Two notions of holism

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Abstract A simple argument proposes a direct link between realism about quantum mechanics and one kind of metaphysical holism: if elementary quantum theory is at least approximately true, then there are entangled systems with intrinsic whole states for which the intrinsic properties and spatiotemporal arrangements of salient subsystem parts do not suffice. Initially, the proposal is compelling: we can find variations on such reasoning throughout influential discussions of entanglement. Upon further consideration, though, this simple argument proves a bit too simple. To get such metaphysically robust consequences out, we need to put more than minimal realism in. This paper offers a diagnosis: our simple argument seems so compelling thanks to an equivocation. The predictions of textbook quantum theory already resonate with familiar holistic slogans; for realists, then, any underlying reality, conforming to such predictions, also counts as holistic in some sense or other, if only by association. Such associated holism, though, does not establish the sort of specific, robust supervenience failure claimed by our simple argument. While it may be natural to slide to this stronger conclusion, facilitating the slide is not minimal realism per se but an additional explanatory assumption about how and why reality behaves in accordance with our theory: roughly, quantum theory accurately captures patterns in the features and behaviors of physical reality *because* some underlying metaphysical structure constrains reality to exhibit these patterns. Along with the diagnosis comes a recommendation: we can and should understand one traditional disagreement about the metaphysics of entanglement as another manifestation of a familiar and more general conflict between reductive and non-reductive conceptions of metaphysical theorizing. Such reframing makes clearer what resources reductionists have for resisting the simple argument's challenge from quantum holism. It also has an important moral for their opponents. Traditional focus on whole-part supervenience failure distracts from a root disagreement about metaphysical structure and its role in our theorizing. Non-reductionists fond of our simple argument would be better off tackling this root directly.

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Holism advertises with suggestive slogans: some wholes are "more than the sum of" or "over and above" their parts (Maudlin 1998). A simple argument says that since elementary quantum mechanics is (at least approximately) true, physical reality must include some metaphysically holistic systems, wholes with features aptly characterized by slogans like these. More exactly, its first premise claims holism—of *some* broadly metaphysical sort—follows immediately from modest realism about quantum mechanics:

IMMEDIACY If elementary quantum theory accurately describes reality, then reality is holistic in character.

Motivating this first premise is entanglement. Minimally, textbook quantum mechanics provides a recipe for predicting the outcomes of experiments, representing physical systems with formal states that encode probabilistic predictions about the outcomes of potential "measurements" of or on various "observables" (cf. Ney 2015). These formal states encode predictions not only about the single outcomes of experiments on individual systems but also about the joint outcomes of combined experiments involving multiple parts of composite wholes. In cases of entanglement, wave functions representing such composite systems are non-separable. They are not straightforward products of formal states representing their parts—and, in fact, the parts require mathematically novel representation. Still, subsystem parts of some formally (and empirically) distinguishable entangled wholes have identical formal representations: entangled singlet and triplet particle pairs, for instance, bear distinct wave functions even though they have, as parts, particles with the very same formal representation. This representation encodes identical predictions for parts of both sorts: no single measurement we can perform on a single particle will reveal whether it belongs to a singlet system or a triplet one.

Nevertheless, distinct entangled wave functions for whole pairs encode different predictions about the joint outcomes of experiments that conjoin measurements on each of two pair members. One such difference appears in experiments with particle spin—roughly, a sort of internal angular momentum, which we can measure along various axes. Though any individual singlet or triplet particle is just as likely to produce an *up* reading as a *down* one on a measurement of spin in some direction θ, quantum theory predicts, and experiment confirms, differing patterns of coordination between the outcomes of pairs of θ-spin measurements, with each performed on one member of some entangled pair. For singlet pairs we should not expect any matched outcomes, while for triplet pairs we should expect matched results for at least some choice of θ. This remains so regardless of how far we separate the pair members, once entangled, for their respective spin measurements, and regardless of how closely in time we perform them.

IMMEDIACY says that if we are realist enough to treat the formal representations of quantum systems as accurately reflecting, somehow or other, underlying physical properties, then we must conclude that entangled wholes bear holistic properties resonating with our familiar slogans. In what sense, though, can any whole really be "over and above" its parts in the way these slogans say? If we start out combining what we think are all the necessary parts but yield a whole without some expected feature, then surely we were, after all, missing out on some crucial ingredient from the start. The key intuition in cases of holism, though, is that incorporating this missing ingredient is not just a matter of adding another self-contained, metaphysically separable part or endowing some such part with additional *intrinsic* properties—ones logically and metaphysically independent of "external" considerations, and so independent of its membership in our subsuming whole (Lewis 1983). Nor, roughly put, is it a matter of building up to our ingredient by arranging multiple independent parts in space-time and conjoining or summing over their individual intrinsic states. Instead, our crucial missing ingredient belongs essentially to the compound whole itself; it is a further collective or relational feature metaphysically coordinating otherwise separate components.

Our simple argument's second premise incorporates a standard way of summarizing this idea in terms of metaphysical necessitation, or supervenience:

INTRINSIC NON-SUPERVENIENCE If reality is holistic in character, then some intrinsic properties of wholes fail to supervene on the intrinsic properties of and spatiotemporal relations among their proper parts.

Unpacking familiar holistic slogans in these terms is popular, in part, because it makes explicit an alleged tension between quantum mechanics and the sort of "reductive" metaphysical outlook subsumed, for instance, in Lewis's doctrine of Humean supervenience. Combined with the realist conviction that elementary quantum theory is at least approximately true, our two premises establish the existence of at least some wholes with intrinsic states for which the intrinsic properties of and spatiotemporal relations among their proper parts do not suffice (Teller 1989, p. 241).[1] It follows from this that our worldly cosmic whole is not a Humean "mosaic" of localized elements (Lewis 1987, p. x).

