Quantum Holism: Nonseparability as Common Ground

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> [T]hat which we conceive as existing ("actual") should somehow be localized in time and space. That is, the real in one part of space, *A*, should (in theory) somehow "exist" independently of that which is thought of as real in another part of space, *B*. If a physical system stretches over parts of space *A and B*, then what is present in *B* should somehow have an existence independent of what is present in *A*. (Einstein to Max Born; quoted in Howard 1997: 121)
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> A human being is a part of the whole called by us "Universe", a part limited in time and space. He experiences himself, his thoughts and feeling as something separated from the rest—a kind of optical delusion of his consciousness. This delusion is a kind of prison for us, ... (Einstein to Robert Marcus; quoted in Sullivan 1972: 20)

Quantum mechanics seems to portray nature as *nonseparable*. Roughly speaking, this means that quantum mechanics seems to allow two entities—call them Alice and Bob—to be in separate places, while being in states that cannot be fully specified without reference to each other. Alice herself thus seems incomplete (and likewise Bob), not an independent building block of reality, but perhaps at best a fragment of the more complete composite Alice-Bob system (and ultimately a fragment of the whole interconnected universe).

We propose to articulate a natural explanatory strategy for quantum nonseparability via *common ground*. Common ground explanations are modeled after common cause explanations. In a common cause explanation one finds a correlation among events and infers the existence of a common cause. In a common ground explanation one finds a connection between entities and infers the existence of a common metaphysical ground, thereby viewing nonseparable entities (such as Alice and Bob) in a holistic light, as scattered reflections of a more unified underlying reality.

Quantum mechanics is often said to implicate some form of "holism." What are we adding? We aim to make the inferential principles involved more explicit, through our conception of common ground explanation. And we aim to make the holistic conclusion more contentful, by exhibiting specific conceptions of what such a common ground might be. In short, we aim to clarify both the rationale for and the meaning of "quantum holism." We do not mean to say that an interpretation of quantum mechanics *must* provide a holistic common ground explanation for nonseparability, but only to say that interpretations that do so gain a respect of plausibility thereby. In this way we hope to understand one of the many interpretive pressures that quantum mechanics generates.

Discussions about the interpretation of quantum mechanics often focus on the debate between "Everett," "Bohm," "GRW," and other rival versions of the mechanics, each which is coupled with its own interpretive options. Where do we come down? Our discussion crosscuts the usual taxonomy. For the nonseparability we are concerned with is found in almost all of these rival versions of the mechanics (arising for deep mathematical reasons, and receiving empirical confirmation). Rather we think that there is pressure towards certain sorts of interpretive options, namely those that provide the kind of common ground explanation fitting for nonseparability.

Overview: In §1 we characterize and motivate common ground explanations. In §2 we review the case of quantum nonseparability, and in §3 we consider the prospects for and implications of a common ground explanation of quantum nonseparability.

1. Common Ground Explanation

We begin by articulating our notion of a common ground explanation. We describe common cause explanation and common ground explanation in its image, and ultimately seek to characterize and motivate a general rational inference principle, running from correlations and connections to the existence of a common causal or metaphysical source.

1.1 Common cause explanation

In accord with a rational principle of default reasoning, one should infer causation from statistical correlation. If distinct events *e1* and *e2* are correlated, while one should not infer that *e1* causes *e2*, one should—rationally speaking, and all else equal—infer that *either e1* causes *e2*, *or e2* causes *e1*, *or e1* and *e2* are joint effects of a common cause *d*:

> *Causal Inference*: If distinct events *e1* and *e2* are statistically correlated, then either (i) *e1* causes *e2*, or (ii) *e2* causes *e1*, or (iii) *e1* and *e2* are joint effects of some common cause *d*.[1]

For instance, given that smoking and lung cancer are correlated, it is rational to infer that either smoking causes lung cancer, or that lung cancer causes smoking, or that the two are joint effects of some common factor such as a gene predisposing its bearers to both. Otherwise the correlation is left as an inexplicable mystery.

Causal Inference is especially useful in cases in which some of the disjuncts of its consequent can be ruled out. In the historically medically important case of smoking and lung cancer, given the assumption that causes precede their effects, one can rule out the prospect that lung cancer causes smoking. The absence of any known gene or other common cause (or mechanism for such a common cause to operate) speaks against the prospect of a common cause. And—most tellingly—the identification of carcinogens in cigarette smoke and the discovery of the mechanisms by which they operate strongly favor the option of smoking causing lung cancer.[2] It is *Causal Inference* that alerts the rational inquirer to the likely presence of some causal connection involving smoking and lung cancer, which decades of medical research went into detailing.

Or consider Reichenbach's hypothetical case of two lamps in a room going out at exactly the same moment. In such a case, a very natural and plausible explanatory thought is that there is a common cause. Thus Reichenbach (1956: 157; c.f. Hofer-Szabó, Rédei & Szabó 1999, Arntzenius 2010) writes:

> In our daily life we often employ [common cause] inferences of this kind. Suppose both lamps in a room go out suddenly. We regard it as improbable that by chance both bulbs burned out at the same time, and look for a burned-out fuse or some other interruption of the common power supply.

Or—to borrow another example from Reichenbach—imagine that two geysers repeatedly erupt at the same time. A very natural explanatory thought is that these eruptions have a common cause, and that the two geysers might actually share a single subterranean source. On this basis, Reichenbach (1956: 157) concludes: "If an improbable coincidence has occurred, there must exist a common cause." Understanding this 'must' in terms of rational default reasoning yields:

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[1] *Causal Inference* is intended as a rational principle of default reasoning (likewise for all subsequent principles marked '*Inference*'), akin to the principle: "If *a* is a bird then *a* can fly." Such principles need not be perfect, and may only hold "all else equal." Rational principles of default reasoning are an important topic in their own right (Koons 2013), but they are not our topic. For present purposes all that matters is that *Causal Inference*, and our subsequent principles marked '*Inference*' are good principles of scientific inference. Whether that is a matter of rationality, or merely pragmatic, or something else entirely, is a side issue.

[2] For a detailed discussion of these mechanisms, see the Surgeon General's report issued by the U.S. Department of Health and Human Services (2010).

> *Reichenbach's Inference*: If distinct events *e1* and *e2* are correlated and simultaneous, then *e1* and *e2* are joint effects of some common cause *d*.

Reichenbach's Inference follows from *Causal Inference* on the assumption that causes must precede their effects (or at least that causes cannot be simultaneous with their effects). For if distinct events *e1* and *e2* are correlated then *Causal Inference* yields three options, and if *e1* and *e2* are simultaneous then—assuming that simultaneous events cannot be causally related—one can rule out the first two options.[3] But *Causal Inference* is more general. Where distinct events *e1* and *e2* are correlated, one might be able to rule out the prospect that *e1* causes *e2* or that *e2* causes *e1* (leaving only the common cause hypothesis standing) for reasons other than temporal reasons. Also one may still use *Causal Inference* in contexts in which simultaneous causation is being considered.

An important feature of *Causal Inference* (also found with *Reichenbach's Inference*) is that it allows one to go from two observed events (*e1* and *e2*), to the prospect of an inferred third event (*d*) as their common cause. In so doing it underwrites as rational a specific sort of *inference to the best explanation* for the presence of potentially unobserved structure, namely a common cause inferred to explain the correlation.

We should emphasize that *Causal Inference* is a good but perhaps imperfect maxim. The correlation involved may in the end be pure coincidence (though repeated observation of correlations of this type may make one ever more confident that the matter is not coincidental). There may be other ways in which correlations can be sustained. For instance, Sober (1988) considers the correlation between the price of bread in Britain and the water levels in Venice (both having been rising), and suggests that the correlation occurs because structurally similar laws of evolution happen to prevail in both domains. Most relevantly for present purposes, quantum nonseparability seems to involve a kind of correlation for which *Causal Inference* fails (van Fraassen 1980: 29). (We agree, but are in the process of detailing a more general principle which does extend to the quantum domain.)

But what is relevant at this stage of the discussion is simply that *Causal Inference* is a good maxim. Its exceptions are few and its power is vast. If one finds that distinct events *e1* and *e2* are correlated but that neither causes the other (like the two lamps that go out at the same time), then one should—all else equal—rationally infer the presence of a common cause. A theory that attributes a common cause in such cases gains a respect of plausibility thereby.

1.2 Common ground explanation

Just as common cause explanations allow one to go from two statistically correlated events to the prospect of an inferred common cause, so there is an analogous form of explanation—common ground explanation—which allow one to go from two modally connected entities to the prospect of an inferred common metaphysical ground. Common ground explanation has much the same structure, and enjoys much the same motivation, as common cause explanation.

