from any two (not necessarily distinct) possible worlds…." In that case, however, we would again have failed to identify a sort of holism which is new in QM (or at least not obviously not so). It seems implausible that whenever, across *all* possible worlds, we find two pairs of massive bodies such that the masses of the bodies in the first pair are the same as the masses of the bodies in the second pair, and the spatial separation between the bodies in the first pair is the same as that between the members of the second pair, then the gravitational potential energy of the pair as a whole is in both cases the potential energy dictated by Newton's law of universal gravitational attraction (to take an example of what is plausibly an intrinsic property of the whole), and the gravitational attraction between the two bodies is in both cases the one dictated by the same law (to take an example of a relation between

[25] For example, two pairs of electrons, or two agglomerations of six top quarks, or....

the parts). To claim otherwise would be declare Newton's law a necessary truth.[26] *Contra* Teller, then,[27] but in keeping with Healey, I will assume that the plausible part-whole supervenience claim to make in the case of classical physics is a claim of mere physical supervenience: that whenever we compare two composite systems of the same type drawn from any two (not necessarily distinct) *physically possible worlds*,[28] we will find that if the parts of one system are in the same set of states as the parts of the other, and the parts of one are spatially related in the same way as the parts of the other, then the two composite systems will themselves be in the same states.[29] And note that this makes things more interesting, for the corresponding point that physical supervenience fails in QM is of course stronger than the claim that there is a failure of metaphysical supervenience.

In sum, then, the proposal I am exploring is that we understand quantum-mechanical holism as the failure of the physical supervenience of the physical properties of wholes on the physical properties of and spatial relations amongst their parts.

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[26] There are some who would claim this – see, for example, Shoemaker (1980). More generally, if properties are individuated by the causal powers they confer on their possessors, then perhaps physical supervenience of the properties of the whole on the properties of the parts (and the spatial relations amongst them) entails metaphysical supervenience; and in that case it would be correct to say that the failure of metaphysical supervenience distinguishes QM from classical physics (as well as the failure of physical supervenience). Nonetheless, there would still be a conceptual distinction between physical and metaphysical supervenience, and it would still be worth stressing that physical supervenience fails in QM, and not merely metaphysical supervenience.

[27] Teller writes, "I want to take the sense of possibility implicit here in the strongest possible way, that is as logical possibility" (1986), p. 71. Teller is commenting on the his formulation of physicalism here, which is the only point in the paper at which he explicitly addresses the modal force of the supervenience claims he is considering, but given the connections he limns between physicalism, local physicalism, and holism in QM, the focus on "logical possibility" (which I am reading as metaphysical possibility) would seem to carry over. For Healey's preference for physical supervenience claims, see his (1991), p. 402, n. 8.

[28] On any plausible unpacking of that notion.

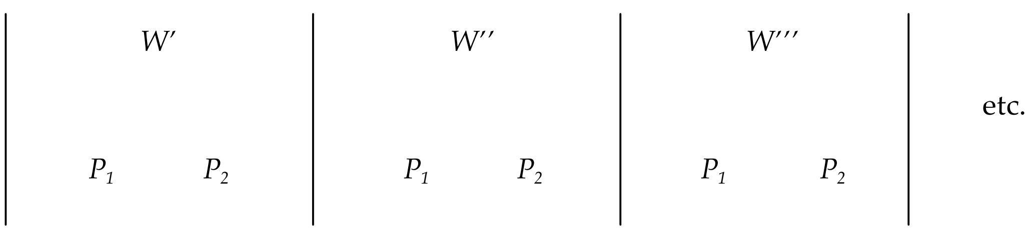
[29] Within the range of physically possible worlds, then, the supervenience claimed for classical physics is interworld, not merely intraworld.

4. Nonsupervenience without holism

For Healey and for Teller, then, quantum-mechanical holism just is nonsupervenience. My first main claim is that this equation misses something important. Formulated in the strongest way, my contention is that holism not nonsupervenience, and my first (and primary) argument for that contention rests on the claim there are, straightforwardly, situations in which nonsupervenience is present without holism. There are difficulties with this way of putting the point, however, and I shall begin by setting things out more cautiously. The argument is nonetheless an essentially simple one.

