

Humean Supervenience, Composition as Identity and Quantum Wholes

Claudio Calosi¹ · Matteo Morganti²

Abstract In this paper, we focus on two related reductive theses in metaphysics—*Humean Supervenience* and *Composition as Identity*—and on their status in light of the indications coming from science, in particular quantum mechanics. While defenders of these reductive theses (at least those who do not simply deny the metaphysical import of empirical data and their proposed interpretation) claim that they can be updated so as to resist the quantum evidence, we provide arguments against this contention. We claim that physics gives us reason for thinking that both *Humean Supervenience* and *Composition as Identity* are at least contingently false, as the very process of composition determines, at least in some cases, the nature of composed systems. The argument has essentially to do with the fact that denying the reductive theses in question allows one to provide better explanations for the quantum evidence.

1 Introduction

It is customary for metaphysicians, at least to the extent that they take seriously the fit of their hypotheses with the indications coming from our best science, to seek a balance between the empirical adequacy of those hypotheses and the maximization of theoretical virtues such as simplicity, economy, parsimony, unification, explanatory power and the likes. One particular aspect with respect to which

✉ Claudio Calosi
claudio.calosi@unine.ch

Matteo Morganti
mmorganti@uniroma3.it

¹ Institute of Philosophy, University of Neuchatel, Espace Louis-Agassiz 1, 2000 Neuchâtel, Switzerland

² Department of Philosophy, University of Rome3, Via Ostiense, 234, 00144 Rome, Italy

virtuous metaphysical hypotheses would be welcome, it seems, is their implied ontological commitment. *Ceteris paribus*, a metaphysical hypothesis implying less ontological cost should be preferred to one implying a higher ontological cost. In view of this, it is easy to understand the appeal of ‘reductive’ theses that promise to account for certain aspects of reality entirely in terms of other, putatively more fundamental, aspects.

This paper focuses on two such reductive metaphysical theses: *Humean Supervenience* (HS)—according to which, roughly, the universe is nothing but a vast mosaic of local facts—and *Composition is Identity* (CII)—according to which a whole is strictly identical to its parts taken collectively. HS and CII share the same driving intuition: namely, that composites do not require any ontological commitment additional to that entailed by their parts. In spite of the apparent strength of this intuition, both HS and CII do not seem to fare too well when it comes to our best current science. Quantum mechanics, in particular, has been taken to offer counterexamples to both theses. Recent defenders of both HS and CII, however, have argued that the views can be amended so as to resist the quantum evidence. Obviously enough, if successful, this would restore, and indeed increase, the plausibility and appeal of the underlying reductionist stance.

On the one hand, the proposed amendment consists in adding the appropriate properties and relations to the ‘reduction basis’ (the meaning of this expression will become clear as the paper progresses). On the other hand, another line of argument has it that reductionism can be preserved by switching to certain non-standard interpretations of quantum mechanics and of the fundamental entities the theory is about.

The present paper provides arguments against both defensive strategies, and in favor of the view that physics does indeed suggest that both HS and CII are at least contingently false. These arguments are essentially based on considerations having to do with explanatory power and the need to avoid positing brute metaphysical facts whenever possible.

Although the paper focuses on quantum composite systems, and aims to add to the extant discussions of HS and quantum physics, the argument should be regarded as more general. Indeed, the examples taken from quantum mechanics illustrate in the most vivid manner what types of facts reductionists need to account for in order to resist anti-reductionist attacks. Even if one is not a realist about quantum mechanics, then, the main argument of this paper still puts into doubt the strength of HS and CII as necessarily true metaphysical theses. In a sense, this is not a problem: for instance, it is well-known that Lewis took HS to be at best contingently true. In another sense, however, it is. First, CII is normally presented as a much stronger, necessarily true, thesis. Secondly, it is plausible to think that the very project of amending HS and CII so as to neutralize putative counterexamples is motivated by (among other things) the conviction that the relevant form(s) of reductionism must be more than just true in a limited subset of all possible worlds.

The rest of the paper will proceed as follows: in Sect. 2, we will look at HS and CII in more detail; in Sect. 3, we will explain the relevance of quantum mechanics with respect to the theses at hand, and introduce a first strategy that reductionists employ to defend their views; in Sect. 4, we will put forward our anti-reductionist

argument, which will be discussed further in Sect. 5; in Sect. 6 we will address the alternative defense of reductionism grounded in what we called non-standard interpretations of quantum mechanics and its ontology; a concluding Sect. 7 will follow.

2 Humean Supervenience and Composition as Identity

We stated in the introduction that HS and CII share the same basic intuition, namely, that wholes require no ontological commitment additional to that entailed by their parts. It is this reductive connotation that makes them appealing and, consequently, motivates their joint philosophical assessment.

But what is exactly the relation between HS and CII? To investigate the prospects of the underlying reductionist programme, it is of course necessary to provide a more precise formulation of the theses in question, and to say something more about how they relate to one another. In line with Lewis (1994: 474) we take HS to amount to the following:

(1) HS: The world is a mosaic of point-like qualities and space–time relations between (some of) them; i.e., all facts either are or supervene on facts concerning point-like qualities and, possibly, (dyadic) space–time relations between the bearers of these qualities.¹

On the other hand, CII maintains that a whole just *is*, strictly and literally, its parts, where the whole in question is nothing but the mereological fusion of those parts. Using plural logic and the standard notion of mereological fusion we can state the thesis as follows²:

(2) CII: If a composite object x is the fusion of a plurality X then $x = X$ ³

As it can be seen from (1) and (2), CII and HS are clearly distinct metaphysical theses. Yet, there are interesting elements of interconnection.

Let us ask, in particular: Does HS entail CII? Prima facie, it looks as though the answer must be in the negative. For, strictly speaking, HS is perfectly compatible with wholes whose ‘qualitative content’ entirely supervenes on that of their parts,

¹ Here’s a significant quote: “[HS] says that all else supervenes on the spatiotemporal arrangement of local qualities throughout all history” (Lewis 1994: 474).

² We use lower-case letters for singular names and variables whereas we use capitals for plural terms (both names and variables). The standard notion of mereological fusion is this: x is a fusion of the X s iff (1) each X is part of x and (2) each part of x shares a part with at least one X . If we abbreviate “ x is the fusion of the X s” with $xFuX$, the thesis that is relevant for our discussion is that: $xFuX \rightarrow x = X$. It is important to point out that we are only interested here in the idea that composition is identity, not in the weaker (but much more imprecise and vague) view that composition is ‘analogous’ to identity. The broader label ‘composition as identity’ is often used to refer to either thesis (and we use it in this sense in the present paper). For details, see Cotnoir (2014).

³ Note that no commitment is made with respect to the truth of the converse implication. If the latter were in fact true, one would have so-called ‘strong composition as identity’, which we need not take into account in the present discussion.

⁴ We will return to this issue later, see Sect. 4.

and yet are non-trivially ontologically distinct from, i.e., not identical to, the latter.⁴ This is because supervenience consists in the fact that there cannot be a difference in what supervenes without a difference in the ‘supervenience basis’, which involves the monadic properties of the relevant entities (and their spatio-temporal relations); it does not entail anything with respect to whether or not the entities whose properties supervene are made of ‘nothing but’ entities belonging to the supervenience basis. However, it is obvious that the supervenience of the properties of x on those of y might be a consequence of the ontological reducibility of x (or, more generally, of entities of the same sort as x) to y (or, more generally, on entities of the same sort as y)—where ontological reduction is ultimately a form of identity. Moreover, on at least one possible interpretation, HS is really a supervenience thesis only with respect to truth and truth-making (there cannot be a change in what facts are true without a corresponding change in what exists ‘out there’ that makes them true); and, at the level of objects and their properties, it does not make a simple claim of co-variance but also, more strongly, a claim of reduction. Indeed, what Lewis seems to have had in mind in his formulation of HS is exactly the dispensability of certain entities when it comes to providing an exhaustive list of what the world is fundamentally made of—something that is not achieved via a mere supervenience claim. On this construal, then, what the supporter of HS claims is that all properties and relations of the whole can be ultimately analysed in terms of ‘Humean’ properties (and their bearers) and relations, i.e., those properties and relations that satisfy HS above, so that ontological commitment can be systematically restricted to such items.