1.2.1 Grounding

We distinguish the fundamental from the derivative. In doing so we follow the tradition of thinking that all sorts of things exist, from particles to pebbles to planets, but that some are more fundamental than others. Moreover, the less fundamental entities are in some sense *grounded in* (or *derivative from*) the more fundamental entities. Grounding is thus a metaphysical relation characterizing the connection from the more to the less fundamental entities.

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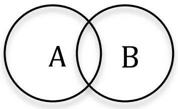
[3] As Hofer-Szabó, Rédei, and Szabó (1999: 378; c.f. Arntzenius 2010) write: "*Reichenbach's Common Cause Principle* is the claim that if there is a correlation between two events *A* and *B* and a direct causal connection between the correlated events is excluded then there exists a common cause of the correlation..."

The notion of grounding we have in mind is a notion akin to "metaphysical causation" (Schaffer forthcoming and 2012: 122; c.f. Sider 2011: 145; Fine 2012: 40). Crudely speaking, just as one can think of causation as driving the world through time from the earlier to the later, so one can think of grounding as driving the world through levels from the deeper to the shallower. For instance, consider some chemicals that comprise a cat. The chemicals and the cat all exist, but the chemicals are each more fundamental than the cat (in general the chemical level is more fundamental than the biological level), and moreover the chemicals are each connected to the cat in the distinctive way that the more fundamental is connected to the less fundamental. In short, each chemical partly grounds the cat.

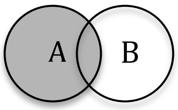
Just as causal relations back causal explanations, so grounding relations back metaphysical explanations. If one wanted to know why there was a cat afoot, one sort of perfectly good explanation would cite one or more causes of the cat's presence (e.g. because we brought the cat home yesterday). But another sort of perfectly good explanation would cite one or more grounds of the cat's presence (e.g. because there are these chemicals arranged in these ways). Causation and grounding are both asymmetric dependency relations with the distinctive power to back explanations.

1.2.2 Common ground explanation

Just as there are common cause explanations, so there are common ground explanations. These arise when a single more fundamental entity gives rise to multiple correlated less fundamental entities. For instance, consider two things with a common part, such as two circles A and B with a lens of overlap:



Assuming that parts ground wholes, A and B have a common partial ground in their common parts. It is thus not so surprising that A and B exhibit modal connections. For instance, if A had been shaded then B would have been partially shaded too:



(Contrast this with the case of two non-overlapping circles which presumably can be colored independently.)

For another example, consider again the various chemicals *c1*-*cn* that comprise the cat, and that also serve as the members of the set {*c1*, …, *cn*}.[4] It is plausible to think that the cat and the set have *n*-many partial common grounds in the chemicals. It is thus not so surprising that the cat and the set exhibit modal connections. For instance, if none of the members of the set existed then the cat would not exist either. (Contrast this with the case of the cat and the set {Socrates} which presumably are independent.)

For one last example, consider some true proposition p, in relation to the propositions $\sim\sim p$ and $p \vee q$. It is plausible to think that the truth of $\sim\sim p$ and of $p \vee q$ is partially grounded in the truth of p. It is thus not so surprising that the truth values of $\sim\sim p$ and of $p \vee q$ exhibit modal connections. For instance, if $\sim\sim p$ were true then $p \vee q$ would also be true. (Contrast this with the case of two atomic propositions which are independent in truth value.)

Just as there are natural and familiar inferences to common causes as the best explanations of statistical correlations, so there are natural and familiar inferences to common grounds as the best

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[4] We follow Fine (1994: 271) in holding that nonempty sets are dependent on their members.

explanations of modal connections. Consider the fact that Jenann has a friend who lives in Chapel Hill, is a philosophy professor, and has a black belt in tae-kwon-do, and the fact that Jonathan has a friend who lives in Chapel Hill, is a philosophy professor, and has a black belt in tae-kwon-do. Suppose moreover that these facts about Jenann and about Jonathan are modally connected. For instance, if Jenann's friend were to leave Chapel Hill for a lucrative career directing vampire movies, then Jonathan's friend would leave Chapel Hill for a lucrative career directing vampire movies. A very natural thought is that Jenann and Jonathan probably have *a common friend*. Facts about this friend serve as a common partial ground for the respective facts about Jenann and Jonathan.

In these cases of inferences to a common ground, one starts with some collection of entities for which there may at first be no recognized connections (the matter may still be open—for instance, Jenann and Jonathan may not yet know if they have a common friend or not). One then uses modal constraints on mutual variation to reveal that some of these entities are not entirely distinct existences, but in fact involve some underlying shared portion of reality (the common friend).

Just as common cause inferences play a crucial role in science, so common ground inferences play a crucial—and perhaps even more fundamental—role in science. The search for "the basic building blocks of nature" is a search for the fundamental substructure that grounds all else, and whose combinations correspond to what is metaphysically possible for a given collection of fundamental individuals displaying a fixed range of quantities and standing in a fixed range of relations.[5] The epistemic setting in which theorizing about the fundamental structure of the world occurs is not unlike the setting in which Jenann and Jonathan try to figure out if they have a common friend.

Or, to use an example made famous by David Lewis, physicists are in many respects like detectives investigating a spate of crimes. The detectives might have a glove from one crime scene, a footprint from another, and a knife from a third. They need to figure out whether these clues lead to a single culprit or many, and what the culprit or culprits are like. The kinds of clues they look for are not just similarities between their criminals (such as the same shoe size, and the same brand of cigarettes), but covariation of their state dependent properties. If the perpetrator of crime number one, for example shows up randomly in various places around the country, but wherever he or she is, the perpetrator of crime number two never shows up simultaneously in a different place, then that is a clue that they may be one and the same. Physicists face the same kind of inferential task in interpreting the results of various measurements. They need to figure out whether various clues lead to a single fundamental entity or many, and what the fundamental entity or entities are like.

For a historical example of a common ground explanation in the sciences, thermodynamics posits a nomic correlation between the pressure, temperature, and volume displayed by an ideal gas (as codified in the Boyle-Charles Law) at a given time. Why are these quantities correlated? The common ground explanation—as detailed by the kinetic theory of gasses—is that these quantities are the joint manifestations of a single underlying phenomenon, namely that of molecular motion.

1.2.3 Grounding inferences

We thus suggest a defeasible inferential principle structurally analogous to *Causal Inference*:

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[5] On this combinatorial way of thinking, basic objects are treated as independently varying elements. Their quantities are treated as dimensions along which they vary internally, and their relations are treated as degrees of freedom in the configurations they can assume. This yields a space of ways a world can be built, from a given collection of individuals displaying a fixed range of quantities and standing in a fixed range of relations. To yield a full notion of metaphysical possibility the approach then needs to be generalized to allow for variation in the individuals, quantities, and relations found. What is metaphysically *im*possible, in this sense, is what is not constructively possible. Independent variation of objects with a common ground turns out to be metaphysically impossible for the same reason that independent variation of the facts about Jenann's friend and about Jonathan's friend is metaphysically impossible.

> *Grounding Inference*: If non-identical entities *a* and *b* are modally connected, then either (i) *a* grounds *b*, or (ii) *b* grounds *a*, or (iii) *a* and *b* are joint results of some common ground *c*.

The cat and the set of chemicals are non-identical but modally connected, and so it is rational to infer that either the cat grounds the set, the set grounds the cat, or (as is most plausible in this case) that the two are the joint outcroppings of some common ground, namely the chemicals. Otherwise the correlation is left as an inexplicable mystery.

We should explain how *Causal Inference* and *Grounding Inference* fit together in the case where they both apply, namely the case of non-identical events. *Causal Inference* is only operative when the events in play are *distinct* (since causation can only relate distinct events). Yet it was never very clear exactly what 'distinct' means in this context. We suggest a metaphysical reading of the notion as saying that the two entities are neither identical nor connected by grounding (neither grounds the other, nor do they have a common ground). Metaphysically, distinct entities are wholly separable portions of reality, with no common roots.[6]

Grounding Inference can then be seen as related to Hume's (1978: 86-87) ban on necessary connections between distinct existences. Thus consider the following very weak—and not very controversial—reading of Hume's claim, which holds merely that it is default rational to reject necessary connections between distinct existences:

> *Hume's Inference*: If entities *a* and *b* are necessarily connected, then *a* and *b* are not distinct existences.

Hume's Inference follow from *Grounding Inference* on the reading of 'distinct' as neither identical nor connected by grounding (in any of the three ways *Grounding Inference* allows). For if entities *a* and *b* are necessarily connected then *Grounding Inference* yields four options: either *a* and *b* are identical or they are grounding connected in one of three ways. On every option one can conclude that *a* and *b* are not distinct existences in the relevant sense.

