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A Quantum-Theoretic Argument against Naturalism

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> Das Wirkliche is uns nicht gegeben sondern aufgegeben
> (nach Art eines Rätsel).[1]
>
> —Albert Einstein

A common misunderstanding, one of which we need to disabuse ourselves, is that quantum theory, while possessing astounding predictive power, actually explains the phenomena it describes. It does not. Quantum theory offers mathematical descriptions of measurable phenomena with great facility and accuracy, but it provides absolutely no understanding of why any particular quantum outcome is observed. The concepts of description, prediction, and explanation are conceptually distinct, and we must always keep this fact in mind. Mathematical descriptions, if they are accurate, tell us what mathematical relationships hold among phenomena, but not why they hold. Empirical predictions, if they are correct, tell us what we will or might observe under certain experimental conditions, but not necessarily why these things will happen. It is the province of genuine explanations to tell us how things actually work—that is, why such descriptions hold and why such predictions are true. The failure to appreciate these differences has given rise to a lot of confusion about what the impressive edifice of modern physical theory has, and has not, achieved. Quantum theory is long on the what, both mathematically and observationally, but almost completely silent on the how and the why. What is even more interesting is that, in some sense, this state of affairs seems to be a necessary consequence of the empirical adequacy of quantum descriptions. One of the most noteworthy achievements of quantum theory, I dare suggest, is the accurate prediction of phenomena that, on pain of experimental contradiction, have no physical explanation. This is perhaps a startling way to state the matter, but no less true because of it. It is such phenomena, and arguments concerning their significance, that will occupy us in this chapter.

In view of the challenge it poses to the philosophical hegemony of physical explanation, it is not surprising that quantum theory poses a problem for naturalism. Ontological naturalism, while exhibiting various niceties of definition, centrally maintains that the sum and substance of everything that exists is exhausted by physical objects and processes and whatever is causally dependent upon them. In other words, the philosophical naturalist insists on the causal closure of the material realm. A corollary of this viewpoint is that there is no such being as God or anything remotely resembling him; rather, according to the naturalist, the spatio-temporal universe of our experience, in which we exist as strictly material beings, is causally self-sufficient. The explanatory resources of this naturalistic metaphysical closure are restricted, therefore, to material objects, causes, events, and processes and their causally emergent properties.[2]

Some discussions of the role of naturalism in science have sought to characterize it instead in terms of an attitude rather than a strict adherence to certain metaphysical tenets.[3] This modification comports well with what both Arthur Fine and Bas van Fraassen have been saying for many years, and is the outworking of a distaste for metaphysics in conjunction with differing degrees of deference that both possess toward accepting the deliverances of science in respect of what sorts of things there are, and toward accepting the approximate completeness of scientific explanations.[4] As van Fraassen describes it, though not uncritically, under this conception "the apparent knowledge of what is and what is not material among newly hypothesized entities is mere appearance. The ability to adjust the content of the thesis that all is matter again and again is then explained instead by a knowing-how to retrench which derives from invariant attitudes."[5] As he goes on to note, however, it is common for the materialist to conflate the theory thereby constructed with the attitudes that generated it, thus generating a false consciousness that perhaps accounts for the conviction that science requires a presumptive materialism.[6] But regardless of whether naturalism or materialism or physicalism consist in certain tenets or are comprised by general attitudes combined with a certain know-how (albeit disingenuous) in respect of retrenchment, I want to argue that the phenomena of quantum theory pose an insuperable problem because they show that materialistic tenets, at root, are false, and that attempts at retrenchment are, at best, an exercise in self-deception.

In light of all this, it is interesting to note that both Fine and van Fraassen have chosen to argue that nonlocal quantum correlations do not need an explanation.[7] This would seem to be the only polemical path around the anti-naturalistic metaphysical conclusion quantum phenomena naturally suggest. Nonetheless, given the aversion both have expressed to any kind of metaphysics, albeit in different ways, I suspect the "no explanation needed" strategy may be their way of saying "a pox on both your houses" to materialist and anti-materialist metaphysicians alike. Regardless, I will argue that this is the wrong response, because such phenomena genuinely do require an explanation, and the correct explanation is manifestly anti-materialist. Before I fill in the details, however, let me set forth in broad outline the argument to be made.

1. The Argument in a Nutshell

Among the distinguishing characteristics of quantum phenomena are nonlocality and nonlocalizability. When quantum systems interact, their existence can become "entangled" in such a way that what happens to one of them instantaneously affects all others, no matter how far apart they have separated. Since local effects obey the constraints of special relativity and propagate at speeds less than or equal to that of light, such instantaneous correlations are called nonlocal, and the quantum systems manifesting them are said to exhibit nonlocality. A result in mathematical physics called Bell's theorem—after the Irish physicist who proved it—shows that no hidden (dynamically irrelevant) variables can be added to the description of quantum systems exhibiting nonlocal behavior that would succeed in explaining these instantaneous correlations on the basis of local considerations.

When additional variables are introduced for this purpose, the predictions of the modified theory differ from those of quantum mechanics. A series of experiments beginning with those conducted by Alain Aspect at the University of Paris in the 1980s has demonstrated quite conclusively that quantum theory, not some theory modified by local hidden parameters, generates the correct predictions. The physical world, therefore, is fundamentally nonlocal and permeated with instantaneous connections and correlations. Nonlocalizability is a related phenomenon in relativistic quantum mechanics and quantum field theory in which it is impossible to isolate an unobserved quantum entity, such as an electron, in a bounded region of space. As we shall see, nonlocality and nonlocalizability present intractable problems for the materialist.

The ground has now been laid to summarize an argument showing not only that quantum theory does not support materialism but also that it is incompatible with materialism. The argument can be formulated in terms of the following four premises and conclusion:

P1: Naturalism is the view that the sum and substance of everything that exists is exhausted by physical objects and processes and whatever is causally dependent upon them.

P2: The explanatory resources of naturalism are therefore restricted to material objects, causes, events and processes.

P3: Neither nonlocal quantum correlations nor (in light of nonlocalizability) the nature of the fundamental constituents of material reality can be explained or understood if the explanatory constraints of naturalism are preserved.

P4: These quantum phenomena require an explanation.

C: Therefore, naturalism (materialism, physicalism) is irremediably deficient as a worldview, and consequently should be rejected not just as inadequate, but as fundamentally false.

The first two premises of this argument are uncontroversial: the first is just a definition, and the second is a consequence of this definition. The key premises of the argument are therefore the third and fourth; once these are established, the conclusion follows directly. As we shall see, the failure of material identity/individuality in the quantum realm not only undermines the ontology of naturalism, it also renders necessitarian theories of natural law untenable. This leads to the conclusion that the empirical regularities of quantum theory are mere regularities unsupported by any natural nomological structure. The presence of (near) universal regularities in nature that lack a physical explanation demonstrates the falsity of a purely naturalistic nomology, creating a second insuperable problem for naturalistic metaphysics. Our efforts therefore will be focused on justifying the claims in premises three and four. Some definitions are in order before we begin.