A paradigm of the sort of quantum-mechanical situation which provokes talk of holism is the one described in section 2, that of a pair of spin-1/2 systems in the spin singlet state, $|\psi_S>$. (The spin state of a system is just the collection of all its dynamical spin properties.) As Teller and Healey both emphasise, the spin state of the pair in this case, $|\psi_S>$, fails to supervene on the spin states of the particles taken separately.[30] Teller and Healey then take this fact to support the identification of holism with nonsupervenience.[31]

It will be helpful to spell out the quantum-mechanical situation in a little more detail. First, here is a schematic diagram of the situation in question:



[30] See Teller (1986), pp. 79-80, and Healey (1991), pp. 417-21. Teller also invokes the original EPR example, which deals with position and momentum rather than spin, but the cases are entirely analogous.

[31] I have just drawn attention to the claim that the spin state of the pair does not supervene on the *spin* states of the individual particles. It does not follow from this, however, that the spin state of the pair fails to supervene on the total states of the individual particles plus the spatial relations between them. Yet it is the latter sort of supervenience with which Teller and Healey wish to identify holism. So is there nonsupervenience of *that* sort? I think there is a genuine question here, but addressing it introduces some significant complications of a more technical nature. I have thus relegated further discussion to an appendix, including my justification for ignoring the problem here.

Here W', W'', W''',… are various physically possible spin states of the pair, and P_1 and P_2 are the corresponding spin states of the individual electrons.[32] The point, then, is that there are a number of distinct, physically possible spin states of the pair which correspond to the same pair of spin states for the individual electrons – and that is physical nonsupervenience of the state of the whole on the states of the pairs. This sort of situation arises over and over again in QM, with composite systems of any size.

Now, if '$|+ - >$' represents a spin state of the pair in which electron 1 has spin up ("+") and electron 2 has spin down ("–"), and '$|- + >$' represents a spin state of the pair in which electron 1 has spin up and electron 2 has spin down (all in, say, the z direction in space), then spin singlet state is written as follows:

$$|\psi_S> = \frac{1}{\sqrt{2}}(|+ - > - |- + >)$$

In this notation, QM tells us that when the spin state of the pair is $|\psi_S>$, the spin states of the individual electrons are:[33]

$$S_1 = S_2 = \frac{1}{2} |+ >< + | + \frac{1}{2} |- >< - | \equiv \frac{1}{2} I_+ + \frac{1}{2} I_-.$$

This means that the electrons considered individually behave like unbiased coins when subjected to spin-z measurements (or, in fact, to spin measurements in any direction). However, there is more than one spin state of the pair in which the individual electrons

[32] In QM the spin state of the whole determines the spin states of the individual particles; it is the reverse sort of determination which does not obtain.

[33] I am taking a certain interpretive stand here by allowing the impure density operators pertaining to a subsystem, obtained by reduction of the density matrix from an entangled pure state of a composite system, to count as representing the dynamical state of the subsystem in question. (These mixtures are of course not to be given an ignorance interpretation, for we are taking the entangled state vector of the whole to be a complete description of the dynamical state of the system.) The alternative route is to deny that subsystems have dynamical states when the composite system is in an entangled pure state, in which case the physical states of the individual electrons would be the sparser states comprising just their mass, charge, total spin, and so on. It will become clear in retrospect, however, that the interpretive choice one makes here does not affect the outcome of my argument.

are in S_1 and S_2. For example:

$$|\psi_T> \;=\; \frac{1}{\sqrt{2}}(\; |+-> \;+\; |-+>\;)\;.$$

($|\psi_T>$ is a state of the pair in which the electron spins "add up" to a total spin of 1; in $|\psi_S>$ they "cancel out" to yield a total spin of 0.) So the situation depicted in the schematic diagram arises. $|\psi_S>$ fails to supervene (even physically) on $< S_1,S_2 >$; and Teller and Healey propose that this nonsupervenience is the holism of which we were originally moved to speak.

The problem with this line of thought emerges when we notice one further aspect of the nonsupervenience of $|\psi_S>$ on $< S_1,S_2 >$. According to QM, one of the other spin states of the pair which is compatible with $< S_1,S_2 >$ (one of the other W's which appears in the diagram) is

$$S_1 \otimes S_2,$$

which can also be written

$$\tfrac{1}{4} I_{++} \;+\; \tfrac{1}{4} I_{+-} \;+\; \tfrac{1}{4} I_{-+} \;+\; \tfrac{1}{4} I_{--},$$

To see the physical content of this state description, imagine that we have four particles altogether, that particle 1 and particle 3 are jointly in state $|\psi_S>$, that particle 2 and particle 4 are also jointly in state $|\psi_S>$, but that particles 1 and 2 have themselves never interacted in any way (and that nor have particles 3 and 4).[34] Then the spin states for particles 1 and 2 taken individually will be S_1 and S_2, just as in the case in which 1 and 2