An important feature of *Grounding Inference* (also found with *Hume's Inference*) is that it allows one to go from two observed entities (*a* and *b*), to the prospect of an inferred third entity (*c*) as their common ground. IIn so doing it underwrites as rational a specific sort of *inference to the best explanation* for the presence of potentially unobserved structure, namely a common ground as the explanation for the modal connection. (We are recommending this inference in the quantum domain.)

We should clarify that *Grounding Inference* is a good but perhaps imperfect maxim. For all we have said, the modal connection involved may ultimately be brute. We have not argued that this is impossible.[7] But what is relevant at this stage of the discussion is simply that *Grounding Inference* is a good maxim. If one finds that non-identical entities *a* and *b* that are modally connected but such that neither grounds the other, then one should—all else equal—rationally infer the presence of a common ground. A theory that attributes a common ground to such entities gains a respect of plausibility thereby.

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[6] Wilson (2010: 601) suggests that two notions of distinctness have been conflated in the literature: nonidentity, and the capacity for either entity to exist without the other. We are suggesting a third sense of the notion, in grounding-theoretic terms. Our notion of distinctness may not be so far from what Hume himself (1978: 634) had in mind:

> Whatever is distinct, is distinguishable; and whatever is distinguishable, is separable by the thought or imagination. All perceptions are distinct. They are, therefore, distinguishable and separable, and may be conceiv'd as separately existent, and may exist separately, without any contradiction or absurdity.

[7] We allow that brute necessary connections are intelligible in a setting in which we have already formed clear and distinct ideas of objects *a* and *b*. For then we can conceive of absolute constraints on their covariation by imaginatively imposing a brute metaphysical restriction on their covariation on top of these preconceived objects. We leave open, however, whether it is possible to form clear and distinct ideas of objects that we cannot discriminate by their observable effects or otherwise preconceive, as is standard with the posits of physics. For a general discussion of the role of modality in an empiricist setting, see (Ismael *manuscript-a*).

Grounding Inference simply says that all else being equal, in the kind of epistemic setting in which we have no direct access to the grounding substructure of a collection of objects, a theory that explains constraints on their modal covariation by reference to a common ground is better than one that regards it as a brute modal connection between distinct existences. If one looks at any theory that gives a non-trivial account of what the fundamental entities are (i.e., if it says that not everything is fundamental), some constraints on mutual variation of *non*-fundamental entities in the world will turn out to be emergent from grounding substructure. *Grounding Inference* expresses a preference for theories that trace modal connections to common grounds over ones that don't.

We think of *Grounding Inference* as deepening and cohering well with *Hume's Inference*. It is because necessary connections suggest a grounding connection that positing brute necessary connections without any metaphysical explanation seems mysterious, in many ways analogous to positing brute correlations between events without any causal explanation. We likewise think of *Grounding Inference* as a natural analogue to *Causal Inference*, and as logically independent from but deepening and cohering well with principles of causal reasoning. Overall we take the combination of *Causal Inference*, *Reichenbach's Inference*, *Grounding Inference*, and *Hume's Inference* to form a plausible and elegant package of rational principles.

1.3 Common source explanation

Common cause explanation and common ground explanation clearly have much in common. We speculate that both may be understood as species of a common genus, namely that of *common source* (or *organic*) explanation. The differentiae of common source explanation are the more specific generative relations, namely causation and grounding. Common source explanation is a unified way of explaining an otherwise mysterious modal connection. When there is a modal connection, it is generally rational (all else equal) to infer a common source that generates the connected outcomes, whether the source generates the connected outcomes via causation or grounding.

Indeed in the specific case where the entities *a* and *b* are non-identical events, and the statistical correlations involved are not merely coincidental but modally robust, one can combine *Causal Inference* and *Grounding Inference* to reach:

> *Source Inference*: If non-identical events *a* and *b* are modally connected, then either (1) *a* and *b* are grounding-connected (/non-distinct), in that either (i) *a* grounds *b*, or (ii) *b* grounds *a*, or (iii) *a* and *b* are joint results of some common ground *c*; or (2) *a* and *b* are (distinct but) causally connected, in that either (i) *a* causes *b*, or (ii) *b* causes *a*, or (iii) *a* and *b* are joint effects of some common cause *c*.

The unity of common source explanation is exhibited through the existence of unified inferential principles such as *Source Inference*.[8]

Source Inference is a useful principle of default reasoning for when one finds non-identical modally connected events, but does not yet know if they should count as distinct or not. This is indeed the characteristic predicament of the physicist, whose connection to unobservable beables is always mediated by measurement and other manifestations, and who is seeking to find underlying unities behind connected phenomena. Given *Source Inference* one can use *the absence of a causal connection* to infer *the presence of a grounding connection*, and possibly even the presence of a common ground *c*. (We apply this idea to quantum

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[8] There is a difficult background issue lurking, concerning when a given notion (such as our notion of "common source explanation") should be regarded as generally unified, or perhaps unified just by analogy, or perhaps unified purely nominally. We think that common source explanation is generally unified, but strictly speaking we only require the claim that *Source Inference* is a default rational explanatory approach. For more on the systematic analogy between causation and grounding, see (Schaffer *forthcoming*).

nonseparability, in order to exhibit the interpretive pressure towards holism via a common ground explanation.)

In speaking of *Source Inference*—and our other principles—as useful principles of default reasoning we make a fairly minimal and somewhat vague claim. We do not claim that things *must* be as our inferential principles say it is default rational to think, and we do not say anything about *the* degree to which it is default rational to think in these ways, or *how easily* these defaults may be overridden. Rather we leave these matters open. We leave these matters open in part because we find it hard to decide these matters in a principled way, and in part so that we can try to understand certain disagreements over the best interpretation of quantum mechanics in terms of *an underlying dispute over the strength of the interpretive pressure toward common source explanation*. Part of the point of identifying interpretive pressures is to understand how one might resist them.

2. Quantum Nonseparability

Where we are: We think that there is a natural and plausible general style of common source explanation, which includes both common cause and common ground explanations as species, and which includes our principle *Source Inference* (§1). Where we are going: Quantum mechanics seems to portray nature as nonseparable, positing non-identical but modally connected events. Quantum mechanics is thus a setting in which *Source Inference* provides rational guidance.

2.1 From entanglement to nonseparability

Textbook non-relativistic quantum mechanics has a fairly standard formulation, which provides a mathematically precise and—to the best of current knowledge—empirically accurate algorithm for calculating the probabilities of observables. The quantum formalism includes rules for assigning quantum states to simple and complex systems, rules for evolving quantum states through time (Schrödinger's Equation), and rules for assigning probabilities to observables on the basis of the quantum state (Born's Rule).

What the formalism *means* is subject to ongoing debate, and indeed several "interpretations" of quantum mechanics would revise the rules for evolving quantum states through time (for instance, Everettians would work with Schrödinger's Equation just as given, Bohmians would add a Guidance Equation, and GRW fans would replace Schrödinger's equation with a probabilistic equation that can undergo collapse). These revisions in turn give rise to further interpretive options. We are mainly focused on the synchronic rules for assigning quantum states to simple and complex systems, and what we have to say is for the most part neutral on the accompanying dynamics, so we will use 'quantum mechanics' to refer to the quantum formalism, leaving matters of interpretation (and potential revisions to the dynamics) open to the extent possible.

2.1.1 Entanglement

The quantum formalism includes rules for assigning quantum states not just to simple systems but also to complex systems such as a pair of particles, an object system and a measuring apparatus, or an observer and her physical environment. These quantum states are what then get fed into the dynamics (Schrödinger's Equation, or some descendant), and what then get used to derive probabilities of observables (Born's Rule). The quantum state-spaces for complex systems allow for *entangled states*, which are states for the whole that cannot be reduced to states for the multiple components.[9] The components of a system in an entangled state behave in ways that are individually unpredictable, but jointly constrained so that it is possible to forecast with certainty how one component will behave, given information about the measurements carried out on the other(s).

The type of coordinated randomness borne by the spatially separated components of a system in an entangled state is not just a straightforward mathematical consequence of the quantum formalism, but

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[9] The mathematical objects that represent the reduced states of the multiple components do not uniquely determine the state of a whole system in an entangled state, but are instead compatible with multiple states of the whole.

moreover is itself an empirically verified phenomenon (Aspect, Grangier & Roger 1981). The difficulties only arise in trying to arrive *at a physical understanding* of how entangled components manage to exhibit such coordinated randomness.