2. A DEFINITIONAL EXCURSUS

2.1 CRITERION OF MATERIAL INDIVIDUALITY (CMI):

> All material individuals I are such that for every property P having a well-defined value or range of values, and all times t during which I may be said to exist, either I exemplifies a definite value (or a definite range of values) of P at t or I does not possess any value of P at t (i.e., I does not possess P at t at all). We include in the scope of such properties attributes like "being at spatiotemporal location (x,y,z,t) in reference frame R."

If this criterion is not met, it would be a mistake to think that we were dealing with a material individual at all, since there is no primitive substantial thisness (material haecceity) in view, no spatiotemporal location in question, and no identity-conferring properties to which we have recourse. In the absence of any individuality, all labels, names, or indices attaching to the purported material entities must be regarded as fictions: no material thing is named if the intended referent has no substantial thisness, no location, and no uniquely identifying properties. If a catchphrase is desired, we could do little better for present purposes than to adopt (*mutatis mutandis*) Quine's dictum: there is no entity without identity.

2.2 INTRINSIC PROPERTIES:

Intrinsic properties (such as mass and charge) are essential properties of particle kinds in quantum physics, with particles of the same kind possessing the same values of their intrinsic properties. These properties are not individuative, however, because they do not serve to uniquely distinguish particles of the same kind.

2.3 STATE-DEPENDENT PROPERTIES:

State-dependent properties (such as position, momentum, energy, and spin-direction) are contingent properties that depend on the quantum state of the particle in question. They are the only candidates for individuative properties of particles of the same kind, but they could only serve this purpose during those times when the particle is not observed if they could be regarded as the objective possession of the particle in and of itself, apart from observation.

2.4 THE PRECISE VALUE PRINCIPLE (PVP):

> Whatever the state of a quantum system or the ensemble containing it, each observable has a precise value for the individual system.

When we briefly consider stochastic hidden variable theories later on, we will relax this assumption so that observables only need to possess an objective dispositional property (propensity) given by a definite probability distribution. Either way, the principle proves quantum-mechanically untenable.

2.5 Common Cause (CC):

Suppose we have two factors, call them A and B, that are statistically correlated in the sense that $P(A|B) \neq P(A)$. If neither A nor B has probability zero, then this is a symmetric relationship that can be expressed by denying their statistical independence, i.e., $P(A\&B) \neq P(A)P(B)$. In such case, factor C functions as a common cause for the correlation between A and B if and only if:

(i) C precedes A and B in time;
(ii) $P(A|C) > P(A|{\sim}C)$ and $P(B|C) > P(B|{\sim}C)$; and
(iii) $P(A\&B|C) = P(A|C)P(B|C)$.

Note that C not only raises the probabilities of A and B but it screens them off from each other, rendering them statistically independent. Note further that specifying that C precedes A and B precludes the possibility of rendering the explanation trivial simply by setting $C = (A\&B)$. As we will note in section 3.2 below, EPR-type correlations cannot be given a local explanation in terms of common causes.

2.6 Spin (intrinsic angular momentum):

In quantum mechanics, spin is the intrinsic angular momentum of a subatomic particle, nucleus, atom, or molecule, which continues to exist even when the particle comes to rest. A particle in a specific energy state may have a particular spin, just as it has a particular electric charge and mass (it may also be in a superposition of spin states). According to quantum theory, the spin is restricted to discrete and indivisible values, specified by a spin quantum number. Because of its spin, a charged particle acts like a small magnet, and is affected by magnetic fields. The direction of the spin of a spin-½ particle is a bivalent property, that is, it can be measured to be in the "up" (+) direction or the "down" (−) direction. We will consider a system of spin-½ particles (in our case, electrons) when we look at the EPR Paradox and Bell's theorems. For a spin-1 system, there are three possible values of the spin: +1, 0, and −1.

3. Local Counterfactual Definiteness and Its Attendant Difficulties

Let's get into the details of why, in principle, there is no physical explanation for quantum correlations. In 1967, Kochen and Specker constructed a geometrical argument using spin-1 systems to show that the Precise Value Principle could not be satisfied. There was a loophole in their result, however, in that it assumed that altering the experimental arrangement by changing the direction in which the spin was measured did not affect the experimental outcome. Closing this loophole requires considering the possibility that the hidden variables governing experimental outcomes might be affected by the experimental context. This can be accomplished by considering a different sort of argument, which originated with John Bell's seminal papers, in which it is assumed that the quantum mechanical observables have definite values independently of measurement, but which values they possess are contextually dependent on the experimental arrangement. Abner Shimony (1984) discusses a nice proof of a no-go theorem for local stochastic (indeterministic) contextual hidden variable theories of the environmental sort, that is, a hidden variable account in which the context is the state of the surrounding physical environment, inclusive of the experimental apparatus, with which the quantum system interacts. I note that such a proof can be given, because for the sake of simplicity of presentation, I'm not going to give it here. Rest assured that, *mutatis mutandis*, the proof I'm going to give could be extended to cover the case of local environmental stochastic hidden variables.

3.1 Wigner's Classification and the Derivation of a Bell Inequality for Local Hidden Variable Theories

We consider an electron spin experiment. Spin measurements in any direction for spin-½ systems can have one of two values, which we will refer to as either "up" (+) or "down" (–). For the purpose of this experiment, electrons are produced in pairs at the source in what is called the "spin-singlet" state. This means that they are linked together in such a way that while the probability of either one of them having a specific spin value, say "up," in a given direction is one-half, if one of them is measured to have spin up in that specific direction, it is known immediately that the other electron has spin down on that axis. No matter what axis of measurement is chosen, the spin values are anti-correlated in this way. Now, we can choose to measure the spin of electron 1 in any direction at station A in the experiment, and to measure the spin of electron 2 in any direction at station B. The values obtained will bear definite probabilistic correlations to each other in the quantum mechanical description.

Given this setup, consider the following argument, based on an assumption of what may be called "local counterfactual definiteness." We begin with two definitions:

Locality (LOC):

All the physical causes of an event lie within the past light cone of that event (have timelike separation from it); i.e., in accordance with special relativity, there is no physically causal influence between events with spacelike separation.

Local Counterfactual Definiteness (LCD):

For each (spin) measurement that could be performed on a quantum system there is a definite value of the measured observable such that, if the (spin) measurement were performed, the result would be that value independent of any other (spin) measurement performed (or not performed) at another location with spacelike separation.

The LCD assumption for state-dependent quantum properties can be used to generate an eightfold particle classification scheme akin to the one used by Eugene Wigner in his derivation of a Bell Inequality.[8]

Suppose we are performing spin-correlation measurements on composite spin-singlet systems (a system in the spin-singlet state has a total spin of zero). Consider three unit vectors $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$, and $\hat{\mathbf{c}}$, which are not, in general, mutually perpendicular. Since we are dealing with spin-singlet systems, a perfect anti-correlation between the particles ensures zero total intrinsic angular momentum. Even though we cannot measure the spin in more than one direction simultaneously, we make the LCD assumption that there is a fact of the matter as to what the measured value (up or down) of the spin would be in any direction we might choose to measure it, and that it would have this definite value independent of any spin measurements performed (or not) at other locations with spacelike separation.