We can find echoes of this reasoning, or something close, throughout discussions of the metaphysics of entanglement. Teller, for example, claims that quantum theory on anything but a "starkly instrumentalist" reading establishes a "relational holism" contrary to a classical reductionism (1989, p. 241; cf. Darby 2012). Maudlin ties such reductionism to a Humean tenet he dubs "Separability": "the complete physical state of the world is determined by (supervenes on) the intrinsic physical state of each spacetime point (or each pointlike object) and the spatio-temporal relations between

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[1] Note that I am using "reductive" to label views that affirm the sort of whole-part supervenience denied by INTRINSIC NON-SUPERVENIENCE. "Reductive" sometimes has stronger connotations: not only do wholes supervene on parts, but parts are—for instance—*more fundamental* grounds of the supervening wholes. Whole-part supervenience is a necessary condition for this stronger view.

those points" (2007, p. 51). On Maudlin's reading, more specifically, Separability requires the intrinsic character of any subworldly whole at some time, to be entirely fixed by the intrinsic properties and arrangement of its proper parts at that time. Yet our singlet and triplet cases violate this requirement (2007, p. 61):

> The upshot is that no physical theory that takes the wavefunction seriously can be a Separable theory. If we have reason to believe that the quantum theory, or any extension of it, is part of a true description of the world, then we have reason to believe the world is not Separable.

Following Teller and Maudlin, Schaffer cites entanglement to support his own anti-Humean monistic metaphysics. He builds one argument against Humeanism from what he deems a consequence of realism: "duplicating the intrinsic properties of the particles, along with the spatiotemporal relations between the particles" in our spin examples does not suffice for certain crucial "intrinsic correlational properties of entangled wholes" (2010, p. 53).

1 The simple argument: an assessment

In stark summary, our simple argument conjoins IMMEDIACY and INTRINSIC NON-SUPERVENIENCE to claim incompatibility between quantum theory, realistically construed, and metaphysical reductionism: if quantum theory is (at least approximately) true, then the intrinsic characters of some wholes are not fixed by the intrinsic properties and arrangements of their salient proper parts. When we put it so starkly, though, the reasoning looks a bit too simple. It attempts to extract a specific and robust metaphysical conclusion—one specific and robust enough, for instance, to refute Humean supervenience—directly from "realism" about elementary quantum theory. While we probably should be wary of attempts to extract substantive metaphysics from "realism" in any setting, there is reason for extra caution in the quantum context. Textbook quantum mechanics provides a remarkably accurate recipe for predicting the outcomes of experiments, but the recipe itself is infamously non-committal about what the world is fundamentally like. Different (so-called) "interpretations" propose different dynamical and ontological backstories about how exactly reality comes to yield experimental outcomes conforming to the textbook recipe (cf. Ney 2015). In principle, different stories might agree that textbook quantum theory is "part of a true description of the world" while disagreeing about the more exact metaphysical relationship between wholes and parts—perhaps even disagreeing about whether they manifest the sort of supervenience failure claimed by our simple argument (Maudlin 2007, p. 61).

Perhaps some broadly sympathetic to our simple strategy already agree, if somewhat begrudgingly, that realism alone does not secure the conclusion they are after. Schaffer (2010), for example, notes that whole-part supervenience failure follows straightforwardly only given some standard interpretational assumptions—something Healey (1991) also points out. Maudlin makes a different but related concession: diehard Humean reductionists probably can find some way to salvage the letter of Separability (2007, p. 61 n. 4). Specifically, they can try relocating fundamental reality to a high dimensional physical space—isomorphic to mathematical “configuration space” (Loewer 1996). If we take the formal states of familiar low dimensional entangled “wholes” to represent, ultimately, intrinsic profiles of *single* elements in this revised space, we can still treat our resulting “mosaic” as a supervenient sum of separable components. Presumably, even this revisionary “Humean” picture preserves the *truth* of quantum theory, and so qualifies as “realist” in the sense allegedly salient to our simple argument; the revisions concern the metaphysical nature of our theory’s ultimate truth makers.

Maybe it is more charitable, then, to interpret *prima facie* endorsements of our simple argument as strict exaggerations: snappy but imprecise summaries that can be, should be, and in some cases, even, already *are* qualified with more careful commentary. If so, then our interest in the simple argument is more broadly dialectical than strictly exegetical: our simple reconstruction, citing mere realism, really approximates some more exact thesis. Any account on which quantum theory is (approximately) true and *also* is otherwise *plausible* or *relevant*, or satisfies some further condition X, will involve holism of our sort. Once we bring out this further condition, though, it becomes quite clear that committed reductionists have more wiggle room than the simple argument suggests. Any more careful counterpart is genuinely dialectically compelling only if the further condition X is one that realists on all sides of the discussion do, or at least can, accept. Then even if minimal realism itself *strictly speaking* allows us to avoid the letter of whole-part supervenience failure while maintaining the (approximate) truth of elementary quantum theory, violation of this background condition X still licenses us to discount any such wiggly efforts on non-question-begging grounds.

Now, perhaps we can find some candidate X that rules out, for instance, our aforementioned revisionary “Humean” option: perhaps all parties in our discussion are happy to restrict their attention to proposals on which textbook quantum theory is (approximately) true and there *also* are at least some fundamental entities in low dimensional space-time. But to get all the way to the specific, robust metaphysical conclusion of our simple argument, we need to exclude all but those accounts on which textbook quantum theory is (approximately) true and we *also* have a very particular link between formal representations of quantum systems and their strictly intrinsic properties. Perhaps those antecedently sympathetic to our simple argument’s conclusion will accept this as some necessary condition on any relevant or viable realist treatment of quantum theory, but committed reductionists have no reason to do so—indeed, from their perspective, any such condition is unacceptably question begging.

In fact we can distinguish, in the abstract, two ways reductionists might loosen the link between formal states and intrinsic properties: they might permit singlet and triplet parts with the very same formal representations to differ, nonetheless, in some intrinsic properties; or they might permit the distinct formal representations of singlet and triplet wholes to mark crucial differences in non-intrinsic features. We can frame our aforementioned revisionary “Humeanism” as a very loose application of the first strategy. On that story, recall, indistinguishable formal representations of singlet and triplet particles turn out to report similar limited aspects of ultimately underlying elements that do differ, crucially, in their more complete intrinsic profiles. Such further differences, though, only show up formally in the theory’s wave function representations of entangled wholes. We can adapt the same strategy to proposals featuring some low dimension fundamental ontology. Roughly, we restore whole-on-part supervenience by conferring on individual singlet and triplet particles distinct intrinsic artifacts—stamps or scars—of prior differentiating singlet- and triplet-producing entanglement interactions (Arntzenius 2012, p. 86). Such differences in individual parts, though, only show up formally when combined in the right ways, jointly undergirding the theory's wave function representations of entangled wholes.