Because the EPR (Einstein, Podolsky & Rosen 1935) thought experiment is so familiar, we use it to illustrate entanglement. In Bohm's (1951) version of EPR, two x-spin ½ particles—Alice and Bob—are prepared together in a joint state in which the total x-spin of the system is 0. Written in the basis of x-spin, the state of the system is:

Singlet: $|\Psi\rangle_{\text{Alice,Bob}} = 1/\sqrt{2}\ [(|\uparrow\rangle_{\text{Alice}}+|\downarrow\rangle_{\text{Bob}}) - (|\downarrow\rangle_{\text{Alice}}+|\uparrow\rangle_{\text{Bob}})]$

In words, *Singlet* is an equally weighted superposition of (i) Alice being x-spin up but Bob x-spin down, and (ii) Bob being x-spin up but Alice x-spin down.[10]

Alice and Bob are then fired off to arbitrarily distant measuring apparatuses set up, after they are fired off, to measure spin in the x-direction. By Born's Rule the pre-measurement probability distribution over possible outcomes is:

Pr(Alice measures out at x-spin up) = .5
Pr(Alice measures out at x-spin down) = .5
Pr(Bob measures out at x-spin up) = .5
Pr(Bob measures out at x-spin down) = .5

The joint state of *Singlet*, however, yields a probability 1 that the total x-spin of the system is zero, so if Alice measures x-spin up, the formalism predicts that Bob measures x-spin down (likewise if Alice measures x-spin down, the formalism predicts that Bob measures x-spin up). So the joint probability distributions are not as one would expect from thinking of Alice and Bob as independent (which would be .25 for each option below) but are rather:

Pr(Alice measures out at x-spin up & Bob measures out at x-spin up) = 0
Pr(Alice measures out at x-spin up & Bob measures out at x-spin down) = .5
Pr(Alice measures out at x-spin down & Bob measures out at x-spin up) = .5
Pr(Alice measures out at x-spin down & Bob measures out at x-spin down) = 0

The difficulty is to understand *how* Alice and Bob engage in this coordinated randomness. How do they "know" not to both measure out at spin-up, and not to both measure out at spin-down?

2.1.2 Incompleteness and nonlocality

It is now standard to distinguish three related physical principles that might be thought to lie behind the phenomenon of quantum entanglement: *incompleteness*, *nonlocality*, and *nonseparability*. For present purposes we are going to assume that nonseparability is the correct principle (§2.1.3). But we pause to explain why we consider this a plausible assumption, by explaining why incompleteness and nonlocality seem implausible.

Incompleteness—which Einstein, Podolsky & Rosen took to be the moral of their thought experiment—makes two main claims, the first of which is:

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[10] *Singlet* is what one predicts if an excited hydrogen molecule with x-spin 0 decays into a pair of hydrogen atoms. By conservation of angular momentum the total x-spin of the pair of atoms must be 0. (Also, by conservation of momentum, the two atoms must head in opposite directions.) Such *entangled* (or *non-factorizable*) states are mathematically permitted in quantum mechanics, since not every vector in the Hilbert space can be written as the tensor product of arbitrary basis vectors. Indeed there is reason to think that entangled states are generic in quantum mechanics, and that *any plurality of particles whatsoever* will be in an entangled state.

> *Incompleteness1*: The components of entangled systems have definite intrinsic states all along, which are merely not fully encoded in their quantum state description.

By *Incompleteness1*, Alice and Bob have definite and opposing *x*-spins the whole time, which are merely not stated in *Singlet*. These are "hidden variables." The second main claim of incompleteness is:

> *Incompleteness2*: If the intrinsic state of a component of an entangled system were described completely, such a complete description would screen off information provided by measurements on the other components, at which point the "entanglement" would be eliminable.

By *Incompleteness2*, a complete description of either Alice's or Bob's intrinsic state would erase their coordination. So the idea is that the seeming coordinated randomness of the components of entangled system is just an artifact of—and perhaps even a sign of—their underdescription in terms of their quantum states.

Incompleteness is implausible because both of the two main claims of incompleteness have run up against powerful "no-go" theorems. *Incompleteness1* runs up against the theorems of Gleason (1957) and Kochen-Specker (1967), which show that a hidden variable theory cannot consistently assign values to all quantum observables at all times. So the first main claim of incompleteness appears to be ruled out on mathematical grounds.[11]

Incompleteness2 runs up against Bell's (1964) Theorem, which shows that no hidden variable theory can match the statistical predictions of quantum mechanics, without positing some sort of superluminal signaling or some form of non-local influence. Bell (1981) shows that one can derive certain inequalities from just the premises of locality (understood in terms of a "screening-off" condition), and of the independence of the state of the whole system on the type of measurement to be performed. These inequalities are violated by the quantum statistics, and this violation has since been empirically confirmed (Aspect, Grangier & Roger 1981). So the second main claim of incompleteness appears to be ruled out on empirical grounds. There is no way of filling in the intrinsic state of the components at the source in a way that would screen off the information provided by results on the other component (assuming no prior knowledge of which measurement would be performed). Though it might be natural to imagine that Alice and Bob were each born (from the excited hydrogen molecule with *x*-spin 0 that decayed into them both) with definite and opposing *x*-spin values, such a picture conflicts with the empirically confirmed quantum statistics.[12]

In the wake of these theorems, it is widely accepted that a hidden variable approach must accept *nonlocality*, in the sense of some sort of superluminal causal influence, as per:

> *Nonlocality*: The measure result on some component(s) of an entangled system causes the other component(s) (no matter how far distant) to go into the coordinated state.

So for instance if Alice measures out at *x*-spin up, *Nonlocality* has it that this causes Bob (no matter how far away he is from Alice) to come into the state of being *x*-spin down. Bell (1964: 199) himself concluded that a hidden variables approach must posit *instantaneous causation*:

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[11] There is an escape clause: strictly speaking the Kochen-Specker Theorem only applies to *noncontextual* hidden variable theories, where a noncontextual theory is one on which the value of a given observable is independent of which other observables happen to be measured along with it. One might still adopt a contextual hidden variable theory. But noncontextuality is a deep principle in quantum mechanics, connected to the standard principles of individuation for quantum observables. So while denying noncontextuality is a formal possibility, the option has found few defenders, and there is little in the way of a clear positive proposal for a contextual hidden variable theory. See (Shimony 1984) and (Cabello 1997) for some further discussion.

[12] For a useful overview of Bell's Theorem and surrounding issues, see (Shimony 2009).

> In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. Moreover, the signal involved must propagate instantaneously, so that a theory could not be Lorentz invariant.

But there is also an option of positing *backwards causation*, on which the later measurement outcome causes the prior states of Alice and Bob.[13] The details of a nonlocal causal story need not concern us here.

It is implausible to posit instantaneous causation because such influences would need to propagate in a preferred reference frame, which looks to violate the spirit if not the letter of relativity. Though we are working within nonrelativistic quantum mechanics, presumably one should want an interpretation that is not essentially tied to the limitations of a given framework.[14] It is also implausible to posit backwards causation, if only because there is no prior or independent evidence for such fanciful behavior in nature.

There is a deeper implausibility to both incompleteness and nonlocality: both are ways of denying that the quantum state provides a complete description of systems, differing only in whether the additional "hidden variables" posited operate locally or not. But the quantum states of systems are all that is needed for the formalism, and for all of the empirical success that quantum mechanics enjoys. So there is underlying pressure (from parsimony-based considerations) to treat the quantum state description as complete if possible, since nothing else seems needed empirically.

2.1.3 Nonseparability

As a working assumption, we adopt the view—which we take to be the dominant view nowadays—that what lies behind quantum entanglement is neither incompleteness nor nonlocality, but instead *nonseparability*. Nonseparability says that the coordinated randomness of entangled systems corresponds to a *failure of mereological supervenience*.[15] The whole system has an intrinsic state that fails to supervene on the intrinsic states of its proper parts plus their spatial relations:

> *Nonseparability*: Entities *a* and *b* are nonseparable if and only if fixing the intrinsic state of *a*, the intrinsic state of *b*, and the spatial relations between *a* and *b* fails to fix the intrinsic state of *a*+*b*.

So the idea behind nonseparability is that the composite Alice-and-Bob system hosts further information (given in *Singlet*) than can be found in Alice or in Bob individually (or in their spatial relations). One may glimpse something holistic in this idea: the whole system seems to be "more than the sum of its parts."[16]

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[13] In this vein, Cramer (1986) develops a "transactional" interpretation on which the measurement outcome sends a backwards propagating absorber wave ("the confirmation wave"), which interacts with a forward propagating emission wave ("the offer wave") at the start of the experiment, to form a standing wave between the start of the experiment and the site of measurement. For further discussion of the transactional interpretation see (Wharton 2010), (Kastner 2013), and (Wharton & Price 2013).

[14] See (Maudlin 2002) for a detailed discussion of the interaction between quantum nonlocality and relativity.