Having made this assumption, it follows that there is a list of types of experimental outcomes, and a fact of the matter as to which type will occur in any measurement that we might make, even if we never make it. For example, a measurement in one wing of the experiment belongs to the type ($\hat{\mathbf{a}}$ +, $\hat{\mathbf{b}}$ –, $\hat{\mathbf{c}}$ +) just in case if we were to measure $\mathbf{S} \bullet \hat{\mathbf{a}}$ (where **S** is the spin operator) we would obtain a spin up (+) outcome, if we were to measure $\mathbf{S} \bullet \hat{\mathbf{b}}$ we would obtain a spin down (–) outcome, and if we were to measure $\mathbf{S} \bullet \hat{\mathbf{c}}$ we would obtain a spin up (+) outcome. Because of the perfect anti-correlation of the spin-singlet state, the measurement in the other wing necessarily belongs to the type ($\hat{\mathbf{a}}$ –, $\hat{\mathbf{b}}$ +, $\hat{\mathbf{c}}$ –). In any given measurement situation, the measurement outcome for the particle pair would therefore belong to one of eight mutually exclusive types. If we represent the populations of each type by $\mathbf{N}_i$, $1 \le i \le 8$, we can catalogue the eight possibilities as in **Table 1**.

If we now suppose that the measurement performed on one particle of the spin-singlet system does not affect a measurement performed on the other particle (for good measure, let them have a spacelike separation), we may reason as follows: suppose that the experimenter at station **A** measures $\mathbf{S} \bullet \hat{\mathbf{a}}$ and discovers the first particle to have spin up (+), and when the experimenter at station **B** measures $\mathbf{S} \bullet \hat{\mathbf{b}}$ he finds it to have spin up (+) also. From **Table 1** we can easily see that the spin singlet pair belongs to either type 3 or type 4, and that the number of particle pairs for which this condition is satisfied is $\mathbf{N}_3 + \mathbf{N}_4$. Since the population in each type is greater than or equal to zero, inequality relations like

$$\text{(1)} \qquad N_3 + N_4 \le (N_2 + N_4) + (N_3 + N_7)$$

must hold. We designate $\mathbf{P}(\hat{\mathbf{a}}+; \hat{\mathbf{b}}+)$ as the probability that in a random trial, observer **A** measures $\mathbf{S} \bullet \hat{\mathbf{a}}$ to be + and observer **B** measures $\mathbf{S} \bullet \hat{\mathbf{b}}$ to be +, and likewise for other paired possibilities. We have straightforwardly that:

$$\text{(2)} \qquad \mathbf{P}(\hat{a}+;\hat{b}+) = \frac{(N_3 + N_4)}{\sum_{i=1}^{8} N_i}.$$

Population	Particle 1 (Station A)	Particle 2 (Station B)
N_1	($\hat{a}$+, $\hat{b}$+, $\hat{c}$+)	($\hat{a}$-, $\hat{b}$-, $\hat{c}$-)
N_2	($\hat{a}$+, $\hat{b}$+, $\hat{c}$-)	($\hat{a}$-, $\hat{b}$-, $\hat{c}$+)
N_3	($\hat{a}$+, $\hat{b}$-, $\hat{c}$+)	($\hat{a}$-, $\hat{b}$+, $\hat{c}$-)
N_4	($\hat{a}$+, $\hat{b}$-, $\hat{c}$-)	($\hat{a}$-, $\hat{b}$+, $\hat{c}$+)
N_5	($\hat{a}$-, $\hat{b}$+, $\hat{c}$+)	($\hat{a}$+, $\hat{b}$-, $\hat{c}$-)
N_6	($\hat{a}$-, $\hat{b}$+, $\hat{c}$-)	($\hat{a}$+, $\hat{b}$-, $\hat{c}$+)
N_7	($\hat{a}$-, $\hat{b}$-, $\hat{c}$+)	($\hat{a}$+, $\hat{b}$+, $\hat{c}$-)
N_8	($\hat{a}$-, $\hat{b}$-, $\hat{c}$-)	($\hat{a}$+, $\hat{b}$+, $\hat{c}$+)

Table 1. Spin Component Matching Under the Assumption of Local Counterfactual Definiteness[9]

Similarly, we obtain that

(3) $$\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{c}}+)=\frac{(\mathbf{N}_2+\mathbf{N}_4)}{\sum_{i=1}^{8}\mathbf{N}_i}\text{ and }\mathbf{P}(\hat{\mathbf{c}}+;\hat{\mathbf{b}}+)=\frac{(\mathbf{N}_3+\mathbf{N}_7)}{\sum_{i=1}^{8}\mathbf{N}_i}.$$

Incorporating **(2)** and **(3)** into the inequality **(1)**, we obtain a Bell Inequality:

(4) $$\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{b}}+)\leq\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{c}}+)+\mathbf{P}(\hat{\mathbf{c}}+;\hat{\mathbf{b}}+).$$

This inequality resulted from two major assumptions: (1) counterfactual definiteness; and (2) the separability of the measurements performed by experimenter **A** and experimenter **B** due to the locality of physical correlations. Taken together, these two conditions constitute **LCD**. What may not be clear is that there are some additional assumptions presupposed by this argument that are hidden from view. Specifically, our reasoning presupposes that every measurement has a result (**EMR**), and that the law of counterfactual conditional excluded middle holds. Counterfactual conditional excluded middle (**CCEM**) is defined as follows:

> It is either the case that if A were true then B would be true, or it is the case that if A were true then *not*-B would be true, that is: (A□→B) ∨ (A□→~B).

We therefore have the following logical relationship:

LCD → EMR & CCEM.

It should be obvious that in order for every measurement that could be performed to have a definite result, we must assume that every measurement has a result (**EMR**). In fact, not every quantum mechanical experiment does have a result, and Arthur Fine exploited this inefficiency loophole to create local models for quantum correlations in which state-dependent properties can have definite values.[10] These so-called "prism models" have the drawback of a somewhat *ad hoc* feel to them, but even more importantly, they require that a certain less-than-perfect level of experimental efficiency not be exceeded. Since the time of Fine's construction of these models, more efficient experiments closing this loophole have been conducted by Mary Rowe and others at NIST.[11] As things now stand, the locality loophole exploiting the possibility of subluminal signals and the detection loophole exploiting experimental inefficiency have both been closed definitively in separate experiments, but never simultaneously in a single experiment. Nonetheless, it is unreasonable to think that a simultaneous test might still yield results disconfirming quantum predictions.