Crucially, the suggestion is *not* to adopt a problematic "local hidden variables" account on which members of each entangled pair agree, before heading to their respective spin-measuring magnets, how each one, individually, will behave upon arrival. On such a hidden variables view, the textbook recipe simply reflects our ignorance of this further secret pact when it predicts that an individual singlet or triplet particle is just as likely to produce an *up* outcome as a *down* one upon measurement, but Bell (1964, 1981) shows this leads to contradiction when we turn to our theory's predictions about slightly more complex spin experiments involving magnets of different orientations.

Our first reductive strategy, however, is more modest. The idea is to pair some recognizably realist interpretational story with an assurance that, despite their indistinguishable textbook representations, individual singlet and triplet particles do, in fact, differ in their intrinsic properties. As a result, the intrinsic states of singlet and triplet entangled wholes, at each time, do supervene on the intrinsic properties and arrangement of underlying proper parts. Even so, one particle's own "singlet" or "triplet" stamp alone makes no difference to its individual evolution or to our theory's predictions about it. To have interesting physical import, individual stamps must be combined and accompanied in the right ways: resulting collections are what serve as the truth makers for attributions of non-separable wave functions to entangled wholes.

For a pair to be in a singlet state, for instance, is in part for *both* members to bear collectively subvening "singlet" stamps. Then we apply the usual textbook recipe: as a matter of fact, the predicted and observed evolution of a singlet pair, with two members bearing such "singlet" stamps, differs crucially from that of a triplet pair, with otherwise indistinguishable members bearing "triplet" counterparts instead. The formal representation of one singlet particle, at a time, reflects only its intrinsic character, yet—since ours is not a local hidden variables story—the predicted forward evolution of this character is sensitive to facts about its partner's evolving intrinsic state too. If we start out with a pair of entangled "singlet"-stamped particles, one of which is then deflected upwards through a magnet set at orientation θ, our story promises some associated change in the intrinsic disposition of the other—the partner now is disposed to be deflected downwards through its θ-spin magnet. But such patterns of physical dependence themselves do not require or entail any failure of supervenience, at any stage along the way, between the intrinsic properties of wholes and the intrinsic properties and arrangements of parts (Miller 2016). At least in principle, then, we might merge the outline of this strategy with the details of some more specific realist interpretation.

To recover the predictions of textbook quantum mechanics, it is not enough to have *some* intrinsic difference between singlet and triplet particles; we need to tie the evolution of one "singlet"-stamped particle to some specific "singlet"-stamped partner(s) with which it is entangled. Perhaps, then, we actually need traces of singlet- or triplet-producing interactions with *particular* individuals: stamps that record, say, some unique haecceities of colliding partners. But—even bracketing doubts about physical plausibility—different philosophical accounts of intrinsic properties will yield different verdicts here. Haecceitistic stamps are fine if intrinsic properties are simply those compatible with loneliness and accompaniment, but they are not if intrinsic properties are supposed to be common to perfect qualitative duplicates (Lewis 1983). In that case, reductionists should change tactics, reframing this proposal as an application of our second strategy instead.

That second strategy gives up on trying to distinguish singlet and triplet particles on the basis of some underwriting intrinsic properties. Rather than insisting that our formal representation of this present particle stage reports its exclusively intrinsic properties—and so conferring on it some intrinsic mark of a past singlet-producing interaction with a haecceitistic partner—we might simply allow our formal representation of, and so attendant predictions about, one part to reflect crucial non-intrinsic factors—including, for instance, present intrinsic properties of a partner with which it is paired thanks to some singlet-producing collision within the intersection of their past light-cones. This second strategy then sidesteps the immediate threat of non-supervenient *intrinsic* whole states by taking the distinct formal states of entangled wholes to mark crucial differences in their less-than-strictly-intrinsic properties as well.

We find concrete application of something like this relational strategy in recent efforts to combine reductive commitments with interpretations of quantum mechanics widely recognized as realist (Esfeld 2014; Miller 2014; Callender 2015; Suárez 2015; Bhogal and Perry 2017). Common to these proposals is the observation that, contrary to the simple argument, realism about quantum mechanics does not demand that we understand a system's formal state as depicting all and only its strictly intrinsic properties—at least not in the particular sense of "intrinsic" at issue in Separability and related reductive metaphysical theses. Some favoring the Bohmian interpretation of quantum mechanics, for instance, propose combining its particular dynamical and ontological supplementation of the textbook recipe with an analysis of formal states as descriptions of the dispositional or relational—rather than strictly Humean intrinsic—profiles of entangled wholes.

On this proposal, singlet and triplet wholes derive their "conditional" wave functions from regularities in the features and behaviors of fundamental individuals throughout space and time—and thus, roughly, from distinct relations particles of the two sorts bear to the universe more broadly. Entangled states of wholes do not supervene on the intrinsic properties and spatiotemporal arrangements of their parts alone, but because these non-supervening states are not intrinsic to the wholes, there is no immediate threat of robust supervenience failure—the entangled states need only, and purportedly do, supervene on the distribution of intrinsic properties across elements of a more global space-time mosaic. We might try developing a similar relational strategy within other realist frameworks; Egg and Esfeld (2015) explore application to GRW, for example.

Now, certainly, we can raise all sorts of philosophical objections to this and various other wiggly maneuvers that try to preserve the truth of elementary quantum theory while avoiding the simple argument's conclusion. In the end, some of these objections might be right in the following sense: perhaps the best or all-things-considered most plausible or *correct* realist interpretation of elementary quantum theory does, in fact, feature wholes with intrinsic properties for which the intrinsic properties and arrangements of their parts do not suffice. But committed reductionists need not, and should not, concede that quantum theory itself, given only the assumption of modest realism, demands as much.

Consider, for example, a challenge for relational reductionism from what we might roughly describe as whole singlet and triplet *universes*. Mathematically, we can characterize what seem to be possible worlds that agree with respect to all localized events across all of space and time and yet bear distinct universal wave functions. Presumably we cannot trace this formal difference to some underlying difference in the universes' relational properties, since there is nothing else for an entire universe to be related *to*. Fans of our simple argument, then, might endorse the following claim: any viable or relevant realist account should render the claims of elementary quantum theory true and *also* mark some genuine physical distinction in the occurrent intrinsic states of our singlet and triplet universes. Since any account like this features wholes with intrinsic properties for which the intrinsic properties and arrangements of proper parts do not suffice, any *relevant* realist account does.