If one interprets the mosaic metaphor literally in this way, it is indeed natural to say that CII is true if HS is. For, if a is reducible to b and c together, how could it possibly be denied that a is nothing but b and c together?⁵ Thus, we have that:

(3) If HS is understood as claiming that all properties and relations not only supervene on, but are *reducible* to Humean properties, then HS entails CII.

-Humean properties being those that satisfy HS-

On the other hand, CII being a mereological thesis, it cannot have any direct consequence with respect to the (non-)supervenience of the properties of composite objects. However, if one assumes CII and also that reality is ultimately constituted by point-like mereological components standing in spatio-temporal relations (and no other relation), Leibniz’s Law seems to guarantee that HS is also satisfied. For the pointlikeness of the parts entails the pointlikeness of their properties, and the identity of composites with their components then yields that the former cannot exemplify any property or enter any relation additional to those admitted by HS. In a nutshell, one can state that:

(4) If reality is ultimately composed of point-like entities standing (only) in (dyadic) spatio-temporal relations, then CII entails HS.

⁴ We will return to this issue later, see Sect. 4.

⁵ Notice that we are glossing over differences that depend on whether properties and relations are parts (as suggested, for instance, by Paul (2002, forthcoming) with her ‘mereological bundle theory’) or just features of parts. Either way, CII follows.

While there is no immediate entailment either way between CII and HS, then, the above analysis suggests that a strong connection exists nevertheless. In particular, [from (3) and (4) above] one has that:

(5) If (a) all properties and relations of composite objects not only supervene on, but are also ontologically reducible to properties of point-like entities plus (dyadic) spatio-temporal relations, and (b) reality is ultimately composed of point-like entities standing (only) in (dyadic) spatio-temporal relations, then $HS \leftrightarrow CII$, and both HS and CII are in fact true.

The obvious question is whether the reductionist picture suggested by (a) and (b) in (5) is correct or, to the contrary, composition is such that, at least in some cases, it prevents such reduction.

3 Reductive Metaphysics and Quantum Evidence

A seemingly obvious counterexample to the intuition underlying CII and HS is provided by quantum mechanics, according to which certain physical systems—so-called ‘entangled systems’—exhibit correlations among their parts which are not reducible to the properties of these parts. That is, the correlations in the whole are not automatically determined by the fact that the parts have the intrinsic properties that they have. The usual illustration is that of two fermions that are ‘put together’ in a certain way (the so-called ‘singlet spin state’) and then separated, sent in different directions and subjected to a measurement of spin (along the same axis for both) at a distance which prevents any causal influence of one of them on the other. While the theory tells us that each fermion has the same probability of turning out to be either spin up or spin down, and thus it should be possible for the two fermions to be both spin up, or both spin down, we are also told that it is instead necessarily the case that the particles have opposite spins.⁶ This appears sufficient for abandoning HS, for the evidence seems to unambiguously tell us that the composite two-particle system has certain features which are not just an immediate by-product of those of the two particles considered together: the properties of the whole system do not supervene on those of the constituent fermions.

In more detail, one could follow Maudlin (2007: 51) and analyse HS in terms of two separate doctrines: *separability*—the state of the world supervenes on the state of its parts—and *physical statism*—all facts about the world, including modal and nomological facts, are determined by its total physical state. On the face of it, quantum entanglement seems to point unambiguously to a violation of separability, hence of HS.

Also, distinct but indiscernible components may give rise to qualitatively distinct wholes, as it happens, for instance, for pairs of exactly similar bosons.

⁶ Upon measurement but, it is also plausible to say, even independently of whether a measurement is actually carried out.

Consider four one-particle quantum systems S1, S1*, S2, S2*—which are considered *separately and pre-compositionally, so to say*—pairwise indiscernible so that S1 and S1* are both in state (6):

$$(6) \frac{1}{\sqrt{2}}|\downarrow_x\rangle + \frac{1}{\sqrt{2}}|\uparrow_x\rangle$$

And S2 and S2* are both in state (7) for the same observable:

$$(7) \frac{1}{\sqrt{2}}|\downarrow_x\rangle + \frac{1}{\sqrt{2}}|\uparrow_x\rangle$$

These systems can constitute composite systems with different monadic properties. In particular, it is possible that S1 and S2 compose S12 in state (8):

$$(8) |\phi\rangle_{12} = \frac{1}{\sqrt{2}}(|\downarrow_x\rangle_1|\downarrow_x\rangle_2 + |\uparrow_x\rangle_1|\uparrow_x\rangle_2)$$

whereas S1* and S2* compose S12* in state (9):

$$(9) |\psi\rangle_{12} = \frac{1}{\sqrt{2}}(|\downarrow_x\rangle_1|\uparrow_x\rangle_2 + |\uparrow_x\rangle_1|\downarrow_x\rangle_2)$$

Crucially, component bosons are in pairwise exactly similar states *also after the composition has taken place*. For, their respective reduced states are the following mixed states:

$$(10) \rho_1^\phi = \frac{1}{2}(|\downarrow_x\rangle\langle\downarrow_x| + |\uparrow_x\rangle\langle\uparrow_x|) = \rho_{1*}^\psi$$

$$(11) \rho_2^\phi = \frac{1}{2}(|\downarrow_x\rangle\langle\downarrow_x| + |\uparrow_x\rangle\langle\uparrow_x|) = \rho_{2*}^\psi$$

Thus, distinct but exactly similar components may give rise to discernible wholes. Indeed, something along these lines seems to be what McDaniel (2008) has in mind when he presents what we will call the ‘argument from duplication’. Here’s our reconstruction and adaptation of McDaniel’s argument.

Two things x, y are singular duplicates if they have the same intrinsic properties, the same mereological structure and the same relations holding among the parts. Plural duplicates are defined similarly. Now, S1 and S1* above are singular duplicates. The same goes for S2, S2* above. But consider the plurality $W = S1, S2$ on the one hand and the plurality $W^* = S1^*, S2^*$ on the other. They should count as plural duplicates (for each part of them is a singular duplicate of a part in the other plurality). Since S12 fuses W , by CII we have that $S12 = W$. By the same argument, $S12^* = W^*$. Since W and W^* are duplicates so should S12 and S12* be. But they are not, in that they are in eigenstates of the total spin operator belonging to different eigenvalues (total spin = 1 and total spin = 0 respectively). Hence, by the eigenfunction-eigenvalue link S12 and S12* have different properties.⁷ Since (regardless of whether duplicates are intended as entities existing in the same possible world or as necessarily inhabiting different possible worlds) duplicates should have all the same properties, CII seems to be in danger.

⁷ This is an example of Miller’s *type-c differences*, namely differences in the wave-function or quantum states of physical systems that are due neither to phase factors, nor can be washed away by symmetry transformations such as velocity boosts (Miller 2013: 572). Other paradigmatic cases are the singlet and triplet states discussed in Maudlin (2007: 59–60).

Putting the foregoing considerations together, if we take our best physics seriously, it looks as though both HS and CII fail in the actual world. However, things are not so straightforward, as defenders of the reductive stance underpinning HS and CII have provided explicit responses to this sort of objections, and to the argument from duplication in particular.