As for assuming the validity of **CCEM**, we can see that this poses no problem in the present context. **CCEM** can be stated symbolically as (A□→B) ∨ (A□→~B). To arrive at the Bell inequalities, we need to use **CCEM** to reason about the Wigner classification as follows: since the eight types of singlet systems are mutually exclusive, counterfactual definiteness necessitates either that if the measurement were performed, then a certain result would be realized, or that if the measurement were performed, that result would not be realized. Now one might worry, as van Fraassen does, that if the counterfactual reasoning we are employing presupposes a form of conditional excluded middle, it is already questionable because of the controversial status of that principle.[12] He urges that we should avail ourselves of a counterfactual logic (like David Lewis's) that does not presuppose conditional excluded middle, thereby doing an end run around questions of counterfactual definiteness and dubious assertions about how facts are related to modality.[13]

Contrary to van Fraassen's hesitancy, however, the employment of **CCEM** in this context is licensed by the fact that one of the things we are testing is whether quantum mechanics is compatible with there being a fact of the matter in respect of the outcome of quantum experiments that have not been performed. The mere assumption that there is a fact of the matter, and hence determinate outcomes that could be known, already entails the truth of **CCEM**. The reason for this is that, under the assumption that there is a fact of the matter to be known, statements having the form of **CCEM** reduce to a disjunction of strict counterfactual conditionals and **CCEM** holds for these. A strict counterfactual conditional is a counterfactual conditional preceded by the necessity operator:

$$\Box(\varphi \Box\!\!\rightarrow \psi).$$

In order to deny **CCEM** under the supposition that there is a fact of the matter about quantum measurement outcomes, we would have to be able to say both (1) that it is not necessarily the case that if we were to perform a spin measurement in a specified direction the result would be spin-up, and (2) that it is not necessarily the case that if we were to perform the measurement in a specified direction it would be spin-down (not spin-up). But assuming that there is a fact of the matter about this situation, and given the bivalent nature of the spin-property, one of these things has to be true! So one of these two denials must necessarily be false and the other necessarily true. If there is a local fact of the matter about quantum events, therefore, the employment of **CCEM** is both uncontroversial and unavoidable.

Before we forget, we've not yet considered quantum mechanical predictions for the measurements performed on this system. Quantum mechanics does not divide the singlet states into certain fractions of particle pairs belonging to specific types; rather it characterizes all singlet spin systems by the same ket:

(5) $$|\,\textbf{spin singlet}\,\rangle = \frac{1}{\sqrt{2}}(|\,\hat{\mathbf{z}}+;\hat{\mathbf{z}}-\rangle - |\,\hat{\mathbf{z}}-;\hat{\mathbf{z}}+\rangle),$$

where the quantization direction has been made explicit, and, e.g., $|\,\hat{\mathbf{z}}+;\hat{\mathbf{z}}-\rangle$ indicates that the first electron is in the spin up state, and the second is in the spin down state.

Using this ket and the rules of quantum mechanics, we can evaluate all three of the terms in **(4)**. Consider $\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{b}}+)$ first. Suppose that observer A measuring at the first station finds $\mathbf{S_1} \bullet \hat{\mathbf{a}}$ to have spin up. Because of the perfect anti-correlation of the singlet state, we know that observer B at the second station will find $\mathbf{S_2} \bullet \hat{\mathbf{a}}$ to have spin-down. To evaluate $\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{b}}+)$ a new quantization axis $\hat{\mathbf{b}}$ which makes an angle θ_{ab} with axis $\hat{\mathbf{a}}$ has to be introduced. The rules of quantum mechanics dictate that when the second particle is known to be in an eigenstate of $\mathbf{S_2} \bullet \hat{\mathbf{a}}$ with negative eigenvalue, the probability that an $\mathbf{S_2} \bullet \hat{\mathbf{b}}$ measurement will yield a positive eigenvalue (spin-up) is:

(6) $$\cos^2\left[\frac{(\pi - \theta_{ab})}{2}\right] = \sin^2\left(\frac{\theta_{ab}}{2}\right).$$

Since the probability of initially observing $\mathbf{S_1} \bullet \hat{\mathbf{a}}$ to have spin up is $\frac{1}{2}$, we obtain that

(7)
$$\mathbf{P}(\hat{\mathbf{a}}+;\hat{\mathbf{b}}+) = \frac{1}{2}\sin^2\left(\frac{\theta_{ab}}{2}\right).$$

This result and its extension to the other two terms in **(4)** lead to our writing the Bell Inequality as:

(8)
$$\sin^2\left(\frac{\theta_{ab}}{2}\right) \leq \sin^2\left(\frac{\theta_{ac}}{2}\right) + \sin^2\left(\frac{\theta_{cb}}{2}\right).$$

This inequality is not always geometrically possible, however. For example, if $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$, and $\hat{\mathbf{c}}$ are all chosen to lie in the same plane, with $\hat{\mathbf{c}}$ bisecting the angle made by $\hat{\mathbf{a}}$ and $\hat{\mathbf{b}}$ so that we can write $\theta_{ab} = 2\theta$, and $\theta_{ac} = \theta_{cb} = \theta$, then **(8)** is violated for $0 \leq \theta \leq \pi/2$. In particular, we find a maximal violation for $\theta = \pi/4$ which gives us the inequality $0.5 \leq 0.292$.

Since the Bell Inequality is violated and its derivation rests on two assumptions—the separability of quantum systems due to the locality of measurement outcomes and counterfactual definiteness—we may infer that at least one and possibly both assumptions fail. If separability/locality actually held, the proper conclusion would be that there is no fact of the matter about what quantum measurements would be apart from their actual occurrence. On the other hand, if counterfactual definiteness held, the facts in question would have to be nonlocal in character, and this would lead us to infer the existence of some sort of nonlocal quantum measurement outcome dependence, whether deterministic or stochastic. In this respect, more needs to be said about deterministic versus stochastic models, faithful measurement, and nonlocality.

As posed, the question of local counterfactual definiteness can be seen to float free of issues related to local deterministic or local indeterministic hidden variables, in fact not even requiring that the correlation be induced by a hidden variable. To see that the proof is independent of the issue of determinism, consider what local determinism entails. If it were applicable, then any two possible worlds (locally) identical in every respect (including all natural regularities) up until the time of measurement would have identical measurement results. But this need not be the case with the assumptions in the situation under examination. All that is required is that (1) there be a measurement result in each of these possible worlds; and (2) there be a fact of the matter as to what the result would be if any of these worlds were actual. Similarly, we need not assume the existence of a local stochastic hidden variable (some sort of propensity or probabilified disposition) that induces the experimental outcome. The proof does not require that there be a fact of the matter regarding objective quantum dispositions prior to a counterfactual measurement, only that there be a counterfactual truth about the outcome if the measurement had been performed. We may further note that when attempts to model quantum correlations locally using hidden variables are made, issues of deterministic versus stochastic models are irrelevant, since Arthur Fine[14] has shown that quantum phenomena have a local stochastic model just in case they have a deterministic one. The proper conclusion, therefore, is that they have neither, since a Bell inequality is generated that certain experimental arrangements violate in each case. Finally, the principle of faithful measurement, which states that the measurement process reveals a value for the measured observable actually possessed by the system prior to being measured, need not hold in this case. It need not hold, first, since it is not necessary to the proof for the system to possess any value of the measured observable prior to measurement. Second, it need not hold because even if the system did possess a value for the observable prior to measurement, it need not be the one revealed by the measurement.