There are a number of things reductionists might say at this point, but one option is simply to deny that realism really requires recognizing a physical distinction of the alleged sort. They might model their response here on more familiar Humean responses to "boring" worlds that, allegedly, match in their occurrent contents but diverge in anti-Humean laws or other modal facts (Beebee 2000). Perhaps some fans of the simple argument will insist that taking "the wave function seriously" really does require accommodating non-supervenient cosmic whole states in the way only non-reductionists can (Maudlin 2007, p. 61). But they should not expect this to sway reductionists, and reductionists, indeed, should not be swayed. Reductionists should say something similar in response to the related charge that Humean relationalists do not adequately distinguish the dynamical and ontological commitments of quantum theory (Dewar unpublished ms). Certainly, there is an interesting and substantive question here: Can an account that seeks to reduce commitments of both sorts to one unified mosaic or basis do everything we would like, physically, philosophically, or otherwise? But to insist that the mere truth of textbook quantum theory already settles the matter is to beg a crucial question against reductionists.

If this assessment of the dialectical situation is accurate, though, it raises something of a puzzle: Why does the simple argument seem compelling? If the argument rests on some implicit question-begging assumption, why does it appear to pose any threat to reductionism at all, and why doesn't any pull dissolve entirely when we make this assumption explicit? We can put this second question more forcefully: we have sketched some strategies reductionists might use to avoid the simple argument's conclusion. From one perspective, though, they all seem sort of beside the point. The simple argument is compelling precisely because its first premise claims that something *neutral* across various physical interpretations and metaphysical maneuvers *already* is enough to secure a recognizable holism: commitment to a reality with underlying features that conform, somehow or other, to the mysterious predictions of quantum mechanics. However ingenious, attempts to preserve or restore the letter of whole-part supervenience within some particular metaphysical framework do not touch that initial conviction.

Now, this might be because we expect all such attempts, when worked out in sufficient detail, to fail. In my own case, though, introspection suggests something different. I am happy to grant that—at least for all I know—some sufficiently motivated and ingenious metaphysicians probably can find a way to accommodate all the predictions of quantum mechanics while respecting the letter of reductive supervenience. Perhaps relationalists are right, and members of singlet and triplet systems bear importantly different relations to other elements throughout the Bohmian universe—securing even global Separability. But this does not weaken IMMEDIACY: if anything, the ubiquitous interconnection of relationalism—even if all the relations involved supervene on our global Humean base—would seem to underscore, not undermine, the thought that reality is holistic in structure. But this verdict does not make sense if the notion of holism at work in IMMEDIACY is the very same one INTRINSIC NON-SUPERVENIENCE explicates.

More plausible: the argument's first premise is true because something more minimal, common to various interpretations, already secures a metaphysically thin but recognizable holism. More specifically, realist endorsement of the textbook recipe brings commitment to a reality with features that exhibit holism by evolving, somehow or other, in conformity with that recipe. The argument then slides from this to a thicker, distinct notion in INTRINSIC NON-SUPERVENIENCE, which also resonates with holistic slogans.

2 Predictive holism: an analogy

Forget quantum mechanics for now and focus on a more ordinary example. A sign down the road flashes "CAUTION!" followed by "SCHOOL ZONE" and then "LIMIT 15 MPH"; the whole screen lights up; then all the pixels turn off briefly. Shortly after that, "CAUTION!" reappears, and the cycle starts again. Knowing what we do about this sign, we can construct a perfectly accurate simple deterministic theory that takes, as input, the current state of the screen and yields, as output, its precise state at the next stage:

- If the screen is in state S_{CAUTION}, it will be in state S_{ZONE} next.
- If the screen is in state S_{ZONE}, it will be in state S_{LIMIT} next.
- If the screen is in state S_{LIMIT}, it will be in state S_{ALL} next.
- If the screen is in state S_{ALL}, it will be in state S_{NONE} next.
- If the screen is in state S_{NONE}, it will be in state S_{CAUTION} next.

To offer any predictions at all, this recipe requires the current state of our entire screen as input. Strictly speaking, it yields the next state of our entire screen as output. But since the state of the screen at any stage is a sum of pixelated substates, we also can use this theory to make predictions about more limited outputs. Consider, for example, one particular pixel, Lori. If our screen is currently state S_{ALL}, the screen will be in state S_{NONE} at the next stage. For the screen to be in state S_{NONE} just is for each individual pixel in the screen to be unlit. So Lori will surely be unlit at the next stage if our current screen state is S_{ALL}.

We also can construct recipes that accept something less than complete global screen states as input. To start, consider an extremely localized clause that predicts

Lori's next state based on just her current one. A run of our sequence takes Lori from lit, to unlit, to unlit, to lit, to unlit—and then back to lit to start anew. Thus:

- If our pixel is lit, then it will be unlit next (probability 1).
- If our pixel is unlit, then the probability that it will be lit next is 2/3, and the probability that it will be unlit next is 1/3.

Here we have traded precise predictive outputs, from global inputs, for less precise ones based on highly localized inputs instead.

Note that in Lori's case, we do not need strictly global inputs to recover maximally precise outputs. Focus in on just four pixels from our sign, which first help form the diagonal of the "N" in the extra large "CAUTION!" and then the (orthogonal) diagonal of the "Z" in "SCHOOL ZONE"; they fall in the blank between the "5" and "M" in "LIMIT 15 MPH"; after that, they all light up with the rest of the screen; then they all turn off; then everything starts again. Every 10 s, our quartet cycles through the following series:

Q_N Q_Z Q_{OFF} Q_{ON} Q_{OFF}

(The light squares represent lit pixels, and the dark squares represent unlit ones. Each stage in the series is just under 2 s.)

Lori is the lower right pixel in our quartet. We can construct a theory that yields perfectly precise predictions about Lori's next state given just the current state of the quartet as input. A run of our series involves transitions between four quartet states: from Q_N to Q_Z, from Q_Z to Q_{OFF} (for screen state S_{LIMIT}), from Q_{OFF} to Q_{ON}, from Q_{ON} back to Q_{OFF} (now for screen state S_{NONE})—and then back to Q_N to start again. Lori is lit in two of these four states, Q_N and Q_{ON}. Each precedes a state in which Lori is unlit, so Lori, if currently lit, is sure to be unlit at the next stage. Lori is unlit in our other two quartet states, Q_Z and Q_{OFF}. In the case of Q_Z, Lori is certain to be unlit at the next stage. In the case of Q_{OFF}—no matter whether the global screen is in S_{LIMIT} or in S_{NONE}—Lori is certain to be lit in the next stage. Hence:

- If (Lori is lit and) the quartet is in Q_N or Q_{ON}, then Lori will be unlit next (probability 1).
- If (Lori is unlit and) the quartet is in Q_Z, then Lori will be unlit next (probability 1).
- If (Lori is unlit and) the quartet is in Q_{OFF}, then Lori will be lit next (probability 1).