[15] *Caveat*: the term 'nonseparable' gets used in many different ways in the literature. See (Healey 2008) for an excellent guide. Our non-relativistic usage corresponds to Healey's (2008: §6) notion of "spatial separability."

[16] In this vein d'Espagnat (1979: 181) concludes: "Most particles or aggregates of particles that are ordinarily regarded as separate objects have interacted at some time in the past with other objects. The violation of separability seems to imply that in some sense all these objects constitute an indivisible whole." Likewise Maudlin (1998: 56) says: "The physical state of a complex whole cannot always be reduced to those of its parts, or to those of its parts together with their spatiotemporal relations… The result of the most intensive scientific investigations in history is a theory that contains an ineliminable holism." And to add just one more of the many examples which could be given, Gisin and Aspect (2014: 43; in a section entitled "Quantum Holism") write: "Roughly speaking, the strange theory of quantum physics tells us

With nonseparability one gives up on the idea of a hidden variable approach altogether, and accepts the quantum state as saying all there is to say about the relevant matters. For instance, all there is to say about the pre-measurement *x*-spins of Alice and Bob is what *Singlet* says. There is something very plausible about this approach, at least vis-à-vis interpreting the quantum formalism: one tries to take the ingredients at face value as fully describing reality.

So we take it as given that quantum mechanics portrays nature as nonseparable. We do not take incompleteness or nonlocality to be ruled out but simply cannot discuss these options further here. We are primarily interested in what nonseparability would suggest for a physical understanding of the theory. Given that all there is to say about the pre-measurement *x*-spins of Alice and Bob is what *Singlet* says, how can one explain what Alice does and what Bob does? (Even the most ardent denier about nonseparability should be interested in that question, if only to understand what she would reject.)

2.2 From nonseparability to modal connection

Quantum mechanics seems to portray nature as nonseparable (§2.1). We now add: nonseparability yields modally connected non-identical events, in a manner that invites the application of *Source Inference* (§1.3). Suppose that Alice measures in at *x*-spin up. Then the modally connected non-identical events are *Alice-up*, which is the event of Alice's measuring *x*-spin up, and *Bob-down*, which is the event of Bob's measuring *x*-spin down. (Had Alice measured in at *x*-spin down the relevant events would be *Alice-down* and *Bob-up*—understood in the obvious ways—and all our crucial points would still apply.)

Given *Singlet*, *Alice-up* and *Bob-down* are connected events. Indeed given *Singlet* these events are perfectly correlated. Given that Alice and Bob were in *Singlet* and that *Alice-up* occurred, it is certain that *Bob-down* occurred as well. Moreover—and crucially for our purposes—*Alice-up* and *Bob-down* are modally connected. Indeed given *Singlet* neither can occur without the other. Given that Alice and Bob are in *Singlet*, the following conditionals hold: If *Alice-up* occurs, then *Bob-down* occurs; and also if *Alice-down* occurs, then *Bob-up* occurs. Thus we have:

> *Quantum Connection*: In a nonseparable quantum system, non-identical events *a* and *b* are modally connected.[17]

What explains *Quantum Connection*? Alice and Bob are in some ways like distant lamps, where the one showing "up" is immediately and robustly correlated with the other showing "down," and moreover where this connection extends counterfactually. What explains this modal connection? Is it just a brutely mysterious modal link, or can it somehow be explained by a common source?

2.3 Who cares?

We are operating with the state descriptions given by the formalism of standard nonrelativistic quantum mechanics. But we have been operating so far without a developed interpretation of the formalism (as is only fitting, since we are looking for interpretive pressures coming out of the formalism). And this formalism itself is clearly provisional, and should presumably give way to relativistic quantum field theories, which themselves will likely be succeeded by a theory of quantum gravity whose structure is not currently known. So, putting

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that it is possible and even commonplace for two widely separated objects in space to form in reality a single entity! And that's entanglement. If we then prod one of the two parts, both will quiver."

[17] In what follows we move back and forth between object talk (Alice and Bob) and event talk (*Alice-up* and *Bob-down*). Our underlying view is that the events are not distinct precisely because the objects they involve are not distinct. Just as the event of Jenann's friend riding a horse is not distinct from the event of Jonathan's friend riding a horse if there is a single common friend, so the event of *Alice-up* is not distinct form the event of *Bob-down* if Alice and Bob themselves spring from a common ground.

these together, we are discussing aspects of a formalism that is both uninterpreted and provisional. What is the interest in that?

We think that this exercise is interesting in at least two ways. First of all, we think that the core phenomena of entanglement—what Schrödinger (1935: 555) called "not one but rather *the* characteristic trait of quantum mechanics"—is likely to persist in successor frameworks. As d'Espagnat (1973: 734) comments: "[W]e may safely say that non-separability is now one of the most certain general concepts in physics." Indeed, though the interpretive problems are transformed somewhat in the context of quantum field theories, entanglement—and the associated theoretical options of noncontextuality, nonlocality, or nonseparability—looks to remain in place.[18]

Secondly, this sort of interpretive exercise can still serve as a useful guide both in interpreting the formalism we have and arriving at a successor. Whether or not entanglement persists in physical theorizing, we proceed in the spirit of trying to identify the interpretive pressures it creates. Perhaps all one can do at this stage of physical knowledge is to issue something in the spirit of "prolegomena to any future philosophy of physics." These prolegomena may include the identification which aspects of current physics create which interpretive pressures. We think that entanglement—understood via *Nonseparability*, in ways that lead to *Quantum Connection*—creates interpretive pressure to identify a common source.

3. Nonseparability as Common Ground

Where we are: We think that there is a natural and plausible general style of common source explanation, which includes both common cause and common ground explanations as species, and which comes together in our default reasoning principle *Source Inference* (§1.3):

> *Source Inference*: If non-identical events *a* and *b* are modally connected, then either (1) *a* and *b* are grounding-connected (/non-distinct), in that either (i) *a* grounds *b*, or (ii) *b* grounds *a*, or (iii) *a* and *b* are joint results of some common ground *c*; or (2) *a* and *b* are causally connected, in that either (i) *a* causes *b*, or (ii) *b* causes *a*, or (iii) *a* and *b* are joint effects of some common cause *c*.

Quantum mechanics—due to nonseparability—allows the events of *Alice-up* and *Bob-down* to be modally connected (§2.2):

> *Quantum Connection*: In a nonseparable quantum system, non-identical events *a* and *b* are modally connected.

It remains to connect these claims. We think that quantum mechanics—given *Nonseparability*—creates interpretive pressure towards a common ground explanation, on which the events of *Alice-up* and *Bob-down* are joint results of some common ground *c* (as per option 1c in *Source Inference*).

3.1 Causal connection

Virtually everyone who encounters quantum nonseparability yearns at first to give a causal explanation, and in particular yearns to identify a common cause. Why a common cause? It seems wrong to say that *Alice-up* causes *Bob-down*, and wrong to say that *Bob-down* causes *Alice-up*. First of all, these events occur simultaneously at arbitrary distances, so if one assumes *either* that causes must precede their effects (or at least cannot be simultaneous with them) *or* that causes must operate locally (no "action at a distance"), then one rules out either causing the other. Secondly, causation is generally considered to be an asymmetric relation, yet the relation between *Alice-up* and *Bob-down* seems perfectly symmetric. It would seem arbitrary to position one as cause and the other as effect.

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[18] We expect replacement theories to preserve the core mathematical structure and empirical successes of the theories they replace, and entanglement looks to have both features. See (Ruetsche 2013) for a deeper, albeit more equivocal, assessment of quantum field theories.

Indeed there might seem to be a perfectly natural common cause story to tell. There is the event *Origin* in which Alice and Bob were jointly prepared (e.g. the decay of an excited hydrogen molecule with *x*-spin 0 into a pair of hydrogen atoms), which begs to be considered the common cause of their correlation. Perhaps in *Origin* Alice and Bob were already jointed loaded (via "hidden variables") with the information about the *x*-spin values they would subsequently manifest. (Picture a playing card face down which is then torn in half, and the halves sent out to arbitrary distances. Whatever one turns over on the one half will match whatever one turns over on the other half. *But there is no mystery here.* Indeed this is a case of common cause explanation in full glory. The two halves match because they were previously torn from a single card.)

But—as explained in §2.1.2—one of the shocking features of quantum mechanics is that no common cause story can be told that locates the common cause in *Origin*—or anywhere in the intersection of the back light cone of particles in an entangled state—while yielding the statistical predictions of quantum mechanics. This is what Bell's Theorem (Bell 1964) shows. *The perfectly natural common cause story is inconsistent with the empirically well-confirmed quantum statistics.*[19]

3.2 Grounding connection

There is more than one way to provide a common source explanation. One can regard *Alice-up* and *Bob-down* as distinct events, in which case the common source explanation would presumably be a common cause explanation. But one is not forced to regard these events as distinct events, in the relevant sense of the notion on which distinctness involves a lack of grounding connection (§1.2). It is not always obvious what grounds what, and so not always obvious what is distinct from what. So perhaps a common ground explanation of quantum nonseparability can be offered, on which *Alice-up* and *Bob-down* turn out to emerge from a common portion of reality?