Based on some remarks by Lewis himself,⁸ first of all, defenders of HS have argued that there is no problem here, for fundamental *quantum entangled relations*⁹ need simply be added to the supervenience basis. In fact, this might be regarded as a welcome result—philosophers should pride themselves of learning from science as the latter progresses, and this can be done in this case without questioning HS, but rather giving it a more precise, and allegedly stronger, formulation. After all, Lewis himself famously stated that he was ready to ‘submit willingly to the best of authority’ in case (an established and agreed upon version of) quantum mechanics were to force him to conclude that HS was false and revise the thesis accordingly (see Lewis 1986; xi). Thus, one could formulate HS as follows:

(12) HS* The world is a mosaic of fundamental, intrinsic point-like qualities and (dyadic) space–time relations, *plus entanglement relations*; i.e., all facts either are or supervene on facts concerning such point-like qualities, together with (dyadic) space–time and, possibly, entanglement relations.¹⁰

For an illustration, let’s go back to our quantum example above, where indiscernible components gave rise to discernible wholes in states (8), (9). The reductionist could hold that, given HS*, in addition to the components’ states and the spatio-temporal relations among them we ought to also take explicitly into account entanglement relations, expressed for example by *n*-fold sums of tensor products of projective operators, namely:

$$(13) P_{corr} = (P_{\downarrow 1} \otimes P_{\uparrow 2} + P_{\uparrow 1} \otimes P_{\downarrow 2})$$

$$(14) P_{anti-corr} = (P_{\downarrow 1} \otimes P_{\downarrow 2} + P_{\uparrow 1} \otimes P_{\uparrow 2})$$

Then state (8) would be determined by the following reductive basis: (10), (11) and (13), whereas state (9) would be determined by (10), (11) and (14).¹¹ In this simple case we could even offer a formulation of entanglement relations in the natural language. The projective operator (13) would correspond to the

⁸ Lewis (2009: 205) addresses whether there are “all-or-nothing *n*-adic relations, at least for smallish *n*”. He envisages possible worlds in which the relation of having opposite electric charge is fundamental and non-reducible.

⁹ The idea that entangled systems exhibit ‘inherent’ relations that are irreducible to fundamental, intrinsic properties of the *relata* comes from Teller (1986). Teller argues that the existence of such relations is one of the most crucial ontological lessons to be drawn from quantum mechanics. Although the view can be questioned (e.g., by contending that entanglement corresponds to monadic properties of certain wholes, or that it does in fact supervene on the properties of the parts, albeit via a functional relation weaker than multiplication (Winsberg and Fine 2003), we will keep talking of (seemingly non-supervening) ‘entanglement relations’ here.

¹⁰ McDaniel (2008:132) explicitly considers such an option, but finds it unconvincing.

¹¹ For simplicity’s sake, we refer to operators here (and elsewhere), while of course it is the corresponding physical properties that are relevant.

entanglement relation expressed by the predicate “having correlated spin”, whereas (14) would correspond to the one expressed by the predicate “having anti-correlated (opposite) spin”.

Recent critics (e.g., Darby 2012) disagree with the reformulation of HS just suggested in terms of HS*, but essentially on methodological grounds having to do with the specific characteristics of the quantum relations that are introduced as fundamental, and their fit with the spirit of the original Lewisian idea underlying HS.¹² This is to say that they accept that entanglement relations can in principle be in the supervenience basis. We think instead that there are very general methodological reasons for rejecting the reductionist stance in view of the evidence.

Before moving on, however, let us ask: how does the foregoing reductionism-saving strategy extend to CII? An answer is suggested by Sider (2007, 2014) and Bohn (2012) in their recent defenses of CII.¹³ Bohn, in particular, explicitly suggests that all quantum mechanics shows is that it is contingently true that there are *collective properties*. That is, properties that are only exhibited by the entire system composed of n parts, but *not* because the system is *an entity additional* to the n entities we already had. Rather, because the n parts collectively have a property that they do not have separately. Compare with the property of surrounding something or someone. As in the case of n men surrounding another man, the argument goes, so in the case of n entangled particles the truth of the claim ‘the system composed by x_1, \dots, x_n together is entangled (surrounds y)’ can be read as a claim merely about the individual n things composing the system, *insofar as these form a collective*. Crucially, although an explicit reference to the collective is needed, no ‘mereological ingredients’ additional to the components of the collective is required.

In connection to this, it is worth reporting that Sider (2014) also exploits so-called ‘Collapse’ to further limit the strength of the objection being moved to CII on the basis of emergent properties. Collapse is a deductive consequence of CII, Leibniz’ Law, some basic mereological axioms, and a somewhat natural Plural Covering Principle for Plural Logic¹⁴: $\forall x \forall y (y \prec x \rightarrow \exists W (xFuW \wedge Wy))$. It consists in the fact that $\forall X \forall z (zFuX \rightarrow \forall y (Xy \leftrightarrow y \prec z))$. That is, y is one of the X if and only if it is part of their mereological fusion. In general, in order to have an admissible plurality—including all and only things of a certain sort—each and every part of the relevant aggregate must itself be a thing of that sort. Given this, there are fewer pluralities than expected, which presumably rules out at least some putative counterexamples to CII.¹⁵

¹² Essentially, Darby complains that it is always the case for entangled states that nothing short of the entire set of n component states and the corresponding n -ary fundamental relations can make sense of the properties of the whole. Thus, HS* holds only at the expense of adding very ‘global’ facts to the point-like, i.e., local, facts that were originally presented as fundamental. We will say something more on HS and globality in a later section.

¹³ We should point out that Sider (2007), while explicitly acknowledging the possibility of adding non-supervenient relations to the supervenience basis, ends up rejecting CII anyway, on the grounds that it would distort plural logic. He then goes on to endorse the weaker thesis, mentioned earlier, that composition is analogous to identity.

¹⁴ $x \prec y$ abbreviates “ x is part of y ”, whereas Xx abbreviates “ x is one of the/among the X ”. Informally, the principle says that if y is part of x , then it is among some W whose fusion is x .

¹⁵ Obviously enough, on the same basis Sider rejects McDaniel’s argument from duplication.

In this case too, we think, the strategy is unexceptionable from the logico-metaphysical viewpoint, and one might perhaps ask whether or not the basic reductionist intuition is preserved by this move; yet, we think that a more serious problem arises. Let us then see what we take to be the most serious difficulty for the form of reductionism under scrutiny in view of the quantum evidence.

4 Quantum Wholes, Quantum Parts and Quantum Composition

We agree that the above strategies to save HS* and CII work, *provided* that one is liberal about what can go in the supervenience basis in the case of HS*, or in the range of properties that non-Collapse-violating collectives can exhibit in the case of CII. However, *we disagree that one can be so liberal*. This, not on the basis of logico-metaphysical or exegetical reasons, but on the basis of considerations of explanatory power.¹⁶

Let us agree for now on the fact that, in light of the available evidence, certain properties of quantum wholes can be regarded as genuine, non-reducible features of physical systems.¹⁷ Now, a crucial point is that reductionists defend HS* and/or CII at the price of taking the existence of these features as a primitive, i.e., of leaving unanswered the question concerning how physical system (may) come to possess these properties.¹⁸ But, as we have seen, the key question concerning these properties arises when we notice that some composites (may) exhibit them, and some don't (may not). Wouldn't it be better in terms of explanatory power, then, to do the opposite, and provide an account of when and how certain features of composite physical systems 'emerge', so to put it, even at the cost of subscribing to a more complicated, non-reductionist ontology?

For instance, consider again states (8)–(9) above. Should we just take it as a fact that indiscernible parts *could give rise* (notice the modal and temporal elements involved) to discernible wholes, albeit in such a way that their individual states *within* those wholes differ?¹⁹ Or should we rather seek an explanation of this fact and, in particular, of the difference in the composite states and, consequently, of the individual components' states *before* and *after* they give rise to the relevant composites? Of course, what is to be explained and what can be taken as primitive is, to some extent, a matter of personal judgment. However, in the case at hand it looks as though no explanation is offered at all by reductionists, who simply claim that certain entities—say, particular collective properties—are to be added to our ontological list when needed, without further analysis, hence leaving a number of questions open (were entanglement relations already part of the mosaic before the

¹⁶ Thus we are not claiming that the reductionist position is internally inconsistent, but rather that it should be considered implausible and uncalled for.