[34] Thanks to Andy Elby for the example of a physical set-up here. And note that $S_1 \otimes S_2$ cannot be given an ignorance interpretation in such a situation consistently with the assumption of the dynamical completeness of the two $|\psi_S>$ state ascriptions.

form a pair in $|\psi_S>$, but in this case the state for the 1+2 pair will be this new state, $S_1 \otimes S_2$. And if we perform joint measurements of components of spin on particles 1 and 2 in this situation, the results will be entirely uncorrelated, just as though we were tossing two fair and independent coins.[35]

When confronted with a pair of particles in this condition, there is no obvious reason to start talking about "holism" – no reason to say that the whole is greater than the sum of the parts in any sense peculiar to QM, or to say that, in some way which is new to us, the properties of the whole do not reduce to the properties of the parts. We simply have two spin-1/2 particles which, putting it loosely, have nothing to do with one another, and the behaviour of which in response to spin measurements would be entirely unremarkable; a pair of electrons which are joined only in thought. There is, in other words, no reason to be found in the features of such a pair of particles for saying that there is anything strange about the relation of the properties of the whole to the properties of the parts. *Yet the state of the whole in this case does not supervene on the states of the parts* – indeed, it fails to supervene precisely because two particles which are individually in spin states S_1 and S_2 can instead be in the state $|\psi_S>$, our original singlet state (and others). So we have here nonsupervenience, just as much as we have it in the case of the original $|\psi_S>$ pair in the EPR-Bohm experiment, and yet we do not have the same sort of reason to talk about holism in this case as we did in the $|\psi_S>$ case. There does seem to be something strange about the relation between the properties of the whole and the properties of the parts in the $|\psi_S>$ case – something suggested by the spooky correlations and the difficulties in explaining them along familiar causal lines – but there is little reason to suppose that that "something strange" is present in the $S_1 \otimes S_2$

[35] In describing the case this way, I have ignored symmetrization constraints as they apply to the entire four-particle system. Describing the situation in a way which reflects those constraints complicates matters considerably, but does not affect the main point, which is that a pair of electrons which is a subsystem of the right sort of larger system can be in the spin state $S_1 \otimes S_2$ (where this description cannot be given an ignorance interpretation). For the symmetric spin state, see the appendix to Thomson-Jones (forthcoming).

case. The "something strange" is thus *not* nonsupervenience, for that is present in both cases. And so if 'holism' is our name for the something strange, then holism is not nonsupervenience. This, then, is my central argument for the claim that Teller's and Healey's proposals do not successfully locate the source of our inclination to talk about holism.

It will prove useful, especially in succeeding sections, if we introduce two terms of art at this point, and make a distinction between a holistic state and a holistic system. Restricting attention to the simple case of composite systems which we are regarding as composed of just two parts, we will say that W is a *holistic state* (or exemplifies *state holism*) relative to P_1 and P_2 if and only W is somehow greater than the sum of P_1 and P_2, and in a nontrivial way which might plausibly be supposed to distinguish QM from classical physics.[36] (This is of course not intended as an illuminating or particularly precise definition of the new term – coming to understand what we mean by the definiens is, rather, the problem we have yet to solve, or so I am arguing.) Given this, we can then say that a composite system is a *holistic system* (or exemplifies *system holism*) if and only if there is some physically possible combination of states for the system and its parts, $< W,P_1,P_2 >$, such that W is a holistic state relative to P_1 and P_2. Notice, importantly, that these characterisations allow that a system might be holistic without its being in a holistic state at a certain time.

In these terms, the central point of this section is that although $|\psi_S>$ may be a holistic state (relative to $< S_1,S_2 >$), $S_1 \otimes S_2$ is not. As $S_1 \otimes S_2$ fails to supervene on $< S_1,S_2 >$, it follows that we can have nonsupervenience without state holism. State holism is thus not nonsupervenience. And much of the talk of holism we are concerned to illuminate would seem to be about state holism – about some strange relationship which can obtain

[36] It is easy to see how this generalises to the case in which we have partitioned a system into more than two components. Apart from the simplicity of the two-component case, however, there is also the advantage that the canonical quantum-mechanical situation described above is one in which we usually the think of the relevant whole has having two parts.

in QM between a particular state of a whole and the corresponding states of its parts. If that is so, then we have already established that the identification of holism *simpliciter* with nonsupervenience must be seen as failing to capture the intuitions which originally led to the talk of holism in QM. Nonetheless, before we turn to consider what is right about the emphasis on nonsupervenience (in §6), I want to add a little more force to the rejection of the identification of state holism with nonsupervenience. Additionally, the argument of the next section will issue in a reason for concluding that it would be an equal mistake to identify system holism with nonsupervenience.