So with slightly expanded, but far from global, inputs, we can provide maximally precise predictions about Lori: we can replace our probabilistic predictions about the evolution of an unlit Lori with certain ones that treat Lori's next state as a function of the current state of our quartet.

Returning to even more restricted inputs, we can apply the same clause to lower-left Lola and upper-right Uri that we applied to Lori: a currently lit pixel is sure to be unlit next; a currently unlit pixel is more likely to be lit (probability 2/3) than unlit (probability 1/3) next. Expanding our inputs again yields improved outputs for Lola and Uri, though different ones than what we got for Lori:

- If (the pixel is lit and) the quartet is in Q_{Z} or Q_{ON}, then the pixel will be unlit next (probability 1).
- If (the pixel is unlit and) the quartet is in Q_{N}, then the pixel will be lit next (probability 1).
- If (the pixel is unlit and) the quartet is in Q_{OFF}, then the probability that the pixel will be lit next is 1/2, and the probability that the pixel will be unlit next is 1/2.

Again this is an improvement, but this time our last clause is still not maximally precise. After all, we can use our very first theory to make sure predictions about Lola and Uri based on whole-screen inputs.

One result is that the best predictions we can make about the next state of our quartet given just its current state as input are not piecemeal combinations (or simple products) of the best predictions we can make, based on this same input, about each of the individual pixelated constituents. Suppose our quartet is currently in state Q_{OFF}, and we want to determine whether it will be in state Q_{N} at the next stage. For the quartet to be in state Q_{N} just is for both Lola and Uri to be unlit and for both Lori and Lori's diagonal partner—George, of course—to be lit. Given the current state of our quartet, the probability that Lola will be unlit is 1/2, the probability that Uri will be unlit is 1/2, the probability that Lori will be lit is 1, and the probability that George will be lit is 1. Thus, the piecemeal probability that the quartet will be in state Q_{N}—with exactly Lola and Uri unlit—given its current state Q_{OFF} is 1/4. Yet we can construct an alternative that more precisely predicts the next state of the quartet as a whole given this very same input:

- If the quartet is in state Q_{N}, then it will be in state Q_{Z} next (probability 1).
- If the quartet is in state Q_{Z}, then it will be in state Q_{OFF} next (probability 1).
- If the quartet is in state Q_{ON}, then it will be in state Q_{OFF} next.

And in the crucial case of input Q_{OFF}:

- If the quartet is in state Q_{OFF}, then the probability that it will be in state Q_{ON} next is 1/2, and the probability that it will be in state Q_{N} next is 1/2.

This improved theory acknowledges a fact about the quartet that our piecemeal calculation misses. Given input Q_{OFF}, the probability that Lola will be unlit at the next stage is 1/2, as is the probability that Uri will be unlit at the next stage; but the joint probability that *both* of them will be unlit is 0.

In any deterministic setting, it is in principle possible to eliminate non-piecemeal outputs, like these, by offering some more precise theory for expanded inputs. In this particular case, our very first proposal—which requests the current state of our entire screen as input—does the trick. Given this input, we can predict, with certainty, the next state of every single pixel and so, by association, the next state of any whole sum of these pixels. Instances of quartet state Q_{OFF} fall into two classes, those in which the screen has state S_{LIMIT} and those in which it has state S_{NONE}. Using these expanded inputs, we can reproduce our best predictions about the quartet by piecing together our best predictions about each component, given the same inputs.

If the screen is currently in state S_{LIMIT}, it will be in state S_{ALL} at the next stage (probability 1), with each of our four pixels lit. The probability that our quartet will be in state Q_N at the next stage (0) is a piecemeal product of the single probabilities that Lori will be lit (1), that George will be lit (1), that Lola will be unlit (0), and that Uri will be unlit (0). If, instead, the screen is currently in state S_{NONE}, it will be in state $S_{CAUTION}$ at the next stage, and thus our quartet will be in state Q_N. So the probability (1) that our quartet will be in state Q_N at the next stage is a piecemeal product of the single probabilities (each 1) that Lori will be lit, that George will be lit, that Lola will be unlit, and that Uri will be unlit.

Incidentally, we also could construct, to the same effect, a *non-Markovian* recipe requesting *temporally* expanded inputs in this case. Roughly put, the idea would be to distinguish S_{LIMIT} and S_{NONE} subcases of Q_{OFF} inputs by requesting not "global" information about the current state of the whole screen but additional "local" information about some earlier state of just our quartet: the S_{LIMIT} cases are those in which our Q_{OFF} quartet state immediately succeeds a Q_Z one, whereas the S_{NONE} cases are those in which our Q_{OFF} quartet state immediately succeeds a Q_{ON} one.

Now, contrast all of this with a variant case: a wire comes loose, leaving our sign to malfunction erratically. Half the time, it operates as usual. The rest of the time, "LIMIT 15 MPH" fails to display, and the whole screen goes dark instead. After 2 s, it carries on as normal: all the pixels light up; then they all turn off; then "CAUTION!" reappears as before. There is no telling whether the speed limit display will work at the third stage of this next cycle through. So our sign irregularly vacillates between two sequences:

- $S_{CAUTION}$, S_{ZONE}, S_{LIMIT}, S_{ALL}, S_{NONE} (and then back to $S_{CAUTION}$).
- $S_{CAUTION}$, S_{ZONE}, S_{NONE}, S_{ALL}, S_{NONE} (and then back to $S_{CAUTION}$).