¹⁷ In Sect. 6 we will discuss interpretations of quantum mechanics that might challenge such a picture.

¹⁸ Reductionist friendly-literature, such as Esfeld (2014), recognizes that this was the preferred reductionist strategy at first (see e.g., Darby 2012). Different ways to save reductionism in the quantum realm have been recently explored in the literature. We will return to those in Sect. 6.

¹⁹ Recall that they enter in different physically relevant relations with other parts of those wholes.

preparation of a couple of fermions in the singlet spin state? If so, where were they exactly, if they are to be regarded as actual pieces of the mosaic at all? If not, how is the Humean–Lewisian intuition preserved exactly?). And, notice, this is *exclusively* done here with a view to neutralizing the potentially problematic consequences of certain pieces of evidence on one’s favored metaphysical view. The charge of ad hocness, it seems to us, is justified.

This leads us to our positive suggestion: at least in some cases, CII and HS/HS* fail because they ignore the crucial role played by the *composition process*, which is active and productive, so to put it, and cannot consequently be reduced ontologically as suggested. In any significant physical example, the idea is, it is the fact that the composite exists, i.e., that *composition has taken place*, that determines the existence of (some of) its properties, as well as of the properties of any well-defined and physically significant proper part of it.²⁰ Indeed, one could go as far as to claim that composition counts (at least in some cases) as the *cause* of the existence of the relevant properties. We don’t mean (nor need) to be committed to any form of realism about causation here (nor, *a fortiori*, to any specific analysis of causation). The sense in which causal concepts are relevant here is that situations like the one we envisaged earlier are entirely amenable to a counterfactual analysis. States (8) and (9) above can certainly be said to differ (merely) with respect to their collective properties at the time of their existence, call it t_2 . However, given that the systems in those states are composed of parts that simply didn’t exhibit such properties at a time t_1 earlier than t_2 —and were consequently exactly similar even when considered as a collective—it is only by invoking composition as an effective ‘difference-maker’ that one can tell a story as to why (6) and (7) have led to (8) in one case and to (9) in another case. Hence, it is only by invoking composition as an effective ‘difference-maker’ that one can tell a story as to what would have happened differently after t_1 if one had done *this* instead of *that* to the original physical systems.

For another, slightly different, example, take, for instance, two quantum systems S_{1234} , S_{1234}^* such that: (1) both are in a non-fully separable state, i.e., are more than the sum of their parts in the sense that their properties fail to supervene on those of their parts; (2) the first is in a maximally entangled state whereas the second is not, e.g., say because S_{1234}^* can be written as $S_{12}^* \otimes S_{34}^*$.²¹ Now, in the case of S_{1234}^* , in order to recover the total state we would not need to add anything to what we know about each individual component and the relations between systems 1 and 2, and

²⁰ This position resembles that recently defended in Cameron (2014), and which he traces back to Fine (1999). Cameron writes: “Fine agrees that the mereological sum of my parts is not me because those parts must be *appropriately arranged*: so the relevant relation gets in on the action with the parts for me to come about” (italics added). That relation is composition, which is, according to Cameron, a *superinternal* relation: that is, a relation R such that, if R holds between x and y , then necessarily the existence of x (or y) depends on the existence of y (or x) and R itself holds in virtue of the existence of y (or x). The crucial thing to notice for present purposes is that this establishes a clear dependence of wholes on their parts, but leaves it completely open whether—the existence of certain things being fixed—composition of those things occurs, and what the result is.

²¹ Roughly, a maximally entangled state is one given which no proper subsystem of it has a complete set of properties of its own, and thus cannot be written as a tensor product of states of *any* of its components parts.

between systems 3 and 4, respectively. However, in the case of S_{1234} , some of the collective properties of, say, S_{12} would be fixed only by considering some larger plurality, namely S_{1234} . Now, isn't it natural to think that there is something specific that has led to this state of affairs, and that this something marks a crucial difference between S_{1234} and S_{1234}^* and, more generally, between maximally and non-maximally entangled systems with exactly similar components? The difference is, incidentally, clearly reflected in the quantum formalism, the reduced state of S_{12}^* being a *pure* state, whereas the reduced state of S_{12} is *mixed*, and the overall state being expressible as a simple tensor product only in the non-maximally-entangled case.

Of course, one could insist that no internal inconsistency has been found in the reductionist programme, and one can legitimately prefer what one may call a 'primitivist' view of certain properties of composite systems to a more articulated metaphysical analysis which, however, loses in terms of ontological simplicity. In the example just put forward, this would amount to taking S_{1234} , S_{1234}^* to only differ with respect to their collective properties—the (non-)exemplification of the latter being a non-further-explicable fact. The advantage would allegedly be that no additional story would then be needed as to what composition is, and how it works. However, it seems clear to us that the primary aim of both physical and philosophical inquiry is understanding and explanation, and simply taking something for granted as a primitive, brute fact should be something like a last resort. After all, what is relevant for systems S_{1234} , S_{1234}^* is not only their current properties, but their origin and the physical processes that led to their existence as composites. Reductionism simply 'takes a snapshot' of the physical world, as it were, ignoring the diachronic evolution of things and, consequently, the question concerning the origin of certain peculiar properties and relations.²² But, we are suggesting, we can, and should, do better.

An objection could be levelled at this point to the effect that we are simply replacing a primitive with another: that is, primitive facts of exemplification of entanglement relations/collective properties with facts of composition. However, it is crucial to notice that here we only rely on a very weak notion of composition as mereological fusion (our basic claim being, in a nutshell, that *when composition occurs it is just mereological composition*, and yet the properties of the whole can have some degree of non-trivial variation, for they are at least partly dependent on *which physical interactions are responsible for the composition in question to occur*). And Humean reductionists are bound to employ this notion too, unless they are compositional nihilists and believe that nothing composes anything, which is certainly a non-negligible additional cost.²³

Summarizing, the opposition that emerges is between (a) a broadly Humean picture based on the (mereological) idea of a mosaic plus fundamental relations—some of which are, however, left entirely unexplained when, from the scientific

²² The reductionist can react by taking the temporal dimension explicitly into account, and consequently conceiving of the Humean mosaic as 4-dimensional. We will discuss this option in Sect. 6, and argue that antireductionism remains preferable. But thanks to an anonymous referee for pointing out the need to make all this explicit already at this stage.

²³ As we will see in a later section, nihilism entails composition as identity. However, the converse doesn't hold.

perspective, it is exactly for them that a careful assessment is required; and (b) a non-reductionist picture that, giving up on the idea that composition is identity and the world is a Humean mosaic, can differentiate between cases that are amenable to a Humean analysis of sorts and cases where, as physics itself seems to suggest, there is much more going on than simple mosaic-making. We claim that (b) is the option to be preferred.

A rejoinder could be that our proposed account leaves in any case unexplained the precise dynamics of physical composition. Indeed, it would be nice to be in a position to tell when and in what way certain parts form a whole. But this is simply a different issue: it was not our aim here to provide an answer to the infamous special composition question ('When does composition occur?'); nor does the reductionist pretend to have such an answer. Rather, in view of the fact that certain properties of composite systems 'emerge' in ways that would otherwise remain mysterious, we are simply suggesting that it is more convincing, given the available evidence, to resist the reductionist claim, and contend instead that:

1. As for HS*, if the supervenience basis is intended, as it seems clear that it should, as the set of everything that counts as a potential piece of the mosaic before the mosaic is created, entanglement relations are simply not in the set—or, maybe better, not all entanglement relations should be considered already in the set; consequently, the actual world doesn't seem to be a Humean mosaic.
2. For what concerns CII, for similar reasons, at least some collective properties are not simply there from the start, but are instead created by the very process that the reductionist would analyze in terms of such properties; but if composition were nothing but identity, it wouldn't possess such 'creative' power. Hence, not in all cases is the whole identical to its parts.