3.2.1 A holistic common ground

Any ground-based account of the modal connection involved in entanglement should presumably be a common ground story on which the component events emerge from a common ground (as opposed to a story on which one component event grounds the other), for reasons analogous to the reasons that a causal story would presumably be a common cause story. First, the events occur simultaneously at arbitrary distances, so having one ground the other would require "simultaneous grounding at a distance." Secondly, grounding is generally considered an asymmetric relation, and it would seem arbitrary to position one event as ground and the other as grounded.

But a common ground story can be told *without running afoul of Bell's Theorem*. We know from Bell's Theorem that one must either give up the premise of locality (understood in terms of a "screening-off" condition), or the premise of the independence of the state of the whole system on the type of measurement to be performed. Like most we would give up locality. The point of a common ground story is to give up locality without positing any hidden variables, and without positing any *causal* connection (as per *Nonlocality*).[20] Thus we take the quantum state description of the composite Alice-Bob system to be a complete description, but add the idea that the composite Alice-Bob system is more fundamental than—and in that sense a common ground of—its Alice component and its Bob component. Alice and Bob are derivative *aspects* (or *fragments*) abstracted from a more fundamental whole. The nonlocal connection between Alice and Bob arises from their spatially spread-out common ground.

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[19] As noted in §2.1.2, there is still the option of a nonlocal retrocausal common cause story, but we are operating under the working assumption that this is not a preferred option. That said we do acknowledge that the retrocausal approach has at the very least an aspect of plausibility, precisely for providing a sort of common source explanation for the correlated randomness of entangled systems. So we see *Source Inference* as helping to account for some of the plausibility that the retrocausal account can boast.

[20] Our thanks to Ned Hall for helping us clarify these issues.

On this sort of common ground approach the way that *Singlet* explains the coordinated random behavior of Alice and Bob is straightforward. *Singlet* is a property of the whole Alice-Bob system. This property of the whole system can explain the behavior of its components (Alice as well as Bob) because the whole system grounds the components.

It may be useful to pause here and explain what difference the direction of grounding makes, to the prospects for explaining the behavior of entangled systems. Suppose—contrary to our recommendation—that one regards the whole Alice-Bob system as grounded in Alice and Bob (parts grounding wholes). Then one should take the features of the whole Alice-Bob system as explained by the features of Alice and the features of Bob, and any fundamental relations between the two. But the whole Alice-Bob system, as described by the quantum state *Singlet*, seems to have "a life of its own" in having a feature—namely, the way in which Alice's random behavior and Bob's random behavior are coordinated—which is inexplicable from the quantum state of Alice, the quantum state of Bob, and at least whatever spatial relations they stand in. From this perspective the coordinated randomness of Alice and Bob is indeed mysterious.[21]

But suppose that instead—as we recommend—one regards Alice and Bob as grounded in the whole Alice-Bob system (wholes grounding parts). Then instead of going up from the quantum state of Alice and the quantum state of Bob to *Singlet*, one is going down from *Singlet* to the quantum state of Alice and the quantum state of Bob. From this perspective the coordinated randomness of Alice and Bob at last has an explanation, in terms of the more fundamental state of the whole. It is by reversing the order of grounding (wholes grounding parts) that one allows for a reversal of the order of explanation, to the only order that actually works.

Elements of such a common ground story may be found in various sources. For instance, consider Lange's (2002: 292; cf. Gisin 2005: 5) interpretive proposal that there is just the single entangled Alice-Bob system and a single scattered event of disentanglement: "Rather than separate effects occurring on the two wings [of the EPR experiment], there is a single effect, an event occurring at the left measuring device and in a region on the right wing." One may treat Lange's proposal as a correct description of the more fundamental story (involving just the single Alice-Bob system), while dropping the eliminative aspect of the proposal so as to allow that Alice and Bob (and the associated events) exist derivatively, as fragments of the whole. Likewise consider Penrose's (2004: 578) claim—from a chapter entitled "The entangled quantum world"—that "a system of more than one particle must nevertheless be treated as a single holistic unit." In this same vein Schaffer (2010a: 54) concludes: "Entangled systems are fundamental wholes."

Where we have arrived: given *Source Inference* and *Quantum Connection*, there is interpretive pressure to regard the separated components of entangled systems as grounded in the whole integrated entangled system, and thus to regard quantum mechanics as a theory that portrays entangled wholes as more fundamental than their parts.[22]

3.2.2 The whole cosmos as fundamental

If quantum mechanics portrays entangled wholes as more fundamental than their parts, what (if anything) does quantum mechanics portray as most fundamental of all? There is a natural line of thought which takes us to the conclusion that quantum mechanics portrays the whole material cosmos as most fundamental of all.

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[21] Perhaps the best alternative is to add fundamental *entanglement relations* to the ontology (Teller 1986; see Morganti (2009: 276–80) and Calosi (2014: 922–26) for specific application of this idea to the inference under discussion in the main text). On this alternative approach the coordinated randomness found in Alice's and Bob's behaviors is to be explained by positing a new fundamental relation alongside their spatial relations. See §3.3 for further discussion.

[22] The idea of the whole being prior to its parts is reminiscent of the classical monistic idea in metaphysics. In this vein Proclus (1987: 79) writes: "[T]he monad is everywhere prior to the plurality… In the case of bodies, the whole that precedes the parts is the whole that embraces all separate beings in the cosmos." See (Schaffer 2010a: appendix and 2010b) for more historical discussion.

For there are two separate lines of thought to the conclusion that the whole material cosmos forms one vast entangled system. First, entangled states are mathematically generic (measure 1 of all wave-functions are entangled), and so if there is a wave-function of the whole material cosmos it is almost certainly entangled. Secondly, given that everything interacts at the Big Bang one predicts initial entanglement, and given that everything then evolves by Schrödinger's equation such entanglement is always preserved. In fact Schrödinger evolution tends to spread entanglements, so that even without initial entanglement, "eventually every particle in the universe must become entangled with every other…" (Penrose 2004: 591).

What exactly might such a view of fundamental reality look like? One option arises from consideration of Wallace & Timpson's (2010) *spacetime state realism*. Wallace & Timpson (2010: 709) offer an ontology for quantum mechanics in terms of the whole universe divided into subsystems, and density operators assigned to the whole system as well as to each and every subsystem. So for Wallace & Timpson the whole material cosmos and each and every subsystem are equally included in the fundamental ontology.

But the Wallace & Timpson picture can and should be trimmed down. As Wallace & Timpson note, due to entanglements one cannot recover the density operator for a whole system from the density operators for any partial subsystems, and so it is necessary to assign a density operator to the whole universe. *But there is no need to assign any further density operators to any subsystems*. In fact, given a density operator assigned to the whole universe, the density operators for every single partial subsystem are in fact uniquely determined, and mathematically recoverable by the partial trace operation.[23] Assigning density operators to anything beyond the whole universe is not only unnecessary, but it also makes for massive redundancy in the fundamental, and blocks free recombination among the elements of the fundamental ontology to boot. So a streamlined version of Wallace & Timpson's spacetime state realism assigns a fundamental density operator only to the whole universe, and regards the quantum state of any subsystem whatsoever (such as Alice, Bob, or the Alice-Bob system) as derivative from this common source.

So, as one way of providing a fundamental ontology for quantum mechanics consistent with our idea of common ground explanation, we offer:

> *Spacetime State Realism Streamlined*: The fundamental ontology is that of the whole spacetime bearing a density operator.

From the whole spacetime one can recover the many derivative subsystems, and from the density operator assigned to the whole spacetime, plus the many derivative subsystems, one can then recover the density operator for any and all of these fragmentary subsystems by the partial trace operation.

We do not mean to suggest that *Spacetime State Realism Streamlined* is the only acceptable fundamental ontology for quantum mechanics, or even to suggest that it is the only fundamental ontology for quantum mechanics that enjoys the plausibility of providing a common ground explanation for the coordinated randomness found in the components of entangled systems. We only mean to provide one precise illustration of a fundamental ontology that provides the kind of common ground explanation we recommend (we are about to provide a second such illustration).