With a Markovian theory, at least, then this is the best we can do:

- If the screen is in state $S_{CAUTION}$, it will be in state S_{ZONE} next (probability 1).
- If the screen is in state S_{ZONE}, the probability that it will be in state S_{LIMIT} next is 1/2 (normal operation), and the probability that it will be in state S_{NONE} next is 1/2 (malfunction).
- If the screen is in state S_{LIMIT}, it will be in state S_{ALL} next (probability 1).
- If the screen is in state S_{ALL}, it will be in state S_{NONE} next (probability 1).
- If the screen is in state S_{NONE}, then the probability that it will be in state $S_{CAUTION}$ next is 2/3 (normal operation), and the probability that it will be in state S_{ALL} next is 1/3 (malfunction).

Notice that predictions based on our quartet-sized inputs in this variant case are just the same as before, since the quartet state is Q_{OFF} regardless of whether the screen shows "LIMIT 15 MPH" (screen state S_{LIMIT}) or malfunctions (screen state S_{NONE}).

As before, suppose our quartet is currently in state Q_{OFF}. The probability that it will be in state Q_N at the next stage remains 1/2. Also as before, this prediction for our quartet is not a piecemeal combination of the predictions, based on our same inputs, for each of the four components. For the quartet to be in state Q_N just is for both Lori and George to be lit and for both Lola and Uri to be unlit. Given the current state of our quartet, Q_{OFF}, Lori and George will each be lit at the next stage, and each of Lola and Uri is equally likely to be lit as unlit in the next stage. For either we are at the final stage of the cycle, in which case the next state will be S_{CAUTION}, with each of Lori and George lit and each of Lola and Uri unlit; or we are in the third stage of the cycle, in which case—malfunction or no—all the pixels will light up in the next stage. So the probability that Lola will be unlit in the next stage, given the current quartet state as input, remains 1/2, and, likewise, the probability that Uri will be unlit in the next stage, given the current quartet state as input, remains 1/2. Thus, on a piecemeal account, the probability that the quartet will be in state Q_N, with both Lori and George lit and both Lola and Uri unlit, should be 1/4.

This time, though, we cannot eliminate these non-piecemeal outputs by expanding our inputs, even if we include our complete screen state—the indeterminism arising from our chancy malfunction prevents it. Instances of quartet state Q_{OFF} fall into two classes: those in which the whole screen has state S_{LIMIT}, and those in which it has state S_{NONE}. If the screen is currently in state S_{LIMIT}, it will be in state S_{ALL} at the next stage (probability 1) as before. If the screen is currently in state S_{NONE}, then the probability that it will be in state S_{CAUTION} at the next stage is 2/3, and the probability that it will be in state S_{ALL} at the next stage is 1/3 (malfunction case). Either way, each of Lori and George is sure to be lit in the next stage. However, Lola will be lit in the next stage only if the screen is in state S_{ALL}. Same for Uri. So the probability that Lola will be unlit in the next stage is 2/3, and the probability that Uri will be unlit in the next stage is 2/3. So the probability (2/3) that our quartet will be in state Q_N—that is, that our screen will be in state S_{CAUTION}—given the current state S_{NONE}, is still not a piecemeal combination (4/9) of the single probabilities that Lori will be lit (1), that George will be lit (1), that Lola will be unlit (2/3), and that Uri will be unlit (2/3).

Notice, there is nothing going on in this case requiring us to deny that the complete state of our sign *supervenes* on an underlying array of metaphysically independent pixels: at each time, the distribution of lit and unlit pixel states suffices for the complete display. Granted, our best predictions about the individual pixels do not always suffice, in any piecemeal fashion, for maximally informed predictive outputs about the whole; and even when we can restore piecemeal outputs by expanding our inputs, we sometimes have to provide surprisingly global information about the screen to do so. As a result, we might say that the whole is a locus of predictive or informational *priority* in our theory. And if we are "realists" about our predictive theory, we might even think of our quartet or even the whole screen *itself* as the locus of *some* corresponding broadly metaphysical priority. Presumably, our theory has the form it does *because* it reflects some underlying features of the systems it is accurately characterizing—and thus there are interesting *patterns* of coordination in the evolutions of such systems. None of this, however, need involve any emergent properties, or constraining laws, or other anti-Humean whatnots. Strictly speaking, it at most requires regularities in the features of our pixels across time, *patterns* highlighted in our predictive theory.

I think the situation with quantum mechanics is similar in essential respects. Any realist interpretation of quantum mechanics subsumes the predictions of the textbook recipe, thereby incorporating non-piecemeal predictions about the behavior of entangled particle pairs. The theory's best prediction about the outcomes of our spin experiments on a singlet pair, given the initial state of the pair and our experimental devices, is not a piecemeal combination of our best predictions about the outcomes for the individual members, given that same input. A piecemeal prediction about the joint outcomes of our θ-spin experiments would assign non-zero probabilities (each 1/4) to *up-up* and *down-down* results.

Now, this non-piecemeal character already suggests some predictive or informational holism, but we can say more. As we have seen, non-piecemeal outputs are sometimes just artifacts of impoverished inputs. For example, by taking as input not just Lori's current state but the state of our quartet, we can make determinate, maximally precise predictions about Lori's next state. Same for George. So if we take as input not just Lori's current state and George's current state but the state of their two neighbors, then we can make determinate, maximally precise predictions about the next state of our Lori-George pair. The resulting output for the pair, given this expanded input, is just a piecemeal sum of our component predictions, given that same input, about the next state of each pair member.

In proving his famous inequalities, though, Bell (1964, 1981) places striking limits on attempts to trace the non-piecemeal character of such predictions to impoverished inputs in the quantum case: any interpretation attempting to improve upon non-piecemeal outputs will have to do so only by requesting surprisingly global inputs. More specifically, Bell shows that a local hidden variables account is flatly inconsistent with some of the textbook recipe's experimentally confirmed predictions about entangled systems: any (non-"conspiratorial") theory reproducing such predictions (and so cohering with experimental observations) must violate his factorizability condition (Goldstein et al. 2011). It follows that any interpretation that tries to improve upon the non-piecemeal outputs of the textbook recipe cannot be a *local* hidden-variables proposal: it only can hope to improve upon the non-piecemeal outputs by requiring what Bell deems "non-local" inputs. Bell (1981) counts among "local" factors λ the initial wave function of the entangled pair along with the entire contents of the intersection of the members' past light-cones—thereby aiming to include anything near enough in space and time to potentially contribute, via subluminal causal influence, to a pair's initial pact.