We thus conclude that, *whatever the exact nature of composition*, the reductive defense described in Sect. 3 cannot save the reductionist from the threat represented by the quantum evidence. While the reductionist position is not internally inconsistent, it sacrifices the possibility of explaining certain fundamental physical facts and differences only with a view to defending a very general metaphysical thesis (that, incidentally, as we have already emphasized, Lewis himself was more than ready to revise, and possibly give up, on the basis of empirical data).

5 The Globality Defence of Reductionism

Let us now consider a possible way out that friends of reductionism might try to take. One could claim that if the reductive theses we are discussing were *global* theses about the entire universe, our proposed strategy wouldn't work, for there would simply be no possible processes of composition that could create new holistic features of certain composites. Thus, one could conclude, CII and HS/HS* could be retained by making them radically global, i.e., by regarding them as claims about the universe as a whole. This is an interesting suggestion but one, that, we think, is not particularly attractive.

To begin with, the suggested interpretation of the reductionist stance would be especially problematic in the case of CII. This is because it would entail that there exists only one composite object, namely the universe. *Prima facie*, this is not an insurmountable problem: for, ‘CII-reductionists’ might be happy to bite the bullet and accept that their thesis leads to this sort of ‘mereological monism’. Indeed, they could go even further, and claim that there is only one object *simpliciter*, the universe, without any (proper) parts. This is a radical metaphysical thesis known as *ontological, or existence, monism*.²⁴ This form of monism is a particular variant of mereological nihilism—the thesis that there are no composites—and, as it is easy to show, mereological nihilism entails CII.²⁵

However, that there is only one composite object, or even just one thing, flies directly in the face of quantum mechanics, which manifestly allows for the description of—and is in practice used to describe—genuinely composite systems smaller than the entire universe. Of course, one might insist that in doing so we only refer to parts, perhaps merely epiphenomenal parts, of the one true quantum object: but it seems clear that this is a rather revisionary thesis that should be avoided if possible. Indeed, at least certain interpretations of quantum mechanics (for instance, the relational interpretation) explicitly reject talk of the universal quantum object. Moreover, CII is not usually taken to go hand in hand with monism, and it is likely that at least some reductionists would not be willing to insist on the truth of CII if the endorsement of monism were the price to pay. In view of all this, we conclude that the suggested ‘globality defence’ is not particularly promising for defenders of CII.

Things might seem brighter for HS/HS*. As a matter of fact, the thesis is usually cast in terms of global differences between distinct possible worlds, beginning with Lewis himself.²⁶ Indeed, our own formulation of the thesis in Sect. 3 only mentions the entire world. The problem is, however, that the very idea of a mosaic seems to suggest that (a) there is more than one thing, and thus ontological/existence monism is false; and (b) the pieces and their properties are in a clear sense more fundamental than the mosaic itself, and thus weaker forms of monism are also ruled out.

In particular, recall how HS, updated so as to take quantum entanglement into account, reads [HS* in (12) above]. Even if one ‘goes global’, the thesis still claims that the world is analysable in terms of smaller parts that compose *it*. That is, the world seems to be clearly intended as ontologically dependent on its basic constituents; consequently, an explanation is in any case due of the evidence that we called into play in our earlier arguments, in particular of the fact that entanglement relations cannot plausibly be considered part of the initial set of mosaic pieces, nor reduced to properties of those pieces.

Our suggestion is, to repeat, that emergent features of the world such as entanglement relations are in fact created (and destroyed) by specific physical

²⁴ For a discussion of *ontological/existence and priority monism* (the view that the universe is the only fundamental object) see Schaffer (2010).

²⁵ This is because if only simples exist it is trivially true that composites are identical to their parts—either because the antecedent of ‘if composites exist, then they are identical to their parts’ is false and the conditional consequently vacuously true; or because one includes in one’s consideration the limiting case of composites with only one (improper) part.

²⁶ For example, in Lewis (1994).

processes. And, we take it, even in the global case one should *not* add entangled relations in the supervenience basis, for these are, so to say, the by-product of composition processes that involve proper parts of the relevant whole(s). Doing otherwise, we submit, would mean to make HS/HS* a rather demanding thesis entailing that, even though it looks as though diachronic processes take place that involve specific parts of the whole and give rise to new facts about those parts considered together, as a matter of fact one is just looking at basic, possibly a-temporal, facts about a Parmenidean One. Clearly, this is not far from just stating that whatever problematic entanglement relation one can think of, that is just a basic epiphenomenal feature of an essentially unchanging reality—which, at least in the context of the present discussion, is hardly satisfactory from a philosophical point of view.

Another, slightly different, way to put our main point is the following: unlike (classical) spatio-temporal relations, which are systematically reducible to facts about pairs of entities and necessarily hold as soon as these pairs of entities exist, entanglement relations are simply not part of the mosaic before ‘the pieces are shuffled and put together’—so to put it. This leads us to two other important (and related) remarks.

First, an important disanalogy arises between classical spatio-temporal relations and entanglement relations—one which, incidentally, we think has not been sufficiently appreciated in the literature. Suppose you have two particles x and y , and consider their spatio-temporal relations. In a classical setting, you can actually change these relations by changing the position of one of the two particles, say x . This won’t change, however, the intrinsic properties of y , which suggests that x and y are somehow independent and thus freely recombinable. Not so for two quantum particles in an entangled state. You can change any entanglement relation between the two by changing any monadic property of one of them, say x , including spatio-temporal properties. But in that case the theory predicts that you would thereby also change some other intrinsic property of, say, y . And this undermines free-recombinability. But it just so happens that HS is intimately tied, among other things, exactly to the principle of free recombinability—no necessary connections between independent existents. Thus, since the principle of free recombinability does not sit well with quantum mechanics, the case against HS becomes stronger. Indeed, the gist of our case study is exactly that, in at least some cases, there are (or, may be) relevant connections between parts that would prevent one from simply recombining the latter the way one pleases; and that the *specific way* in which parts are put together plays a fundamental role. Of course, reductionists might try to preserve their views giving up free recombinability, but this would undoubtedly make their position even weaker, and in fact question the very motivation for endorsing Humean reductionism in the first place.

The second, related point is the following. In the quantum domain, distance relations (can) become dependent on the other properties of systems in entangled states, so that the relative location of particles might be modified by measuring other properties of one or more of those particles. Thus, the fact that it is only meaningful to talk of the ‘total’ or ‘collective’ properties of the physical systems in these states once entanglement has arisen, i.e., once composition has taken place, is likely to also extend to spatio-temporal relations. For instance, by ‘preparing’ a two-fermion entangled system one thereby makes the component fermions lose their exact position in space(-

time) in favour of an holistic property that encodes (1) actual sameness of location and (2) a disposition to localize in well-defined separate regions upon measurement. This means that some of our most entrenched intuitions about spatio-temporal relations, which are undoubtedly at work in the very formulation of HS/HS*, need to be questioned when one moves to the quantum domain. Which clearly leads even further away from the initial mosaic-plus-coordinating-fundamental-relations picture.

In conclusion, in light of the foregoing considerations, we contend that a global formulation of HS/HS* and CII is not helpful for the reductionist, and a non-reductionist approach to mereology and composition along the lines suggested above remains preferable.