5. Holism without nonsupervenience

In QM, as we have seen, $|\psi_S >$ does not supervene on the corresponding spin states for the individual electrons, $< S_1,S_2 >$. But imagine a world containing many of the same sorts of particles as ours, one in which those particles can be in many of the same sorts of states, but in which the range of physical possibilities (or the laws, or the nomic facts) are somewhat different. And suppose that there is a world of that sort in which $|\psi_S >$ *does* physically supervene on $< S_1,S_2 >$.[37] Do we want to say that there is no holism involved when a pair of electrons is in $|\psi_S >$ in such a world?[38] My suggestion is that we would not. A system in $|\psi_S >$ in such a world could be in all intrinsic respects just like a pair of electrons in that state in our world, after all. In particular, it would behave in just the same ways on joint spin measurements. The story I told in section 2 to motivate talk of holism could thus be told in exactly the same way in such a world. (That story, importantly, contained no mention of any spin states pairs of electrons could be in other than $|\psi_S >$; in particular, it did not say whether there are other spin states of the pair

[37] Where S_1 and S_2 are again not to be given an ignorance interpretation.

[38] To put it another way, suppose we discover that $|\psi_S >$ supervenes on $< S_1,S_2 >$ in our world, and that we do so by discovering that the nomic facts are not what we took them to be, so that individual electrons in various *other* sorts of situation (corresponding to other spin states for the pair) always turn out to have features which we had previously failed to appreciate. Would we then change our minds about whether there is some sort of holism involved in the EPR-Bohm experiment?

which are physically compossible with the same spin states of the parts.) So it seems that we would have just as much reason to talk of holism in such a world as we do in the actual world. If this is correct, then the fact of nonsupervenience in some particular case is not only insufficient for the presence of a holistic state in that case (as I argued in the last section), it is also unnecessary. And this makes for an even more emphatic weakening of the link between holism and nonsupervenience.[39]

The guiding intuition here is that if a certain state of affairs is a holistic one, then it is so purely in virtue of its intrinsic features. The fact that the state of a certain whole at a certain time fails to supervene on the states of the parts at that time, however, is presumably not an intrinsic feature of the state of affairs in question (namely, the whole's being in *W* whilst the parts are in P_1 and P_2).

Note also that if $|\psi_S>$ is a holistic state (relative to $<S_1,S_2>$) in the situation just described, then it follows that the system in question is a holistic one. We thus have system holism without nonsupervenience, and so system holism also cannot be identified with nonsupervenience.

6. The significance of nonsupervenience

Despite the fact that, on my view, it is a mistake to identify holism with nonsupervenience, there is something right about Teller's and Healey's focus on the latter relation. I will now say what that is, and I will do so by presenting a simple argument for the existence of both state and system holism in QM. The argument will be

[39] A possible objection to this line of argument is that on hearing the first part of the story told in section 2, in which one learns that the individual electrons behave like fair coins, one automatically and tacitly expects to learn that the total state of the pair is an entirely uncorrelated one. Thus on learning that the state of the whole is some other, correlated state, one immediately recognises that this is not the only possible spin state for the pair compatible with the "fair coin" spin states for the individual electrons. So one is aware of the nonsupervenience of as soon as one hears the story.

The response to this objection, however, is simple: One could only become aware of the metaphysical nonsupervenience of the spin state for the pair in this way, but, as I have argued in section 3, the only plausible identification is of holism with physical nonsupervenience (leaving aside the considerations mentioned in n. 26).

laid out in relatively loose and intuitive terms, but I will follow it with some remarks aimed at clarification.