3.2 Local Hidden Variables in Terms of Common Causes

I will not go through the derivation of the Bell Inequality in this case, but if it is assumed that there is a common cause (in the sense of definition 2.5 above) that explains EPR-type correlations in quantum mechanics, then it is again possible to derive Wigner's eightfold classification and thereby a Bell Inequality that is violated by the quantum system.[15] Those interested in this derivation can find it in van Fraassen's book on quantum theory, along with a discussion of the various assumptions (e.g., local determinism) feeding into the proof.[16] The quantum mechanical violation of the Bell Inequalities in this case shows that, if the world is either locally deterministic or locally stochastic, there is no physical cause and hence no naturalistic explanation for the correlations.

4. Nonlocality and Nonlocalizability: The Demise of Physical Causality and Material Objecthood

This leaves us to consider the issues of nonlocality and nonlocalizability. What if we drop the locality constraint and countenance the existence of nonlocal correlations in the experiments that have no local physical explanation, as most physicists and philosophers of science think that we must? In mathematical description, entangled quantum states, such as the spin-singlet system of the EPR experiment just discussed, exhibit nonlocal correlations that prohibit joint probabilities for the outcomes of the components in each pair of measurement events from being factored into individual probabilities. The question that now confronts us is whether such nonlocality defies all attempts at physical explanation. This mandates critical scrutiny of the nonlocal interpretive options of which there are basically two: the deterministic de Broglie-Bohm theory, and the indeterministic relational holist (dynamic emergence) model. We turn to this task now, saving a consideration of nonlocalizability in the context of relativistic quantum theory and algebraic quantum field theory until section 4.4 below.

4.1 Nonlocality and the de Broglie-Bohm Theory

The nonlocal deterministic option is represented by the de Broglie-Bohm or pilot-wave theory. In the non-relativistic case, this approach privileges the position representation and makes use of either a second-order quantum potential or first-order guidance equation controlling the dynamic behavior of structureless point particles.[17] It is generally acknowledged that this approach solves the quantum measurement problem in the non-relativistic case, though I contend (and will argue briefly in the discussion of quantum theory and physical law in section 4.6 below) that even non-relativistic Bohmian mechanics fails to rescue a viable notion of material objecthood[18] and necessitarian (deterministic causal) nomology.

Even more tellingly, pilot-wave theory seems to be fraught with insurmountable technical problems in the relativistic context such as: (1) casting it in a viable Lorentz-invariant form,[19] given the related fact that relativistic pilot-wave bosons can travel at superluminal speeds and reverse their direction in time;[20] (2) the fact that fermionic relativistic pilot-wave theory cannot account for particle-number variability under strong external potential couplings, nor the related existence of anti-matter, which is wedded to negative energy states in standard relativistic quantum mechanics;[21] and (3) the fact that when the pilot-wave approach is extended to field theory, as it must be, the appropriation of fields (however represented) as fundamental "beables" undoes the sole remaining virtue of non-relativistic Bohmian mechanics by rendering the measurement problem unsolvable.[22] So any way you look at it, salvation for philosophical naturalism is not to be found in the de Broglie-Bohm theory; neither, as we shall see, is it to be found in relational holist ontology.

4.2 Nonlocality and Relational Holism (Dynamic Emergence)

The nonlocality of quantum phenomena has served as the basis for metaphysical proposals concerning the "emergence" of the macroscopic from the microscopic realm within the context of a naturalistic metaphysics; such is the case with the treatment of indeterministic nonlocality under what Paul Teller calls "relational holism,"[23] and Fred Kronz and Justin Tiehen call "dynamic emergence." This is the form of emergence or methodological holism that will be our primary concern. Whatever may be said of the descriptive utility of this idea in other contexts, its application to nonlocal quantum phenomena is not just explanatorily vacuous, it also leads to ontological contradictions.

Emergence as limit behavior: descriptively true but metaphysically unhelpful

There is, of course, a useful sense of "emergence" appropriate to quantum physics in which classical (Maxwell-Boltzmann) statistical behavior can be understood to emerge from quantum (bosonic and fermionic) statistics in what physicists call the "classical limit." While these limits are useful in understanding how quantum descriptions can give rise to classical appearances, they are metaphysically unenlightening where relevant, and irrelevant in the case of nonlocal behavior. Let me briefly explain.[24]

With the standard definitions of the Poisson and commutator brackets, the *classical mechanical limit* (CM limit) of a quantum system is defined to be

$$\lim_{\hbar \to 0} \frac{1}{i\hbar}[\hat{A}, \hat{B}] = \{A, B\}.$$

This limit is fictional, of course, because ħ is a physical constant. The limit represents the transition between the quantum and classical *descriptions* of a system; classical behavior "emerges" when quantum effects are dampened to the point of negligibility. It is important to note, however, that there are still residual effects (dependent on Planck's constant) even after the classical mechanical limit is taken and the underlying reality is still quantum-mechanical in character.

Statistical mechanics mathematically relates the thermodynamic properties of macroscopic objects to the motion of their microscopic constituents. Since the microscopic constituents obey quantum dynamics, the correct description must lie in principle within the domain of quantum statistical mechanics. Under thermodynamic conditions of high temperature (T) and low density (n), however, classical statistical mechanics serves as a useful approximation. With this in mind, the *classical statistical limit* (CS limit) may be defined as the situation represented by:

$$T \to \infty \text{ and } n \to 0.$$

These are the same conditions as those governing the applicability of the ideal gas law ($pV = nRT$), so the CS limit could equally well be called the ideal gas limit. Unlike the CM limit, the conditions governing the CS limit are subject to experimental control. In respect of quantum statistical behavior, both the CM and the CS limits are continuous, so the quantum indistinguishability arising from permutation symmetry is not removed, even though it is dampened in the limit. Quantum "particles" retain their indistinguishability even when their aggregate behavior can be approximated by a Maxwell-Boltzmann distribution.

These reflections lay the ground for understanding why any emergentist account of the dependence or supervenience of the macroscopic realm on the the microscopic realm, while perhaps descriptively interesting, will be unenlightening as a metaphysical explanation. It is environmental decoherence (essentially, statistical damping through wave-function orthogonalization) that gives quantum-mechanical ephemera a cloak of macroscopic stability, but decoherence is not a real solution to the measurement problem. The apparent solidity of the world of our experience is a mere epiphenomenon of quantum statistics; the underlying phenomena retain their quantum-theoretic essence while sustaining classical appearances.

Emergence and Supervenience

The essence of emergentism is a layered view of nature. The world is divided into ontological strata beginning with fundamental physics and ascending through chemistry, biology, neuropsychology, and sociology. The levels correspond to successive organizational complexities of matter, and at each successive level there is a special science dealing with the complex structures possessing the distinguishing causal characteristics of that level. Higher-level causal patterns necessarily supervene on (are dependent upon) lower-level causal interactions, but are not reducible to them. The picture, then, is of emergent nomological structures irreducible to lower-level laws, with emergent features that not only affect the level at which they appear, but also exercise "downward causation" on lower-level phenomena.