6 Reductionism, Primitive Ontology and Humean Laws

We have so far restricted our analysis to what one may call the ‘standard’ interpretation of quantum mechanics—the standard not being identified, notice, with the Copenhagen interpretation often referred as the orthodoxy, but with all those interpretations that (1) share the basic postulates of quantum mechanics and a minimally realist²⁷ understanding of the states represented in the relevant Hilbert spaces, and (2) do not add anything to, or modify, the basic formalism.²⁸ However, a reductionist stance has been advanced recently within non-standard interpretations of quantum mechanics, most notably in Miller (2013) and Esfeld (2014). The former focuses on Bohmian mechanics, whereas the latter extends the case for reductionism to the so-called primitive-ontology²⁹ interpretations. These include, alongside Bohmian mechanics, the canonical GRW interpretation (Ghirardi et al. 1986) and the flash-GRW interpretation (Tumulka 2006). The arguments presented in the aforementioned works are well worth an independent scrutiny, especially because they suggest a form of wave-function realism that, although compatible with a generally Humean stance, is claimed not to entail, unlike other proposals along the same lines which we will discuss in a moment, that the fundamental space has more than three dimensions. While acknowledging the appeal of these proposals, which we will collectively dub ‘new wave-function realism’ (NWR), we will argue here that quantum mechanics still poses a formidable threat to reductionism, as a comparative account of NWR-based Humeanism and anti-reductionism still favours the latter.

Let us start with the general argument for NWR. Despite the difference in their fundamental ontological commitments, primitive ontology theories share a common structure, as argued in Allori et al. (2008). This structure is given by (1) local matters of particular facts, or *local beables* in Bell’s terminology,³⁰ distributed in

²⁷ See footnote 34 on the question of “minimal realism”.

²⁸ In so doing we conform to the extant literature. Indeed, a restriction to the Copenhagen interpretation or, for that matter, to any particular view on the collapse of the wave-function would be made superfluous by the fact that the issues being dealt here are simply independent of the measurement problem. For, the issue has to do—roughly—with the way in which certain properties relate to other properties at specific times, not with the way in which properties evolve diachronically.

²⁹ See Allori et al. (2008).

³⁰ See Bell (1987, chapter 7).

physical space, which constitute the primitive ontology of the theory (be it particles—Bohmian mechanics—, continuous distribution of matter—GRW—, or events—flash-GRW) and (2) a law that “governs”³¹ the temporal development of such a primitive ontology.

As for (2), in particular, according to the new Humean approach to the ontology of quantum mechanics the wave-function is not an entity which exists on a par with the elements of the primitive ontology. It is rather a nomological entity, somehow physically relevant without being part of the ‘furniture of the world’. Building on this supporters of NWR suggest that all the quantum-Humean has to do is to treat the universal wave-function as a Humean law, i.e., a law that, in line with a straightforward Humean understanding of laws, simply summarizes facts about the primitive ontology,³² without constituting an addition to the latter. Schaffer (2008), for instance, describes the main feature of Humeanism about laws exactly in these terms, namely with the slogan “laws reduce to histories [of local entities and properties]”³³ (Schaffer 2008: 82).

All this is water to the reductionists’ mill, of course. For now the reductionist can claim that the inherent, non-supervenient entanglement relations that allegedly threatened the reductive account are in fact nothing but nomological relations that, given the non-ontological status of the universal wave-function, reduce to the entire mosaic of local facts which they summarize and describe. The local facts can then be defined more precisely, according to one’s favourite realist rendering of the theory³⁴: wave-function realism in configuration space, the Bohmian one-particle interpretation, the Bohmian many-particle interpretation, the GRW interpretation and the flash-GRW interpretation.

The first option is arguably the more ‘costly’ option. It is the ‘traditional’ wave-function realism, defined on the basis of standard quantum mechanics, that maintains that the wave-function does not exist in traditional physical space, and yet is an *actual field*. This view, more particularly, achieves locality and vindicates HS

³¹ As we will see later on, a better term would be “describes”.

³² This is a move already made by Dürr et al. (2013) and recently endorsed by Callender (2014). The idea is, in particular, that the Best System Analysis of laws should be adopted, so that, e.g., “what makes it the case that there is a pilot wave is that the best system description of the physical world speaks in terms of it, and this description speaks in terms of it because it is part of an efficient and effective summary of what is fundamental” (Miller 2013: 580).

³³ We will return to this in a moment.

³⁴ We intend realism here in the very general sense that the theory describes objective features of reality, and the latter is not dependent on the minds of knowing subjects in any way. Two other realist interpretations are worth mentioning: the Everettian many-world interpretation and Rovelli’s relational interpretation (Rovelli 1996). The latter holds that every quantum state has an irreducible relational character, so that it only makes sense to attribute a state to a particular system from the perspective of another particular system. Although it is claimed (see Rovelli and Smerlak 2007) that this neutralizes EPR-type worries by rendering the consideration of space-like separated properties and events meaningless, hence seemingly lending support to the reductionist picture, this interpretation too might be regarded as too high a price to pay for saving reductionism. Something similar seems to apply for Everettians, since friends of reductionism would have to spell out clearly what their reductionist stance amount to in that setting. Should we take HS to apply to a single world or to the totality of Everettian worlds? In the latter case, is it worth to multiply worlds, as it were, in order to have a form of reductionism that only applies to their entirety, and not to any single one of them?

at the price of moving the fundamental local facts from 3-dimensional physical space to $3N$ -dimensional configuration space (N being the number of particles), where the real wave-function field lives and evolves. Although defended by some authors on the basis of interesting arguments (see Albert 1996, 2013; Lower 2004; North 2013; Ney 2012, 2013), this move, it seems fair to say, is arguably the most radical and revisionary quantum metaphysics on the market, and should be one's last resort. In Maudlin's words (2007: 61fn), it "constitutes the ultimate elevation of Separability [i.e., HS] as a regulative principle, rather than an empirical theory, and urges even more strongly the question of motivation".³⁵

This sort of reductionism, in particular, requires an account of the way in which 'canonical' composite objects reduce to the wave-function field in the first place. Ney (2013)³⁶ argues convincingly that traditional mereological reduction is not a viable option. The reason is that the spatial decomposition of the wave-function in configuration space does not correspond to any mereological decomposition of a composite system in its proper parts. Ney considers reducing composite objects to Dennettian *patterns*³⁷ in the wave-function. However she goes on to claim that this account cannot rescue the reductionist thesis according to which *objects are nothing over and above the fundamental physical entity*, i.e., the wave-function. This is because "this model of reduction is so bleached out as to be unilluminating [...]. This appeal to Dennett's account [i.e., the account in terms of patterns] fails to specify the metaphysical relation grounding the putative fact about over-and-aboveness" (Ney 2013: 177). Ney concludes that reduction is based "not on a mereological relation, but on some distinct kind of reductive, metaphysical relation" (Ney 2013: 181). In the case at hand, a composite object would be reducible to its wave-function insofar as it is decomposable and analyzable into "various modes at each point in configuration space that are instantiated to varying degrees. Each mode corresponds to a slightly different classical version of itself" (Ibid.).

Leaving the vagueness of this proposal aside, and the radically revisionary character of the proposed move from physical space to configuration space, the original reductionist stance is in any case betrayed at least in the sense that mereological considerations played a crucial role in the original programme, but now reductionism can only be preserved by assuming that the relations connecting the basic pieces of the mosaic are *sui generis* non-mereological relations. That is, the supervenience of the whole on its local parts is still warranted, but is now grounded in something much less 'innocent' than traditional and intuitive part-whole relations. What sort of mosaic are we talking about, exactly?

Having said this, let us now get back to our main discussion and to the various alternatives that are available to the wave-function realist. The second option above can be discarded for reasons similar to those just mentioned: in a Bohmian one-particle interpretation, wave-function realism entails that there exists simply one fundamental particle that lives in configuration space. Obviously, the earlier worries

³⁵ For other critiques, see Monton (2006, 2013).

³⁶ See Ney (2013: 175).

³⁷ The notion traces back to Dennett (1991). Wallace (2004) discusses the possibility of reducing composite objects to Dennett-patterns in the corresponding wave-function.

with the move from physical space to highly-dimensional configuration space persist in this case. Moreover, we add, the problems related to the seemingly necessary commitment to monism re-emerge. Lastly, in connection to this, notice that in the Bohmian view under scrutiny the one existing particle is a mereological atom. This is an extreme version of mereological nihilism for material objects, the view that there exist only mereological atoms. And, as we already pointed out, mereological nihilism *logically* entails both CII and HS/HS*, which renders these theses *metaphysically* uninteresting.