Without yet having a satisfactory account of what is meant by talk of holism in QM, this much is clear: If there is, by the lights of some physical theory, no holism in the world, then whenever we have a composite system, the state of the whole (or, alternatively, the facts about the whole) must in some sense "reduce to" the states of (or facts about) the parts; furthermore (or perhaps this is the same thing), the states of the parts must "fix" or "determine" the state of the whole. Now even though all this is rather vague, we can see that no matter how we go on to circumscribe the meanings of 'reduce,' 'fix,' and 'determine,' if our efforts are to preserve the intent of the original slogans, it must turn out that if there is *no* holism about, then *given a way the parts can be, there is only one way the whole can be*.[40] We might call this the "uniqueness constraint"; the claim is that it is a constraint any theory must satisfy if it is to avoid the suggestion of holism.[41] It follows from this that if, in some theory, the state of the whole does not in general supervene on the states of the parts, then there is holism about. For if we understand a "way the parts can be" to be a set of states for the parts, together with a set of spatial relations amongst them, then the uniqueness constraint just is the constraint that the states of wholes should supervene (physically) on the states of the parts and the spatial relations amongst them. Given that there is nonsupervenience of the relevant kind in QM, then, we can conclude that there is holism in QM.

It may seem for a moment as though a conclusion drawn in the course of presenting this argument contradicts one of my earlier claims. I argued in section 4 that nonsupervenience is insufficient for holism; did I not claim precisely the opposite a moment ago? In fact there is no contradiction here, something which is easily seen once

[40] Again, I take the 'can' here to pertain to the physical possibilities, according to the theory in question.
[41] The uniqueness constraint, does not, however, act as a guarantee of the absence of holism; see the preceding section for an argument that it does not.

we make careful employment of the distinction between system holism and state holism. The point of section 4 was that nonsupervenience is insufficient for state holism; the argument just given relies, however, only on the claim that it is sufficient for system holism.

Still the possibility of confusion persists, for the definition of system holism is such that if there is system holism, then there is state holism. So surely (someone might say) if nonsupervenience is sufficient for system holism, it is *a fortiori* sufficient for state holism. Well, yes and no – there is an ambiguity here. If, according to a certain theory, the state of the whole does not supervene on the states of the parts, then (I have just argued) there is system holism according to the theory. That is, there are systems (or at least, it is physically possible for there to be systems) which *can* be in such a combination of states that the state of the whole does not reduce to the states of the parts (and likewise for 'fixing,' 'determining,' and so on). And this means that state holism is a *physical possibility* according to such a theory. This is the sense in which nonsupervenience is sufficient for state holism. But it does not follow from this that *every* combination of states such a system can be in is one in which the system is in a holistic state relative to the states of its parts – recall the $< S_1 \otimes S_2, S_1, S_2 >$ case. Consequently, a system can be in a combination of states, $< W, P_1, P_2 >$, which is such that W does not supervene on $< P_1, P_2 >$ without W being holistic relative to $< P_1, P_2 >$; a nonsupervening state is not necessarily a holistic one, in other words. This is the sense in which, in section 4, I denied that nonsupervenience is sufficient for state holism. And here there is clearly no contradiction.

As a further elaboration of the picture being proposed here, consider the following two claims. First, if we have a set of physical possibilities of the sort depicted earlier:

W'	W''	W'''	
			etc., to W^n
P_1 P_2	P_1 P_2	P_1 P_2	

then *at least (n-1) of the W's must be holistic states, relative to* $< P_1,P_2 >$. This, I am taking it, is a consequence of the internal structure of the idea of reduction invoked in the initial attempt to flesh out talk of holism, regardless of how we go on to make the idea more precise: at most one *W* could reduce to a given $< P_1,P_2 >$, and so at least (n-1) must be holistic states. A second, logically separate claim is that *one of the W's may be nonholistic relative to* $< P_1,P_2 >$; that is, it may be that one of the *W*'s reduces to $< P_1,P_2 >$ in the appropriate sense, whatever that is. (Again, recall the $< S_1 \otimes S_2,S_1,S_2 >$ case.) To draw on another of the locutions employed at the very outset, the intuitive picture behind this second claim is that holism has something to do with there being, in some nontrivial sense, additional facts about the whole over and above the facts about the parts. And from the claim that, given a particular set of facts about a particular set of parts, there *may* be additional facts about the whole, it does not follow that there *have* to be any – hence nothing rules out the possibility that one way the whole might be involves no holism. Note, furthermore, that it might be possible to make this "additional facts" picture comport nicely with the idea that there can be a multiplicity of holistic states, for given a set of facts about the parts, there may be more than one set of further facts about the whole we can add in.[42]

The merits of this attempts at elaboration aside, however, it should now be clear that Teller and Healey are right to stress the importance of failures of supervenience in their attempts to support and develop the widely held view that the whole is often

[42] It is worth emphasising that this talk of "reduction" and "additional facts about the whole" is not intended to provide a satisfactory account of quantum-mechanical holism, and certainly there are ways of understanding each of those locutions which would not make sense of these ways of using them. These are intended only as suggestive remarks.

greater than the sum of the parts in QM. The argument I stated at the beginning of this section is intended to provide us with grounds for saying that there is holism in QM, and the claim that, in QM, the states of composite systems do not generally supervene on the states of their parts plays a crucial role in that line of reasoning.[43] Indeed, I have argued that nonsupervenience is a sufficient condition for the physical possibility of both holistic states and (therefore) holistic systems.