3.2.3 The wave function as fundamental

Spacetime State Realism Streamlined is not the only fundamental ontology that provides the kind of common ground explanation we recommend. A second very different way of telling a common ground story leaves

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[23] More precisely, the partial trace operation allows one to recover the density operator for any partial subsystem *A* from the whole system *AB* by tracing out *B*. Wallace & Timpson (2010: 710) are right that we need a decomposition of the universe into parts like *A* and like *B* to make sense of this, but it does not follow that we need to assign any density operator to *A* or to *B* in the fundamental ontology. Once we have a universe replete with parts, the only fundamental density operator needed is the universal one. (We thank David Wallace for discussion of these points.)

manifest three-dimensional space behind entirely, so as to treat the "fundamental image" of Alice and Bob as co-mingled in a more fundamental space. In this vein Albert (1996) proposes *wave function realism*, on which the fundamental action in quantum mechanics plays out in a massively high-dimensional *configuration space*, in which Alice and Bob are not even to be found.[24]

For the wave function realist, assuming that there is even such a thing as familiar three-dimensional space, it is to be treated as a *derivative* (or *emergent*) structure, and not a fundamental aspect of reality. Likewise assuming that there are even such things as Alice and Bob, they are to be treated as derivative entities. As North (2013: 198; c.f. Ney 2013: 180) writes:

> A *grounding relation* captures the way that the wave function's space is fundamental and ultimately responsible for ordinary space, while at the same time allowing for the reality of ordinary space. This is an explanatory relation that captures the way in which one thing depends on or holds in virtue of another, without implying that the dependent thing does not exist.

Loewer (1996: 180) in fact suggests wave function realism as reconciling entanglement with Humean principles: "We can think of the manifest world—the world of macroscopic objects and their motions—as shadows cast by the quantum state and the world particle as they evolve in configuration space." We are pointing out that it is built into this picture that these many shadows are cast by a common source.

In a related vein, Ismael (*manuscript*) suggests that quantum entanglement (and also complementarity) "intimate a fundamentally non-spatiotemporal ordering to reality." She proposes that manifest three-dimensional space be viewed as a "low-dimensional projection of a higher dimensional reality" (such as the wave function realist's image of reality), culminating in "the idea of a universe in which what we see in different parts of space are not really distinct existences." She concludes:

> Where common sense sees distinct existences interacting in a four-dimensional space-time, one begins to see redundant glimpses of a higher dimensional structure refracted and reflected to provide multiple representations in a lower-dimensional space.

For Ismael, the essential inference is from many modally connected events in manifest space to some sort of underlying unity being "refracted and reflected," inferred via an organic (/common ground) explanation.

Wave function realism itself comes in many forms, and is neutral between the usual "Everett," "Bohm," and "GRW" classifications. As Albert makes clear, one can couple a wave-function-only ontology with different dynamical laws, so as to reach the wave function realist image of the Everett or the GRW interpretations. And one also add a world-particle to the ontology so as to reach the wave function realist image of Bohm's interpretation. Our recommendation of a holistic common ground explanation is likewise neutral between these many forms of wave function realism.

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[24] For a system of n particles, the associated configuration space has $3n$ dimensions. Imagine the one has a system of two particles in a three-dimensional space, where one is only interested in positions at times. Then one needs to specify, for each time, six pieces of information: the x-, y-, and z-coordinates of particle1, and the x-, y-, and z-coordinates of particle2. One can equally specify six pieces of information in terms of a point in six-dimensional space, where the location of the point in the first three dimensions represents the x-, y-, and z-coordinates of particle1, and the location of the point in the second three dimensions represents the x-, y-, and z-coordinates of particle2. So explained, configuration space might seem like a (perhaps perverse) way of mathematically representing the action in manifest space. But in quantum mechanics, configuration space has a life of its own. The wave function is a complex amplitude field living in configuration space. Schrödinger's equation describes the temporal evolution of the wave function. To the extent that Schrödinger's equation gives the dynamics, there is then a "face value" reading of the dynamics as describing the temporal evolution of a field in configuration space. There is thus a "leave your preconceptions at the door" way of thinking about quantum mechanics—which the wave function realist adopts—on which the fundamental action is in configuration space.

So, as a second way of providing a fundamental ontology for quantum mechanics consistent with our idea of common ground explanation, we offer:

> *Wave Function Realism*: The fundamental ontology is that of the wave function in configuration space (and perhaps the world-particle as well).

The shape of the wave (and perhaps the place of the world-particle) allow one to explain the coordinated behavior of Alice and Bob from a common source.

That said, it may be questioned whether *Wave Function Realism* actually provides the sort of common ground explanation we are seeking.[25] For, even though the coordinated behavior of Alice and Bob is being treated as arising from a common source, that source still seems to have multiple independent degrees of freedom. For what happens with Alice will be grounded in how the wave spreads along three particular dimensions of the $3n$-dimensional configuration space, and what happens with Bob will be grounded in how the wave spreads along three other distinct dimensions of this massively high-dimensional space. But the spread of the wave along Alice's three dimensions looks metaphysically distinct from the spread of the wave along Bob's three dimensions, just as motion along the x-dimension in ordinary three dimensional space looks distinct motion along the y-dimension.

We offer two replies, the first of which is that the spread of the wave along Alice's three dimensions is not metaphysically distinct from the spread of the wave's along Bob's three dimensions, and the analogy with three dimensional motion is misleading, because in configuration space these are *not* independent degrees of freedom after all. There is a global constraint on the shape of the wave function, which is that its squared amplitudes must sum to 1. (Nothing else allows the wave function to play its calculational role with respect to the probabilities of observables. Since the amplitudes are squared to produce probabilities, a wave function whose shape violated this constraint would produce mathematical impossibilities.)

Our second reply is that, in a wave which is actually entangled with respect to its Alicey and Bobby aspects, the spread of the wave along the associated dimensions is also not independent. It is true that there are other waves—those unentangled with respect to the relevant aspects—for which this second point does not hold. But it still holds for the particular wave under discussion.

It might then be rejoined that both of our two points about the wave (the global constraint that its squared amplitudes must sum to 1, and the factual constraint that its Alicey and Bobby aspects are entangled) represent merely contingent happenstance. On this rejoinder the wave still has multiple modally independent degrees of freedom, once both of these "contingencies" are allowed to vary. We are skeptical of treating both of these matters as contingencies, but need not pursue the point further, insofar as our purpose here is merely to exhibit a second fundamental ontology for quantum mechanics consistent with our idea of common ground explanation. For that, *Wave Function Realism* plus the follow-up claim that either of our two points above the wave are real constraints rather than mere contingencies well serve. So augmented, *Wave Function Realism* does provide a common ground explanation in terms of the shape of the wave (and perhaps the position of the world particle as well), in which the ground for Alice and for Bob are truly co-mingled and not even separable as degrees of freedom.

3.3 The rationale for, and the content of, quantum holism (and a relational alternative)

Quantum mechanics is often said to implicate some form of "holism," but both the rationale for, and the content of, "quantum holism" is often highly unclear. We aim to clarify both matters as follows:

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[25] We thank Ned Hall for raising this line of questioning.

> *Quantum Holism, Rationale*: There is interpretive pressure from *Source Inference* and *Quantum Connection* to regard the components of entangled quantum systems as joint manifestations of a common ground.
>
> *Quantum Holism, Content*: *Spacetime State Realism Streamlined* and *Wave Function Realism* provide examples of holistic views of quantum mechanics, which treat the components of entangled quantum systems as joint manifestations of a common ground.

Putting this together: quantum mechanics creates interpretive pressure (via *Source Inference* and *Quantum Connection*) for treating the components of entangled quantum systems as joint manifestations of a common ground (as exhibited by *Spacetime State Realism Streamlined* and *Wave Function Realism*).

It may be worth contrasting our common ground approach with an alternative explanation of quantum nonseparability that is sometimes proposed (and sometimes even dubbed "holistic": Teller 1986; c.f. Healey 1991, Morganti 2009, and Calosi 2014) on which one continues to treat Alice and Bob as distinct entities, but posits an additional fundamental *entanglement relation* alongside the spatiotemporal relations. On this picture the fundamental ontology might include particles like Alice and Bob, their intrinsic properties, and spatiotemporal relations like being a mile apart, as well as (the new addition) entanglement relations like being anti-correlated in *x*-spin.

We do not seek to rule out this alternative, or to co-opt it as holistic. Indeed we regard this as *a plausible alternative* to the sort of quantum holism we recommend. (Those set on avoiding holism may settle for this.) We only want to explain why the kind of interpretive pressure we are concerned with favors a common ground approach over the posit of a new fundamental entanglement relation.