What about the other interpretations, then—that is, those more properly belonging to the NWRist camp (as they do not require a commitment to realism about configuration space)? The first of these, the Bohmian many-particle interpretation, claims that the fundamental blocks of the mosaic are traditional particles, and their fundamental properties are their positions. In connection to this, it adds the so called pilot-wave equation on top of the ordinary Schrödinger evolution. Obviously enough, both the pilot-wave and the Schrödinger equation are taken to be Humean laws. Miller (2013: 574) argues that the Bohmian (or, in Miller’s terms, ‘Bohumean’) is free to regard positions as the only intrinsic properties of physical systems, capitalizing on the fact that measurement of any property bottoms out in a position-measurement. Hence, for example, entangled spin-states as the one we constructed in Sect. 3, should not be problematic at all for her. To the contrary, HS appears vindicated (and there is consequently no need to endorse HS*), as all relations, including entanglement relations, ultimately reduce to either monadic positional properties, or to relations between positions. Esfeld (2014) is even more radical. He claims that we should not even regard positions as properties of physical systems. Nor should we regard them as properties of points of space–time (the property of being occupied, or not). Positions too are simply attributed on the basis of our descriptive needs, so that the same best system analysis applied in the case of laws applies here, and with the same ontologically deflationary outcome. Here is how Esfeld concludes: “In a nutshell, thus, applying Humeanism to the primitive ontologies theories of quantum physics amounts to physicalism *without properties*” (Esfeld 2014: 9, italics added).

One might object to this that the Lewisian picture crucially *involves properties* (in particular, perfectly natural properties). After all, the thesis is that all the rest supervenes on *them*. On the other hand, Esfeld can insist that the basic elements of reality are local, property-less, bits of matter (or, alternatively, space–time points interpreted in supersubstantialist terms, so that material objects and spatio-temporal regions are identified), and the fact that they strictly speaking exhibit no properties at all does not contradict the Humean view. For the basic local facts constituting the supervenience basis now correspond, so to put it, to ‘yes’ or ‘no’ answers to questions concerning whether particular points of space are occupied by matter or not. We will not take sides on this issue here, as we think the real problem lies elsewhere. Before moving on, however, let us complete our quick overview. As for the remaining two NWRist options, Esfeld suggests that the foregoing can be easily extended to GRW-theories, insofar as these put forward a conception of matter and the ultimate constituents of reality which is different from the Bohmian case, and yet, as mentioned, shares with the latter the very same structure. Indeed,

all these views seem to consist in a primitive ontology of matter distributed in physical space and a law (or some laws) governing the temporal evolution of such matter purely on the basis of local facts.

Having thus laid the options for the supporter of NWR, and of the new, sophisticated quantum Humeanism more generally, let us now critically assess them from the viewpoint of this paper.

Given the understanding of the universal wave-function as a global Humean law, the primitive-ontology defense can be seen as a sophisticated variant of the globality defense we mentioned in Sect. 5. And a perplexity we raised in that section still lingers here. If someone takes the mosaic metaphor seriously, it should be difficult for her not to concede that the parts of the mosaic are mosaics themselves. That is, if you were to restrict your attention to parts of the entire Humean manifold, you should still be able to describe those parts fully simply by looking at their component parts and the relations between them. But this is exactly what you cannot do here. Only facts about the entire universe will fix the relevant relations between component parts of composite systems that are different from the universe itself. In other words, the universe is a Humean mosaic, yet its parts are not.³⁸ This is not a fatal blow to reductionism, but surely is something worth weighing when assessing its tenability.

And things get worse. As Esfeld himself recognizes, quantum-Humeans cannot claim that the universal wave-function supervenes on the distribution of local beables *at any given time*. This is because, for any time t , the various possible distributions of local facts about the primitive ontology are all compatible with different wave-functions leading to different temporal developments of such primitive ontology. To avoid such underdetermination, one has to claim that the universal wave-function is a Humean law that summarizes not only global spatial facts but also *global temporal facts*. That is, it reduces to *the entire history of the whole universe*, or, to use Esfeld's words, it "supervenes on local matters of particular facts throughout the whole of space and time" (Esfeld 2014: 5).

Thus, Humeans can avoid metaphysical holism, i.e., the violation of the separability condition that is necessary for HS to get off the ground, only at the cost of making the mosaic global and four-dimensional³⁹: the tension seems evident.

As an illustration, let us consider again two quantum systems S1 and S2 that compose at time t a system S12 in an entangled state. S12 *seems* to display intrinsic properties or inherent relations between S1, S2 that are not reducible to intrinsic properties of S1 and S2. Our favorite explanation of such a fact, recall, goes as follows. Composition is a difference-maker and, as such, in the present case it

³⁸ One may object that this is not the case for Bohmian conditional wave-functions for proper subsystems of the universe, which can seemingly be made as local as one wishes—for instance, one can effectively obtain the wave-function of a sharply localised particle a by evaluating the universal wavefunction ψ at the position of a at a given time t . This is, we think, an interesting avenue of inquiry, but it has to deal with the problem that the local conditional wave-function appears to still depend (especially for its temporal evolution) *both* on the a and on the global ψ . Thanks to an anonymous referee for drawing our attention to this particular Bohmian scenario.

³⁹ Of course, this is not a problem in itself, and might even be regarded as a welcome result in view of the intimations of relativity theory. Our argument in the main text still applies, though.

brings about some new relations between S1 and S2, or intrinsic properties of the whole S12, that simply were not there before t , i.e., before composition occurred. Here's the primitive-ontology explanation instead. The relevant relations between S1 and S2 (or intrinsic properties of S12) simply appear to emerge out of nothing in virtue of the distribution of local matters of fact in the whole of space and, more importantly, the whole of time including the remote future. To be sure, this is not impossible in a four-dimensional block universe; yet, it should appear clear to everyone that the sort of global interconnectedness pulls decidedly away from the original Lewisian intuition. In the sophisticated Humean account, ultimately, it is the universal wave-function that encodes the information regarding the relations that hold together quantum entangled systems. This allows one to stick to a supervenience basis that only includes local facts plus spatio-temporal relations, as demanded by HS—but at the cost of going **very** global. In our preferred account, on the other hand, such information is conveyed by composition and only involves the composing entities. Ironically, this could be interpreted in the sense that *our preferred account is more local than that of the sophisticated Humean*, for the relevant information about any composite system is stored in that system and its history, whereas on the sophisticated Humean account that information is 'stored globally', and involves parts of the universe that are sharply distinct from the system in question, and very distant from it both in space and in time.

In the end, our basic claim is simply that the “composition as difference-maker” explanation is a better explanation than the primitive ontology explanation, which is in any case committed to a radical form of global interdependence of the fundamental blocks of the mosaic that appears to betray the spirit, if not the letter, of Humean reductionism. Moreover, our proposed explanation is neutral with respect to the issue concerning the metaphysical status of space–time and the relation between space and time, which also appears to be a plus. In connection to this, last but not least, it must also be mentioned that the nomological interpretation of the wave-function, that we took for granted so far, does instead have its share of problems. As forcefully argued by Belot (2012) and Suárez (2015), first, the modal force of the wavefunction seems in fact parasitic on that of the dynamical equations of the theory, and especially the Schrödinger equation. Second, and more importantly, contrary to nearly every understanding of physical laws, the wave-function appears to be time-indexed, in the sense that its content changes, and is determined at each instant by the Schrödinger equation. The foregoing certainly casts doubt on the neo-Humean understanding of the quantum wave-function as a nomological entity.