Bohmian mechanics is one existing realist interpretation that treats the non-piecemeal outputs of the textbook recipe as theoretically eliminable approximations: on the Bohmian account, the pre-measurement state of the universe already fully determines the outcome for each of the component subexperiments on the members of our entangled pair. In principle, then, we can replace textbook quantum theory's probabilistic predictions with fully determinate piecemeal ones. So Bohmian mechanics traces quantum mechanical violations of Bell's factorizability condition to the impoverished character of λ—the limitation to "local" inputs. Still, the Bohmian story ensures that we, as epistemic agents, are inescapably ignorant of much of the information beyond λ that more precise predictions would require as input (Dürr et al. 1992). As a result, the non-piecemeal predictions of the textbook recipe are the best we can hope to offer when it comes to anticipating the behavior of physical systems. Moreover, even in-principle recovery of piecemeal outputs comes at a steep cost with respect to inputs. As a rule, fully informed predictions about the behavior of any one particle should take into account the state of the entire universe, since the Bohmian guidance equation explicitly relates the movement of any particle at one time to the global configuration of all particles (Dürr et al. 1992, 2009). And importantly, the kind of sensitivity we see to global inputs in the Bohmian case differs markedly from what we see in, for instance, classical Newtonian gravitation—explaining why quantum theory seems *distinctively* holistic in a way that this predecessor is not. In the quantum case, even modest departure from strictly global inputs can prompt a dramatic resurgence of non-piecemeal outputs—a point of divergence that comes through especially clearly in cases of counterfactual prediction.

Strictly speaking, Newtonian gravitational theory already requires inputs about the entire universe to make maximally precise predictions about one small part. To predict the motion of object o_1, we need to know the net force on it, which sums individual contributions from every other object. For maximal precision, then, we need to know the mass of each and its distance from o_1. Since gravitational force diminishes with distance, however, we frequently can make excellent approximations with highly restricted inputs. Like Newtonian gravitation, Bohmian mechanics offers approximate predictions based on partial inputs, thus treating the evolutions of some particles as more or less independent from others. In the Bohmian case, though, spatial separation between particles is no guarantee of the relevant sort of independence: instead such independence is highly contingent on the particular form of the universal wave function.

In the quantum case, moreover, even modest departure from strictly global inputs can prompt a dramatic resurgence of non-piecemeal outputs, coming through especially clearly in cases of counterfactual prediction: in science, we are interested in predicting not only what *will* happen given some actual input but also what *would* happen were our actual input different, or what *would have* happened had our input been different. In the Newtonian case, we can determine what the net force on o_2 would be *were* the mass of o_1 different using very minimal inputs—changing an isolatable summand in a calculation of net force. Because the calculation of net force is a simple sum of individual component contributions, we can counterfactually isolate the contribution that each object makes to the net force exerted on another based on very little input: if we know the actual masses and accelerations of objects o_1 and o_2 and the actual distance between them, then we know enough to evaluate the precise counterfactual effect on o_1 of a change in the mass of o_2. We can work backwards to the actual net force on o_2 from its actual mass and acceleration, and we can work out o_1's actual contribution to that net force from the actual masses of and distance between o_1 and o_2. We then can make an isolated change to the mass of o_2, calculating the effect of this change on the net force, while holding "fixed" the rest of our original global input.

Compare our sign example: suppose we know that Lori is currently unlit, and that Lori was unlit and Lola was lit at the previous stage. We want to predict how things would have been different for Lori now if Lola had been lit at the last stage as well. Just from the current states of Lori and Lola, we can work out that our quartet actually just went from state Q_N to state Q_Z. To evaluate the counterfactual, however, we cannot alter just Lola's previous state, piecemeal, while holding fixed everyone else—our physical theory does not recognize any state with exactly three lit pixels. Instead, we have to make a further adjustment to the whole: knowing what we do about our physical system, we know the only way Lola and Lori both could have been lit in the previous stage is if our quartet had been in state Q_{ALL} instead. But if the quartet had been in that state instead, then it would be in Q_{NONE} currently, with Lori unlit.

In a Bohmian context, evaluating a counterfactual change to some part likewise may demand further adjustment to the state of the whole, but determining what particular adjustment it requires *also* depends on knowing something more about the actual global state. At the very least, to determine how the rest of some whole would have had to be different in order for some particular part to have been, we at least need to know that whole's actual state, but maybe also something more about the contingent character of the universal wave function. As in our Newtonian case, the state of one Bohmian particle reflects some net influence of the global configuration of particles, but now there is no guarantee that we can isolate the contribution of any one member to the total in a way that lets us evaluate counterfactuals based on highly partial inputs. In order to determine how the velocity of one particle would be different were the position of another different, for example, it is generally not enough to consider the states of just these two particles and relations they bear only to one another. Instead, the contribution of our one particle depends on the global context: both the character of the universal wave function and the configuration of other particles in the universe. In general, even complete information about the positions and velocities of our two particles will not equip us to recover enough information about the global state to evaluate our localized counterfactual.

3 Morals: predictive holism, patterns, and metaphysical explanation

Textbook quantum theory predictively privileges wholes over parts. Thanks to Bell's theorem, an interpretation can compensate for non-piecemeal outputs, even in principle, only by resorting to surprisingly global inputs. Recognition of such predictive holism is enough to incline even minimal realists to endorse IMMEDIACY. For as soon as we take our predictively holistic theory to be "part of a true description the world", we grant that reality is holistic by courtesy: it exhibits patterns conforming to our predictive recipe (Maudlin 2007, p. 61). Such predictive—or, if we prefer, pattern—holism, though, does not entail the specific, substantive metaphysical result claimed by INTRINSIC NON-SUPERVENIENCE. To see this, we need only think back to our sign. There we encountered predictively holistic recipes, yet we did not need to presuppose whole-part supervenience failure, at any stage, to do so.

What about the *rules* underlying the predicted holistic patterns in our example? The fact that some patterns are best captured by holistic predictive structures need not in and of itself commit us to any non-supervening constraints on their evolutions. At least in principle, we might adopt an explicitly reductive account of such rules themselves, treating them as efficient yet powerful summaries of patterns in the contingent evolutions of pixelated elements (Beebee 2000). Now such a reductive account of laws faces various challenges of its own, and exactly how to adapt it to the quantum context is a complicated matter (Dewar unpublished ms). But there is not any entirely novel challenge for reductionists here, and we can think of our toy analogy as an initial proof of concept.