Moving beyond hand-waving declarations of the "lawful" character of emergence requires giving an account of the relationship between basal physical conditions and emergent properties. McLaughlin and Kim have both attempted articulations of emergence in terms of what O'Connor and Wong term "synchronic strong supervenience":[25] given basal conditions C at time t, an emergent property P strongly supervening on conditions C will appear at time t. McLaughlin defines such emergent properties in terms of strong supervenience as follows:

> If P is a property of w, then P is emergent if and only if (1) P supervenes with nomological necessity, but not with logical necessity, on properties the parts of w have taken separately or in other combinations; and (2) some of the supervenience principles linking properties of the parts of w with w's having P are fundamental laws.[26]

McLaughlin defines a fundamental law as one that is not metaphysically necessitated by any other laws, even together with initial conditions. While Kim also understands emergence as a form of strong synchronic supervenience,[27] it is important to note that he regards emergent properties as epiphenomenal and challenges the tenability of non-reductive physicalism on this basis (he is a physical reductionist). These arguments need not concern us here but have received responses from Loewer and Shoemaker.[28] The property-fusion account of emergence developed by Humphreys circumvents Kim's objections because it is not synchronic and because emergent properties are fusions of the basal properties, which then cease to exist.[29]

The supervenience account of emergence will not suffice in the quantum context for two reasons. The first is that nonlocal phenomena quite evidently do not supervene on the properties of the various subsystems taken separately or in other combinations (the relevant joint probabilities are not factorizable), so supervenience is the wrong conception to be using here. The second is that any viable account of nomological necessity in the quantum realm would have to connect objective properties of the system immediately prior to measurement with the measurement results obtained. We have seen that such a restriction leads to empirically false consequences for both local deterministic and local stochastic models, and have remarked that, quite apart from the insurmountable technical obstacles confronting the necessary extension of de Broglie-Bohm theory to the relativistic context, the structureless point particles of nonrelativistic Bohmian mechanics are incapable of supporting a sufficiently robust conception of material objecthood to ground necessitarian nomology. As we shall see momentarily, however, a non-supervenient description of quantum emergence suffers from a sort of explanatory vacuity, and it also founders on ontological contradictions arising from the postulation of nonlocal wholes (unless there is a privileged reference frame).

Property Fusion as an Account of Emergent Ontological Hierarchies

Paul Humphreys[30] has developed a concept of emergence in terms of "property fusion" that he suggests can be used to describe entangled states in quantum theory. His account assumes the existence of a hierarchy of distinct ontological levels, which he expresses in the form of a "level-assumption**"** **(L)**:

> **(L)** There is a hierarchy of levels of properties, $L_0, L_1, \ldots, L_n, \ldots$ of which at least one distinct level is associated with the subject matter of each special science, and L_j cannot be reduced to L_i for any $i < j$.

A property P^i is then defined to be an "i-level property" just in case i is the lowest level at which instances of the property occur. A set of properties $\{P_1^i, P_2^i, \ldots, P_m^i, \ldots\}$ is associated with each level i, where P_m^i denotes the m^{th} property at the i-level. A parallel hierarchy of entities is postulated: x^i is an i-level entity just in case i is the *lowest* level at which it exists and x_m^i denotes the m^{th} entity at the i-level.

In order to characterize the property-fusion operation, Humphreys uses the notation $P_m^i(x_r^i)(t)$, which denotes an instantiation of property P_m^i by entity x_r^i at time t, because he regards property instances as being more fundamental than properties. We will suppress references to specific individuals and times to simplify the notation. The fusion operation [.*.] is defined by Humphreys as a process that combines two i-level properties P_m^i and P_n^i to form an $(i+1)$-level property $[P_m^i * P_n^i]$; this fusion could equally well be represented by the notation $P_{m,n}^{i+1}$. Once the basal properties have fused in this manner, they cease to exist and the new emergent property is all that remains.

Humphreys argues that entangled (or nonseparable) states in quantum mechanics lend themselves to description in terms of property fusion, maintaining that the emergent entangled state will remain intact so long as nonseparability persists. He thinks that this can be the case even after the interaction ceases, whereas Kronz and Tiehen (2002) adopt Humphreys's conception of property fusion but argue that persistence of the interaction is necessary for continued emergence. The arguments for this difference need not concern us. The more pressing concern is whether this technical account of emergence is explanatorily useful and metaphysically tenable in relation to nonlocal phenomena.

The Kronz-Tiehen Taxonomy for Quantum Mereology

On the basis of their discussion of fusion in the context of quantum chemistry, Kronz and Tiehen suggest that there are at least three ways that philosophers could develop a metaphysical account of emergence in mereological terms; they advocate the last of the three.[31] Since it is instructive to do so, we will briefly consider all three options.

Before examining these accounts, however, we need definitions of two background ideas employed by Kronz and Tiehen: independent characterizations of entities and contemporaneous parts. A characterization of an entity is an exhaustive list of the properties that are instantiated by that entity, and this characterization is said to be independent just in case the elements on the list of its properties make no essential reference to some other entity. Second, an entity is said to be a contemporaneous part of some whole just in case that part exists while the whole does (in relativistic contexts, Kronz and Tiehen make this relation reference-frame dependent in order to preserve standard interpretations of Lorentz invariance in terms of the relativity of simultaneity). So armed, they define three conceptions of emergence:

Prototypical Emergence

The idea here is that every whole consists of contemporaneous parts that have independent characterizations, but there is some criterion for distinguishing between part-whole relationships that are emergent from those which are merely resultant. The British emergentists take this line and use additivity as the relevant characterization of a resultant as opposed to an emergent property.[32] The difficulty with this view is that it seems to trivialize the notion of emergence when quantum mechanics is brought into view, either rendering every part of the universe emergent because it is entangled through past interactions with everything else in the universe, or nothing emergent, because the universe is an undivided whole that has no parts with independent characterizations. A proper interpretation of quantum theory would seem to require grasping the second horn of this dilemma.

Radical Emergence

The idea behind radical emergence is that only resultant wholes have contemporaneous parts, emergent wholes do not. Kronz and Tiehen interpret this as Humphreys's view. Emergent wholes are produced by a fusion of entities that can be likened to parts, but these parts cease to exist upon fusion, only existing when the whole does not, and vice-versa. An example of this sort of thing presumably would be a nonseparable quantum state. Prior to interaction, quantum "particles" might be taken to have independent existence, but after they interact and their wave-functions become entangled, they cease to exist as "parts," and a new entity at the next level in the ontological hierarchy comes into being. Again, it is hard to see on this view why there is not only one quantum entity: the universe itself.

Dynamic Emergence (Relational Holism)

Kronz and Tiehen proclaim themselves advocates of what they call "dynamic emergence," which seems to me a reinvention of Paul Teller's idea of relational holism. Teller defines a relationally holistic property as one in which the relevant property of the whole does not supervene on the non-relational properties of the relata,[33] as, for example, the tallness of Wilt Chamberlain relative to Mickey Rooney supervenes on the nonrelational height of each. In Kronz and Tiehen's reformulation, emergent wholes have contemporaneous parts, but these parts cannot be characterized independently of their respective wholes. These wholes are produced by an essential, ongoing interaction of their parts. Ultimately, of course, quantum theory is going to imply that every contemporaneous part of the universe, at least in its "material" respects, cannot in the final analysis be characterized independently of the whole universe, though for all practical purposes we can often treat subsystems of the universe as proximately independent.