7 Conclusions

In conclusion, we contend that reflection on some real-world cases as they are presented by quantum mechanics allows one to see that the theses of Humean Supervenience and Composition as Identity may well have an appeal in terms of ontological economy and simplicity, but rest on pre-theoretical intuitions that, upon scrutiny, turn out to be problematic if not altogether untenable—especially so if one takes the data coming

from the actual world as it is described by our best science to constitute an important test for our metaphysical conjectures. In particular, even though the usual arguments having to do with entangled systems and emergent properties can perhaps be resisted, either by aptly characterizing HS and CII or by switching to a non-standard interpretation of quantum mechanics (and the wave-function in particular), a careful evaluation of the distinctive features of entangled systems seems to tell us that this is in any case unsatisfactory. In particular, we emphasized the dynamics whereby entanglement is created; the way in which initially indiscernible entities can come to compose qualitatively distinct wholes, and *consequently* find themselves in different states at a later time; and, lastly, the nature of classical spatio-temporal relations as compared with their quantum counterparts and with entanglement relations. These considerations suggested that insisting on reductionism in spite of the evidence coming from quantum mechanics would imply (at the very least) a serious loss in explanatory power and/or a radically holistic/global conception of physical reality that sharply departs from the initial ‘mosaic intuition’. In connection to the foregoing, it is barely worth pointing out that abandoning reference to actual world systems of things and their properties is even less appealing than trying to save HS(HS*) and CII by ‘tweaking’ them in some way. Not only from a naturalistic, science-oriented perspective on metaphysics (which we subscribe to), but also from a more general viewpoint. After all, one may well be an antirealist about physical theory, or even disagree that science is a privileged source of information about reality. Still, quantum systems should at least qualify as metaphysically possible, and metaphysical hypotheses formulated from a non-naturalistic viewpoint should at least be required to account for the possible, on pain of becoming totally uninteresting.

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References

- Albert, D. (1996). Elementary quantum metaphysics. In J. Cushing, A. Fine, & S. Goldstein (Eds.), *Bohmian mechanics and quantum theory: An appraisal* (pp. 277–284). Dordrecht: Kluwer.
- Albert, D. (2013). Wave-function realism. In D. Albert & A. Ney (Eds.), *The wave function: Essays in the metaphysics of quantum mechanics* (pp. 52–57). Oxford: Oxford University Press.
- Allori, V., Goldstein, S., Tumulka, R., & Zanghì, N. (2008). On the common structure of Bohmian mechanics and the Ghirardi–Rimini–Weber theory. *British Journal for the Philosophy of Science*, 59, 353–389.
- Bell, J. (1987). *Speakable and unspeakable in quantum mechanics*. Cambridge: Cambridge University Press.
- Belot, G. (2012). Quantum states for primitive ontologists. *European Journal for Philosophy of Science*, 2, 67–83.
- Bohn, E. D. (2012). Monism, emergence and plural logic. *Erkenntnis*, 76, 211–223.
- Callender, C. (2014). One world, one beable. *Synthese*, 1–25. doi:10.1007/s11229-014-0582-3.
- Cameron, R. (2014). Parts generates the whole, but they are not identical to it. In D. Baxter & A. Cotnoir (Eds.), *Composition as identity* (pp. 90–107). Oxford: Oxford University Press.
- Cotnoir, A. (2014). Composition as identity. Framing the debate. In D. Baxter & A. Cotnoir (Eds.), *Composition as identity* (pp. 3–23). Oxford: Oxford University Press.

- Darby, G. (2012). Relational holism and humean supervenience. *British Journal for the Philosophy of Science*, 63, 773–788.
- Dennett, D. (1991). Real patterns. *Journal of Philosophy*, 88, 27–51.
- Dürr, D., Goldstein, S., & Zanghi, N. (2013). *Quantum physics without quantum philosophy*. Berlin: Springer.
- Esfeld, M. (2014). Quantum Humeanism: Or physicalism without properties. *The Philosophical Quarterly*, 64, 453–470.
- Fine, K. (1999). Things and their parts. *Midwest Studies in Philosophy*, XXIII, 61–74.
- Ghirardi, G. C., Rimini, A., & Weber, T. (1986). Unified dynamics for microscopic and macroscopic systems. *Physical Review D*, 34, 470–491.
- Lewis, D. (1986). *The plurality of worlds*. Oxford: Blackwell.
- Lewis, D. (1994). Humean supervenience debugged. *Mind*, 103, 473–490.
- Lewis, D. (2009). Ramseyan Humility. In D. Braddon-Mitchell & R. Nola (Eds.), *Conceptual analysis and philosophical naturalism* (pp. 203–222). Cambridge: MIT Press.
- Lower, B. (2004). Humean supervenience. In J. Carroll (Ed.), *Readings on laws of nature* (pp. 176–206). Pittsburgh: University of Pittsburgh Press.
- Maudlin, T. (2007). *The metaphysics within physics*. Oxford: Oxford University Press.
- McDaniel, K. (2008). Against composition as identity. *Analysis*, 68(2), 128–133.
- Miller, E. (2013). Quantum entanglement, Bohmian mechanics and Humean supervenience. *Australasian Journal of Philosophy*, 92(3), 567–583.
- Monton, B. (2006). Quantum mechanics and 3 N-dimensional space. *Philosophy of Science*, 73, 778–789.
- Monton, B. (2013). Against 3 N-dimensional space. In D. Albert & A. Ney (Eds.), *The wave function: Essays in the metaphysics of quantum mechanics* (pp. 154–167). Oxford: Oxford University Press.
- Ney, A. (2012). The status of our ordinary three dimensions in a quantum universe. *Nous*, 46(3), 525–560.
- Ney, A. (2013). Ontological reduction and the wave function ontology. In D. Albert & A. Ney (Eds.), *The wave function: Essays in the metaphysics of quantum mechanics* (pp. 168–183). Oxford: Oxford University Press.
- North, J. (2013). The structure of a quantum world. In D. Albert & A. Ney (Eds.), *The wave function: Essays in the metaphysics of quantum mechanics* (pp. 184–202). Oxford: Oxford University Press.
- Paul, L. A. (2002). Logical parts. *Noûs*, 36(4), 578–596.
- Paul, L. A. (forthcoming). Mereological bundle theory. In H. Burkhardt, J. Seibt, & G. Imaguire (eds), *Handbook of mereology*. Munich: Philosophia Verlag.
- Rovelli, C. (1996). Relational quantum mechanics. *International Journal of Theoretical Physics*, 35, 1637–1678.
- Rovelli, C., & Smerlak, M. (2007). Relational EPR. *Foundations of Physics*, 37, 427–445.
- Schaffer, J. (2008). Causation and laws of nature: Reductionism. In T. Sider, J. Hawthorne, & D. Zimmerman (Eds.), *Contemporary debates in metaphysics* (pp. 82–107). Oxford: Blackwell.
- Schaffer, J. (2010). Monism. The priority of the whole. *Philosophical Review*, 119(1), 31–76.
- Sider, T. (2007). Parthood. *Philosophical Review*, 116, 51–91.
- Sider, T. (2014). Consequences of Collapse. In D. Baxter & A. Cotnoir (Eds.), *Composition as identity* (pp. 211–221). Oxford: Oxford University Press.
- Suárez, M. (2015). Bohmian dispositions. *Synthese*, 1–26. doi:10.1007/s11229-015-0741-1.
- Teller, P. (1986). Relational Holism and quantum mechanics. *British Journal for the Philosophy of Science*, 37, 71–81.
- Tumulka, R. (2006). A relativistic version of the Ghirardi–Rimini–Weber model. *Journal of Statistical Physics*, 125, 155–227.
- Wallace, D. (2004). Protecting cognitive science from quantum theory. *Behavioral and Brain Sciences*, 27, 636–637.
- Winsberg, E., & Fine, A. (2003). Quantum life: Interaction, entanglement and separation. *Journal of Philosophy*, 100, 80–97.