That is not to suggest, of course, that a reductive move of this sort will satisfy everyone. The simple argument is especially compelling for those who expect quantum theory not only to *truly* describe underlying features of reality but also to point towards some underlying structure that *makes* reality behave in accordance with its predictions. Physical systems exhibit conforming patterns of this sort *because* of some underlying structure: emergent dispositions of wholes, for instance, *constrain* them to behave in ways only encoded in a holistic predictively recipe. By design, our reductive move runs contrary to this expectation; at root, here, is a deep disagreement about the nature of explanation and, relatedly, metaphysical methodology.

Compare Newtonian criticisms of Leibnizian relationalism about space (Maudlin 2012, pp. 17–34). Roughly, Leibnizians about space think the only fundamental location facts are facts about the relative locations of—the distances between—objects, and the only fundamental facts about motion are facts about the relative motions of—changes in the distances between—objects. Newtonians, in contrast, conceive of space as an arena of absolute locations. So Newtonians admit that the following scenario is a genuine physical possibility: starting with a universe of just five particles and empty space, we pick up all the particles and move them ten meters, changing their locations without disturbing the distance between them and their relative motions. Leibnizians disagree: if none of the relational facts linking some objects change, then there is no change in the physical facts about their locations or motions. Still, Leibnizians count as *realists* about space. Leibnizians believe that space *exists*, and that (many) Newtonian claims about space and locations and motion are literally *true* descriptions of the world. But Leibnizians think the ultimate truthmakers for claims about space are the relative positions and motions of objects, while Newtonians understand those claims differently.

One Newtonian objection to relationalism about space is that relationalism fails to provide the right sort of metaphysical structure to adequately *explain* certain predictions underwritten by physical theory. Consider, for instance, a universe comprising two identical globes connected by a rope and rotating in space so that the globes revolve around the rope's midpoint. Classical physics predicts that such a scenario will produce tension in the rope, and Newtonians can say in this case that the predicted and observed tension in the rope is due to the motions of the globes in absolute space (Maudlin 2012, p. 23). Leibnizians cannot make a parallel claim; since the spheres circulate steadily at a fixed distance, there is no objective relative motion between them and so, it seems, nothing to point to as an explanation for the predicted tension in the rope. Leibnizians can say *something* about the tension in the rope; they can say, for instance, that there are dependable patterns of tension arising in systems like these in such cases. Perhaps they can posit some novel causes that, they claim, reliably produce this tension. But they cannot cite some facts about metaphysical structure guaranteeing that spheres *must* rotate as they do.

As a result, Newtonians think Leibnizian attempts to explain the theoretically predicted and observed tension in the rope fall short. The alleged explanatory advantage draws essentially on Newtonian convictions about the structure of space that Leibnizians do not share: an adequate explanation of the predicated and observed behavior of the rope must cite the rotation of the spheres in absolute space. Still, if we are implicitly operating with this sort of explanatory picture in place, then the move from some pattern or structure in the predicted and observed behavior of physical systems to some robust underwriting metaphysical structure is almost automatic.

Now compare our quantum case. Those committed to the view that quantum theory entails some robust supervenience failure may make a similar move: committed reductionists lack sufficient metaphysical structure to adequately account for the predicted and observed behaviors of entangled systems. A truly adequate account must appeal to ingredients "over and above" what reductionists can offer. Thus we have an addition to our story about the simple argument: the slide between our notions of holism looks especially tempting, maybe even entirely unproblematic, given a particular conception of the relationship between a theory's predictive structure and the underlying metaphysical reality it describes. Even so, what is doing the work here is not just some minimal conviction that "quantum theory, or any extension of it, is part of a true description the world", but rather an assumption that quantum theory's holistic predictive structure is best underwritten or explained by a particular sort of metaphysical structure (Maudlin 2007, p. 61).

As a result, one way to offer a valid replacement for the simple argument is to make this background conception of the explanatory relation explicit (cf. Ismael and Schaffer 2016). A related moral, however, is that our simple argument leads us back to a more general, deeper, and familiar conflict between reductive and non-reductive convictions about explanation, also at issue, for instance, in disputes about whether Humean laws can be genuinely explanatory or can account adequately for our inductive and inferential practices (cf. Loewer 1996; Beebee 2000; Hall unpublished ms). Presumably any or almost any minimal realist about quantum theory takes the theory to have the structure it does because—in *some* sense of "because"—it reflects the underlying metaphysical character of reality. Reductionists can agree that underlying metaphysical structure explains the structure of quantum theory's predictions and reality's conformity to them: the experimentally confirmed predictions of quantum theory accurately capture or reflect regularities in the features and behavior of quantum systems. They can be realists in good standing, and they even can share a broadly explanatory conception of metaphysical theorizing according to which we invoke metaphysical structure to explain those practices: we cite properties and relations of physical systems in order to make systematic sense of a variety of predictive and epistemic practices. Still, this is not enough to license a move from some predictive privileging of wholes to some robustly holistic metaphysical privilege. To make that further move, we need methodological premises that reductionists are antecedently predisposed to reject. For their opponents, though, these premises come part and parcel with any genuinely explanatory, forthright metaphysics. To take "the wavefunction seriously" is to confer on a whole some metaphysical priority that undergirds and explains the crucial predictive importance of its entangled state (Maudlin 2007, p. 61).

So the main moral, again, is that we should understand debate about the metaphysics of entanglement as reflecting a deeper disagreement about the character of the *explanatory* link between our predictive theory and underlying reality. But this verdict for our simple argument also has a secondary moral for those eager to draw more robust metaphysical conclusions on the basis of such explanatory considerations. Such conclusions need not involve, or even go by way of, the sort of consideration so central to INTRINSIC NON-SUPERVENIENCE. Committed anti-reductionists can agree that there is some substantive metaphysical sense in which a whole quantum system is privileged over its parts, in a way that constrains it to behave in accordance with quantum theory's holistic predictions, without taking that constraining to involve supervenience failure between the intrinsic properties of wholes and parts per se. If explanatory considerations are truly at the root of holistic metaphysical convictions, then allegations of supervenience failure are, in the end, beside the point—as are reductive attempts to preserve the letter of whole-part supervenience. Committed non-reductionists, then, would be better off directly invoking some stronger notion of metaphysical holism, one characterized explicitly in terms of grounding, priority, or metaphysical explanation (Kim 1993).

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