Despite the significance of nonsupervenience when we are trying to understand holism, however, I hope to have provided good reason, in sections 4 and 5, to think that an account which identifies holism with nonsupervenience is on the wrong track. Consequently, we would seem still to be in need of an account of the unfamiliar relationship between parts and wholes which is apparently rife in QM. At least two desiderata on any such account emerge readily from the discussion so far: a good account must provide us with the resources to distinguish between state and system holism, and it must allow holistic systems sometimes to be in nonholistic states. In addition, we might ask that an account of holism explains, or makes clear, how nonsupervenience is possible. This might mean that the account will specify a number of "degrees of freedom" in the relation between holistic states of the whole and the corresponding states of the parts, thereby making it clear how it is that many different states of the whole are compatible with a single set of states of the parts when we are dealing with holistic systems.[44] It might not be a good idea, on the other hand, to require that a good account of quantum-mechanical holism should provide us with an explanation of the violation of the Bell inequalities; even less should we insist that it provide a non-causal explanation. Nevertheless, I will conclude by showing that there is a suggestive link connecting state holism to the existence of nonclassical correlations

[43] The qualification ("generally") is included because (to hold to our favourite example) there are pairs of spin states for the individual electrons which *are* compatible with only one state of the whole. In this sense, the nonsupervenience is not universal.

[44] I am indebted to Allen Stairs for suggesting this last desideratum.

between the parts of a composite system. In particular, I want to argue that all such correlations are produced by holistic states. [45]

7. Holism and the correlations

I will continue to frame my discussion in terms appropriate to a two-component system, but the argument which follows generalises quite straightforwardly to the *n*-component case.

First, a little formalism. Let H_1 and H_2 be the quantum-mechanical state spaces for the components of a two-component system (such as two electrons, which are the two components of an electron pair). The tensor product space, $H_1 \otimes H_2$, is the state space for the composite system (such as the pair). A quantity pertaining only to the first component of the system (such as "spin-*z* of electron 1") is represented on this latter state space by a Hermitian operator of the form $Q \otimes I$, where Q is an operator defined on H_1 representing the corresponding property of the first component (such as "spin-*z*") and I is the identity operator; similarly for quantities pertaining only to the second component of the system and Hermitian operators of the form $I \otimes R$.

The crucial mathematical fact is then this: It is a simple matter to prove that for any state on $H_1 \otimes H_2$ which can be written in the form

$$D_1 \otimes D_2$$

(where D_1 and D_2 are density operators on H_1 and H_2 respectively, representing the states of the two parts of the system),[46] there are *no* correlations between the outcomes of measurements of quantities represented by operators of the form $Q \otimes I$, and those

[45] The argument of the next section involves a little more in the way of technical detail than that of previous sections. The hope is that the reader who is not well versed in the ways of QM will nonetheless be able to make out the general thread.

[46] $S_1 \otimes S_2$ is an example of such a state.

represented by operators of the form, $I \otimes R$. Consequently, any state of the whole which gives rise to correlations between outcomes of measurements on the two subsystems will be a state which cannot be written in the $D_1 \otimes D_2$ form.[47]

Now let *W** be some state of a two-component whole which gives rise to spooky, nonclassical correlations. *W** will give rise, by reduction of the density matrix, to two unique density operators, one on H_1 and one on H_2, representing the states of each of the parts. Let those density operators be *A* and *B*, respectively. $A \otimes B$ is then a density operator on $H_1 \otimes H_2$ representing a state the whole can be in – a state, moreover, in which the parts are in states *A* and *B*, respectively (by a trivial application of reduction of the density matrix).[48] Yet $A \otimes B$ is clearly a state distinct state of the whole from *W**, for by hypothesis *W** is a state which gives rise to correlations between the outcomes of certain measurements on the subsystems, and we know that no such state can be written in the $D_1 \otimes D_2$ form. It follows that both *W** and $A \otimes B$ fail to supervene on <*A*,*B*> (each thanks to the physical possibility of the other). Consequently, by the argument of section 6, at least one of them must be a holistic state (relative to <*A*,*B*>). Now certainly I wish to allow for the possibility that one of these two states of the whole is a nonholistic state. Yet surely if either of them is to be declared nonholistic, it will be $A \otimes B$, for that is a state which gives rise to no correlations of any sort, and in which the parts of the so-called composite system need be nothing more than two completely independent systems which we have arbitrarily grouped together in our quantum-mechanical representations. Thus it follows that *W** must be a holistic state of the system. And as nothing was assumed about *W** other than that it gives rise to nonclassical correlations between the outcomes of

[47] $|\psi_S>$ is an example.