Relational holism and quantum nonlocality: a very holey story

Granted that relational holism (to use Teller's term) seems the most reasonable description of quantum ontology, what more can be said? As Kronz and Tiehen have noted, speaking of contemporaneous parts for nonlocal wholes requires, in view of the relativity of simultaneity, a relativization of contemporaneousness to reference-frames. Though they do not discuss how this is to be done, the most plausible candidate is Gordon Fleming's theory of hyperplane dependence,[34] in which judgments of simultaneity are relativized to hyperplanes constituted by three-dimensional temporal slices of space-time; this is the solution appropriated by Teller.[35] The difficulty here is that the properties of a nonlocal quantum system can be different depending on which hyperplane is in view. In some hyperplanes, for example, the wave-function of the system may have collapsed, while in others this will not yet have happened. But there are an infinite number of such hyperplanes, some of which intersect, and it will be the case at the point of intersection that ontologically inconsistent properties are attributed to the quantum system—for example, that it has both collapsed and not collapsed. I take this situation to be suggestive of two things. Read one way, it could be a harbinger of the nonlocalizability of so-called particles, pointing to the fact that particle ontologies are not ultimately tenable because the relata don't have intrinsic states: that is, they don't really exist. This reading could be mitigated by the existence of an undetectable privileged reference frame, but as we will see in section 4.4 below, the nonlocalizability of unobserved "particles" still holds if the assumption that there is no privileged reference frame is dropped, so the conclusion that particle ontologies are untenable is secure. Taken another way, the ontological contradiction to which hyperplane dependence gives rise suggests the metaphysical necessity of an undetectable privileged reference frame that resolves the issue. A metaphysician committed to presentism rather than eternalism is forced to this position regardless, but there are indicators on the frontiers of research in quantum gravity that at least some of the physics community may also be moving this way in the effort to reconcile quantum field theory with general relativity.

As a characterization of quantum nonlocality, however, while relational holism or dynamic emergence may be descriptively accurate and revelatory of the challenge to ontological interpretation that quantum theory poses, it is explanatorily vacuous. One might protest that the "individual" described by quantum theory must ultimately be the quantum system itself, with its Hilbert Space of states, with the ontological difference between particle and field a mere matter of representation for a selected set of states, all of which are allowed and used by quantum field theory. But this remark will not suffice to deflate the pressing question of ontology (see section 4.3 below), nor will it obviate the fact of systematic, predictable correlation without causation: instantaneous adjustment of nonlocal relational wholes to local systemic changes, whether called "emergence" or some other term of art, remains a flagrant violation of relativistic causality that lacks a physical explanation and is present, if anything, to an even greater extent in quantum field theory than quantum mechanics.[36] Invoking "emergence" in such contexts seems little more than a terminological gambit to obscure things for which no adequate physical explanation currently exists and which arguably will not yield to the kind of explanation being sought. Furthermore, while it pays lip service to a variety of ontological levels, emergentist metaphysics, at least as we have considered it in this section, is still a species of philosophical naturalism, since it only recognizes physical properties and things that are ontologically dependent on them. Its explanatory vacuity further reinforces the untenability of ontological naturalism as a metaphysical stance.

4.3 To Be or Not To Be . . . Maybe: The Myth of Ontological Deflation

Before we move on, we need to countenance an objection based on the mathematical "equivalence" of first-quantized particle theories and second-quantized (Fock Space) field theories, since this has figured in discussions of the ontological significance of quantum statistics. In particular, Van Fraassen has suggested that the moral of this equivalence is that the whole issue of ontological interpretation can be dispensed with, because non-relativistic quantum field theory can be given either a particle interpretation or a particleless interpretation; the choice of ontology here is thus a matter of convention, not metaphysics.[37] I have dealt with this misrepresentation more thoroughly elsewhere,[38] but let me handle the matter expeditiously by making two points, one about the residual inequivalence underlying this supposed "equivalence," and the other regarding the untenability of "indexed particle" quantum field theory, since it has been proffered as evidence for the conventionality of ontology.

Are First and Second Quantized Theories Equivalent?

First and second quantized theories are equivalent only in the sense that the solution of the (second quantized) Fock Space Schrödinger equation

(9) $$[i\hbar(\partial/\partial t) - \mathrm{H}]|\Psi_n\rangle = 0$$

can be put in the form

(10) $$|\Psi_n\rangle = (n!)^{-1/2}\int d^3x_1 \ldots \int d^3x_n \psi^\dagger(\mathbf{x}_n)\ldots\psi^\dagger(\mathbf{x}_1)|0\rangle \times \Psi_n(\mathbf{x}_1,\ldots,\mathbf{x}_n),$$

with the n-particle wavefunctions satisfying the many-particle Schrödinger equation

(11) $$[i\hbar(\partial/\partial t) - H_n]\Psi_n(\mathbf{x}_1,\ldots,\mathbf{x}_n) = 0.$$

But they are inequivalent in the important sense that *not every solution has this form*, rather just ones that that are simultaneous eigenstates of the total number operator N defined by

$$N \equiv \int d^3x \psi^\dagger(\mathbf{x}) \psi(\mathbf{x}). \tag{12}$$

In this respect the Fock Space formalism is more general than that of many particle quantum mechanics, because it includes states that are superpositions of particle number, whereas many-particle quantum mechanics obviously does not. On the other hand, not all solutions of the wave equation **(11)** have the form

$$\Psi_n(\mathbf{x}_1, \ldots, \mathbf{x}_n) = (n!)^{-\frac{1}{2}} \langle\, 0 \mid \psi(\mathbf{x}_1), \ldots, \psi(\mathbf{x}_n) \mid \Psi_n \,\rangle, \tag{13}$$

with $|\Psi_n\rangle$ satifying the Fock Space equation **(9)**. The only ones that do are those satisfying the symmetry condition:

$$\Psi_n(\mathbf{x}_1, \ldots, \mathbf{x}_n) = \pm\, \Psi_n(\mathbf{x}_1, \ldots, \mathbf{x}_{i-1}, \mathbf{x}_n, \mathbf{x}_{i+1}, \ldots, \mathbf{x}_{n-1}, \mathbf{x}_i).$$

Thus, in this regard, the wave equation is more general than the Fock Space equation because it includes the case of *n* non-identical particles by allowing for unsymmetrized wave-functions. *So the representations are equivalent only for Fock Space states that are eigenstates of N, and only for wave-functions that are either symmetric or antisymmetric.*

It is also instructive to note that total particle number is conserved in every system having the Fock Space Hamiltonian Operator H in **(9)**, because in this case the total number operator commutes with the Hamiltonian, i.e., $[N,\mathrm{H}] = 0$. But not all Hamiltonians commute with the total number operator. In quantum field theory it is possible to have a situation when two or more fields are interacting and the interaction term does not commute with the number operator for one of the fields. This highlights another aspect of the difference between non-relativistic quantum field theory and many-particle quantum mechanics. The "equivalence" between the two representations is therefore anything but complete, and it certainly does not bear the weight of the ontological deflation that van Fraassen places on it. Many-particle quantum mechanics predicts the existence of nonsymmetric states, whereas Fock Space does not. This shows not only that the two representations are logically inequivalent, but also that the first quantized formalism is empirically deficient because the nonsymmetric states it predicts do not exist. Furthermore, if the two representations were equivalent in the sense required for ontological deflation, the Fock Space representation would need to have an empirically adequate indexed particle model, and as we shall see, it does not.