The situation with respect to interpreting quantum mechanics, with entanglement understood via nonseparability, is that we have two modally connected but causally disconnected events. We argue that it is rational to infer a common ground to explain the modal connection (§1). One could posit a new fundamental relation instead, but rationally speaking such a move is *ad hoc*, and sits poorly with *Hume's Inference* (§1.2.3). Positing a new relation is *ad hoc* insofar as there is no independent empirical evidence for any such relations elsewhere in nature (in this respect the posit is as implausible as positing nonlocal causality: §2.2). And positing such a new relation sits poorly with *Hume's Inference* from modal connections to a lack of distinctness (or a brute necessity), since if one could freely posit new fundamental relations, then there would be no call to ever infer a failure of distinctness (or a brute necessity).

Consider our examples of inference to a common ground. When Jenann's friend and Jonathan's friend turn out to have correlated features, one could in principle posit a brute relation of "being döppelgangers" that keeps two people correlated, but in fact it is more plausible to suppose that there is a common friend. Or when pressure, temperature, and volume turn out highly correlated, one could in picture posit a brute correlating relation, but in fact it is much more plausible to infer underlying molecules in motion. Or consider our guiding analogy with inference to a common cause. In the case of causal inference, when the two lights go out at the same time, one could in principle posit a brute "columinescence" relation, but in fact it is far more plausible to suppose that there is a common cause (e.g. a burned out fuse). We are extending this natural reasoning.

(Our quantum holism interacts with *Source Inference* in a further interesting way: it rules that no manifest events whatsoever are distinct. This rules out any causal relations at all in the manifest realm, and so seems to cripple *Causal Inference* in a worrisome way: when the two lamps darken at exactly the same moment, the plausible inference to a common cause such as a burned-out fuse seems blocked by the ruling that the darkenings are indistinct. Have we lost something? Arguably not: arguably there is no fundamental causation, but rather merely a derivative and approximate relation between derivative events that are only approximately distinct. What is owed here is a more detailed story concerning how *Causal Inference* can still be a useful guide—and what it is still a useful guide to—in a world that comes fundamentally as an integrated unity.[26])

3.4 Einstein revisited

We used Einstein's EPR case to illustrate entanglement (§2.1.1), and mentioned that Einstein took the case to support incompleteness (§2.1.2), before the various "no-go" theorems came to light. We conclude by considering why Einstein resisted a holistic picture, for we think that Einstein put his finger on a main source of discomfort (though we also think it is not a major discomfort).

What common ground explanations of quantum entanglement reject is the idea that separation in manifest three-dimensional space entails metaphysical separation. Of the many things that Bohr says in reply to EPR, the following passage (quoted in Einstein 1949: 681) seems to us to get things exactly right:

> If the partial systems *A* and *B* form a total system which is described by its Ψ-function, Ψ_{AB}, there is no reason why any mutually independent existence (state of reality) should be ascribed to the partial systems *A* and *B* viewed separately, *not even if the partial systems are spatially separated from each other at the particular time under consideration.*

That is, the partial systems *A* and *B* are not metaphysically distinct, insofar as both are the joint manifestations of a common ground *AB* (whose complete description is given by Ψ_{AB}). *A* and *B* are mere fragments of the integrated whole *AB*.

By way of reply, Einstein (1949: 682) offers the following principle: "The real states of spatially separated objects are independent of each other." That is:

> *Einstein's Inference*: If non-identical entities *a* and *b* are spatially separated, then *a* and *b* are distinct existences.

Einstein's Inference, if plausible, would seem to offer some countervailing pressure against a common ground explanation for quantum nonseparability. For *Einstein's Inference* recommends the conclusion that *Alice-up* and *Bob-down* are distinct existences and thereby not grounding-connected. They are independent portions of reality. But is *Einstein's Inference* so plausible?[27]

We side with Bohr on the matter: we do not find *Einstein's Inference* compelling. We do not see any empirical grounds for requiring such a connection between spatial separation and metaphysical grounding (indeed we are currently looking at empirical grounds pointing in the opposite direction). And we certainly do not see any conceptual grounds for treating spatial separation and metaphysical grounding as so connected.[28] Einstein himself (quoted in Howard 1997: 121) offers a sort of transcendental argument, based on the idea

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[26] One option would be to treat causal connections pragmatically, as strategic pathways to bringing about ends for creatures that can only intervene on the world at the macroscopic level. The approximate, emergent separability of the world at the macroscopic level would then be enough to support *Causal Inference* as a good principle for such creatures. See (Ismael 2013) for further exploration of this view.

[27] Maudlin (2014: 11–12) says: "Einstein offers two possible ways to reject the conclusion of his argument: accept telepathy or reject the claim that systems spatially separated from one another even have 'independent real situations'. Unfortunately, Einstein never discusses this second option in detail." Maudlin also says that it is obscure what this second option would be, or how it would impact Einstein's argument. We are attempting to clarify exactly this. (Maudlin then supposes that the theory might posit no local beables whatsoever; we are suggesting that the theory may posit no local *fundamental* beables but may still posit local *derivative* beables, and thereby make sense of laboratory experiments.)

[28] Indeed *Einstein's Inference* clashes with many historical philosophical ideas, ranging from Aristotle's idea that the heart and the lungs are both grounded in the common organism, to the classical monistic idea that all separate parts of the cosmos are grounded in the encompassing whole. We are not saying that these ideas are correct, but only that they are in any way conceptually incoherent.

that without separability "physics in the sense familiar to us would not be possible" since we would not have closed systems and so no way to establish "empirically testable laws." We can allow that this may have been a plausible rationale at the time. But one of the crucial things that has since emerged—especially through the work of Zeh and Zurek on *decoherence*—is that nonseparable quantum systems nevertheless typically *approximate* separable closed classical systems very closely. Such approximate separability seems to us fully sufficient for the possibility of physics.

But rather than downplaying *Einstein's Inference* further, we think it may be more interesting to conclude by noting that the issues play out in different ways given the two examples we have provided of holistic views, namely *Spacetime State Realism Streamlined* and *Wave Function Realism*. Given *Spacetime State Realism Streamlined*, what is fundamental is the whole material cosmos. Alice and Bob are spatially separated but not distinct existences, precisely because they are grounded in the whole. So the friend of this view should (for better or worse) reject *Einstein's Inference* outright.

But matters are subtler for the friend of *Wave Function Realism*. For once one distinguishes between manifest three-dimensional space and some more fundamental space (e.g. configuration space) from which manifest space is said to emerge, *Einstein's Inference* becomes ambiguous between the following two principles:

> *Einstein's Inference, Manifest*: If non-identical entities *a* and *b* are separated in manifest 3-dimensional space, then *a* and *b* are distinct existences.
>
> *Einstein's Inference, Fundamental*: If non-identical entities *a* and *b* are separated in the fundamental space, then *a* and *b* are distinct existences.

Einstein's Inference, Manifest is implausible in a setting in which manifest 3-dimensional space is treated as a merely derivative emergent realm. It is only separability in a fundamental realm that might plausibly be connected with metaphysical distinctness.

An elegant feature of *Wave Function Realism* is that the more plausible *Einstein's Inference, Fundamental* may still be upheld. For instance, for the wave function realist, the fundamental image of Alice and Bob (and *Alice-up* and *Bob-down*) are not separated in the fundamental space. Indeed none of the derivative denizens of manifest 3-dimensional space are separated in the fundamental space. Though this option of course requires abandoning anything like:

> *Manifest Principle*: The fundamental space is manifest 3-dimensional space[29]

We don't find this principle compelling either, but for present purposes are only noting that the friend of *Spacetime State Realism Streamlined* can uphold *Manifest Principle* but not *Einstein's Inference*, while the friend of *Wave Function Realism* can uphold *Einstein's Inference, Fundamental* but not *Manifest Principle*. So it is not clear that there is a single form of discomfort that covers quantum holism in its various forms. Rather we suspect that any discomfort comes from a background *atomistic picture* of fundamental entities as little independent bits living in familiar 3-dimensional space. We are saying that quantum mechanics pushes against this picture.

By way of an overall summary, we have attempted to extend the notion of a common cause explanation to that of a common ground explanation, and generalize these to the notion of a common source explanation. We have suggested that an interpretation of quantum mechanics that permits a common source explanation of nonseparability gains some plausibility thereby, and offered multiple examples of such

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[29] For a defense of something more sophisticated but in the vicinity of *Manifest Principle*, based on the idea that a physics which would explain the manifest world needs at least a foothold of "primitive ontology" in manifest space, see (Allori 2013). Though for a development of the alternative picture, based on the idea that the fundamental space plays an individuative role vis-à-vis the fundamental entities, see (Ismael *manuscript-b*).

interpretations. We have not attempted to choose between these interpretations, or even to argue that any of these interpretations is overall plausible, but only to discern an aspect of plausibility they share. In this way we hope to have shed some light on both the rationale for and the meaning of "quantum holism."[30]

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