[48] Note that, at least in principle, we can always find a system in the $A \otimes B$ state (where $A \otimes B$ cannot be given an ignorance interpretation on the present approach) simply by selecting appropriate subsystems from a pair of two-component systems each of which is in *W**. (This is a generalisation of the strategy described in section 4 for creating an $S_1 \otimes S_2$ pair.)

measurements on the two subsystems of which it is composed, it follows that any state which gives rise to nonclassical correlations in QM is a holistic state.[49]

8. Conclusion

Here, then, are the main points I hope to have established:

> 1) There can be failures of supervenience without (state) holism in QM (§4).
>
> 2) There could be (state) holism without nonsupervenience (although this is not so in QM) (§5).
>
> 3) Failures of supervenience are sufficient for system holism, and so for the physical possibility of state holism (in QM and in general) (§6).
>
> 4) Spooky correlations are always produced by holistic states (§7).

Furthermore, if these claims are correct, they place implicit constraints on the shape of any new account of what it means to say that, in QM, the whole is often greater than the sum of the parts. What, then, is the way forward from here?

This, of course, is where things become particularly difficult. Perhaps a long history of inquiry about parts and wholes in metaphysics might be expected to help, but the application of those traditional discussions to our present difficulties is not so straightforward. Attention in mereology seems to have focussed on questions about the

[49] The astute reader will have noticed that this argument can easily be generalised to prove a rather stronger conclusion than the one just stated – namely, that *any* correlations, spooky or not, between outcomes of measurements on subsystems of a composite whole must arise from holistic states. This may seem odd until one realises that once one has opted for an approach to the theory which regards its state descriptions as complete (thus rejecting any talk of hidden variables), *all* such correlations should be regarded as "spooky" in the sense that they will in fact have no familiar sort of causal explanation. Once one has made such an interpretive commitment, the fact that *some* of these correlations, such as the perfect correlations between spin measurements in the same direction on the electrons in a $|\psi_S>$ pair, *could* be given a common cause explanation by another theory (or by the current theory supplemented with hidden variables of one variety or another) is beside the point – the correlations are mysterious nonetheless on the interpretive approach in question.

ontological status of various putative composite entities or their putative parts (such as the question of whether an arbitrary collection of objects composes a whole, or the question of whether arbitrary subregions of the region occupied by a spatial whole correspond to parts of that whole), questions about the part-whole relation itself (such as the question of whether the relation of parthood, where it obtains, obtains necessarily, or the question of whether there is a unique relation of parthood), and questions about the logic of inferences concerning parts and wholes.[50] Our questions, on the other hand, are about the relations which can obtain between the properties of a whole and the properties of its parts. There may, nonetheless, be some connections to be explored, and the possibility is certainly an intriguing one. In any case, I hope at least to have reinforced the conviction that there is good reason to speak of holism in QM; and I hope, too, to have added force to the sense that if we are to succeed in understanding the metaphysical implications of this most enigmatic of modern physical theories, then further illumination of such talk is sorely needed.

[50] See, for example, Simons (1987) and van Inwagen (1990).

Appendix

I noted at the beginning of section 4 (in n. 31) that the nonsupervenience of $|\psi_S>$ on the spin states of the individual electrons in the pair does not entail its nonsupervenience on the total states of the individual particles plus the spatial relations amongst them, which is the sort of nonsupervenience Healey and (with a little reformulation) Teller are interested in. It is a simple matter to see that $|\psi_S>$ does indeed not supervene on the spin states of the individual electrons (see section 4), but a more complex question whether it fails to supervene on the more inclusive supervenience basis.

The issue is symmetrization constraints. The electrons in an electron pair are identical spin-1/2 particles, and so the total dynamical state of the pair must be an antisymmetric one. This means that if the spin state of the pair is $|\psi_S>$, which is anti-symmetric, then its spatial state must be symmetric. If $|R>$ is an idealized one-particle spatial state corresponding to an electron's being localised within some region at the right-hand end of the room, say, and $|L>$ similarly represents an electron's being localised at the left-hand end, then the spatial state might be

$$|\psi(R)_S> \quad = \quad \frac{1}{\sqrt{2}}(|RL> + |LR>)$$

Suppose, then, that we attempt to make the case for nonsupervenience by pointing out that

$$|\psi_T> \quad = \quad \frac{1}{\sqrt{2}}(|+ \; -> + |- \; +>)$$

is a spin state for the pair in which the individual electrons have the same spin states as in the $|\psi_S>$ case (namely, S_1 and S_2). The problem is that this new spin state is symmetric, and so to yield a total dynamical state which is antisymmetric, the spatial state itself must now be antisymmetric:

$$|\psi(R)_T> \quad = \quad \frac{1}{\sqrt{2}}(|RL> \; - \; |LR>)$$

Now certainly the individual electrons have the same *individual* position states whether the pair is in $|\psi(R)_S>$ or $|\psi(R)_T>$; in either case, both particles are in the state:

$$\frac{1}{2}|R><R| \; + \; \frac{1}{2}|L><L|$$

But the question is whether the total state of the pair (including its dynamical spin state) supervenes on the total states of the particles taken separately *plus* the spatial relations between them. And arguably there is information about the spatial relations between the two electrons contained in the joint position state ($|\psi(R)_S>$ or $|\psi(R)_T>$, as the case may be) which is not provided when we simply give the position states of the individual electrons. (Certainly Teller would seem committed to saying this, given that he would want to claim that *spin* relations captured by $|\psi_S>$ and $|\psi_T>$ are not captured in $<S_1,S_2>$ – the situations are entirely analogous. And Healey mentions the spatial relation of "not being spatially coincident" as an example of the sort of spatial relation which belongs in the supervenience basis in the quantum-mechanical case, despite the absence of other spatial relations such as those depending on (or yielding) precise positions for the particles. That the electrons in our pair of particles are not spatially coincident *is* represented by $|\psi(R)_S>$ and $|\psi(R)_T>$, but not by saying merely that each electron is individually in $(1/2)|R><R| \; + \; (1/2)|L><L|$.) If that is true, then we have not established supervenience of the desired sort, as the two spin states in question ($|\psi_S>$

and $|\psi_T>$) seemingly correspond to *different* sets of spatial relations between the particles (represented by $|\psi(R)_S>$ and $|\psi(R)_T>$, respectively) – at least, it is not obvious that they do not. And perhaps it will turn out that spin states in general supervene on the more inclusive supervenience basis for this sort of reason.

Where does this leave us? If in fact the spin state of a pair of electrons *does* supervene on the total states of the individual electrons plus the spatial relations between them, then it is entirely straightforward that any holism present in the $|\psi_S>$ case cannot identified with the failure of such supervenience, and Teller's and Healey's proposal is thwarted at the outset. The issues here are somewhat complex and unsettled, however, so I have laid this worry aside in the body of the discussion. This laying aside amounts to assuming, at least for the sake of argument, that both the dynamical properties of the individual particles and the spatial relations between them can be held fixed as we move from the $|\psi_S>$ to the $|\psi_T>$ case (or the $S_1 \otimes S_2$ case, for that matter), so that the question of the supervenience of the spin properties of the pair reduces to the question of whether these spin states supervene on the *spin* states of the individual electrons –the answer to that question being a clear no.

Note, separately, that one might plausibly claim on physical grounds that failure of the spin properties of the whole to supervene on just the spin properties of the parts is mysterious enough. The idea here would be that spin is a sufficiently *sui generis* quantity that the spin properties ought to depend only on the spin properties of the parts. One might then go on to propose that the holism found in the $|\psi_S>$ case is nonsupervenience of this more restricted sort. In that case, however, the arguments laid out in the main body of the paper would apply; and we should note anyway that this is a new proposal.

Incidentally, at one point Healey mentions the case of a pair of particles in $|\psi_S>$ which are *not* identical particles – the case of an electron-positron pair (1991, p. 418). In that case, it is true, the symmetry constraints do not apply in the same way, and the questions raised in this appendix might appear to become moot. However, holism in an electron-positron $|\psi_S>$ pair is presumably the same thing as holism in an electron-electron $|\psi_S>$ pair, and so the questions raised here still have a bearing on the electron-positron case, albeit by a slightly indirect route.

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