"Indexed Particle" Quantum Field Theory?

Since van Fraassen's attempted ontological deflation also relies on Willem de Muynck's construction of an "indexed particle" version of Fock Space, we need to make a brief excursion into this topic as well. De Muynck begins his discussion with the well-worn distinction, due to Jauch,[39] between the intrinsic and extrinsic properties of quanta. We alluded to this distinction earlier: intrinsic properties are defined as those independent of the state of the quantum system, whereas extrinsic properties are those dependent on the state of the system. Quanta are "identical" when they have all of the same intrinsic properties. De Muynck's suggestion is that labels (indices) might be regarded as intrinsic properties of quanta, because they are independent of the state of the system, i.e., not supposed to have dynamical consequences. This proposal motivates the attempt to construct an indexed quantum field theory that allows for the conceptual distinguishability of individual quanta despite their observational indistinguishability.

The central problem that de Muynck confronts in the context of non-relativistic quantum fields is the construction of a formalism permitting the creation and annihilation of indexed quanta. He takes as his starting point the Fock Space description of non-indexed quanta and the "equivalence" to many-particle quantum mechanics that we discussed in the last section. An indexed theory cannot get by with a single field operator, however. Rather, if all of the quanta are indexed, a different field operator $\psi_i(x)$ has to be associated with *each* quantum. The vacuum state $|0\rangle$ in this context is the direct product of the vacuum states $|0_i\rangle$ of all of the quanta in the system (indexed by $i \in \mathrm{I}$), and defined as is customary by

(14) $$\psi_i(x) \mid 0 \rangle, \qquad \text{for all } i \in \mathrm{I}.$$

By analogy with **(10)**, the state vector corresponding to a system of n quanta with different indices and wavefunction Ψ_n $(\mathrm{x}_1, \ldots \mathrm{x}_\mathrm{n})$ is defined by

(15) $$\mid \Psi_{1,\ldots,n} \rangle = \int dx_1 \ldots \int dx_n \Psi_n(\mathbf{x}_1, \ldots, \mathbf{x}_n) \psi_n^\dagger(\mathrm{x}_n) \cdots \psi_1^\dagger(\mathbf{x}_1) \mid 0 \rangle,$$

where (cf. **(13)**) the wave-function is related to the state vector by

(16) $$\Psi(\mathbf{x}_1, \ldots, \mathbf{x}_n) = \langle 0 \mid \psi_1(\mathbf{x}_1) \cdots \psi_n(\mathbf{x}_n) \mid \Psi_{1,\ldots,n} \rangle .$$

De Muynck then goes on to impose as restrictions on the individual field operators only those relations which are equally valid for both bosons and fermions, deriving a number of results that are independent of the "statistics" of the quanta and therefore hold for uncorrelated quanta as well. With no symmetry requirements imposed on **(15)** and **(16)**, what we get isn't ultimately that interesting because it is not an indexed version of Fock Space yielding quantum statistics, but rather a theory with no application. If symmetry considerations are introduced, the indexed theory will have to be permutation invariant in the requisite sense if it is going to produce the same results as non-relativistic quantum field theory. De Muynck protests that the idea of permuting quanta requires an interaction in order to make physical sense, and suggests that an indexed theory creates a new possibility—an interaction that exchanges just the quantal indices.[40] From a *de re* perspective, where the indices are intended to be rigid designators for the quanta in question, the idea of index swapping is a metaphysical impossibility. De Muynck seems to recognize as much, since he remarks:

> [W]hen index exchanging interactions are present it is no longer possible to use this index for distinguishing purposes. As a matter of fact precisely the presence of this kind of interaction would give the index the status of a dynamical variable. So a theory of distinguishable particles is possible only when the interactions are index preserving.[41]

In short, if the indexed theory were capable of reproducing the experimental predictions of Fock Space, the indices would have no *de re* significance.

Be this as it may, de Muynck's purpose is to develop an indexed theory as far as he can, and he pushes on to present a theory of indexed boson operators.[42] Presenting the technical details in full is not relevant for our purposes. Suffice it to say that de Muynck succeeds in developing a formalism involving annihilation and creation operators for indexed bosons, reproducing to a limited degree the correlations of symmetric bosonic statistics. These operators are not, however, simply interpretable as creating or destroying a particle with a given index in a single particle state, because the single particle states have a restricted meaning in light of the quantum correlations. For example, although the indexed creation operator adds a quantum with a specific index and single-particle state to the initial state of the system, due to (potentially nonlocal) interaction correlations, the quantum may be in a different single-particle state at the end of its interaction with the system.[43] The indexed annihilation and creation operators also have the undesirable property of being defined outside the Fock Space of symmetric states, where they have no physical meaning.[44] Furthermore, the dynamical description of a system of indexed bosons using the indexed annihilation and creation operators diverges from the Fock Space description in significant ways, not least of which the Hamiltonian sometimes has a different energy.[45] Also, in the indexed theory, the order in which particles are created or annihilated is dynamically relevant, but this is not the case in Fock Space. For this reason, the probability amplitudes associated with the indexed and non-indexed theories are different when the initial and final states are coherent superpositions of states with different numbers of particles.[46]

What we see, then, is that an indexed theory is not capable of reproducing the experimental predictions of the Fock Space description, and to the extent that it is empirically feasible, the quantal indices have no *de re* significance, i.e., they are fictions. This, along with the realization that the indexed theory of "bosons" that de Muynck develops retains the nonlocal correlations and quantal nonlocalizability characteristic of the standard formalism, confirms that quantal individuality cannot gain a foothold in the context of non-relativistic quantum fields by way of an empirically deficient theory of indexed quanta.

4.4 Nonlocalizability and Algebraic Quantum Field Theory

Let's focus on the nature of material individuality. In order for a particle to be a material individual it must possess one or more well-defined and uniquely identifying properties. A prime candidate for such a property is spatiotemporal location. In order for a material simple to exist as an individual material object, it must uniquely occupy a certain volume of space at a certain time.[47] If it does not, then whatever it is—if it's anything at all—the manner of its existence is not as a material object. The problem with this (apart from the superposition principle in quantum theory) is that the particles of relativistic quantum mechanics are not so localizable, nor do Newton-Wigner position operators in relativistic quantum field theory either localize quanta or behave so as to eliminate nonlocal correlations at spacelike separations. We can demonstrate these claims, respectively, through the consideration of Hegerfeldt nonlocalizability in relativistic quantum mechanics and the consequences of the Reeh-Schlieder theorem in algebraic quantum field theory.

The impossibility of particle interpretations of QFT

Hegerfeldt and Malament have shown that subject to the relativistic constraints that (1) a particle cannot be two places at once and that (2) the operators representing observables associated with disjoint spatial sets that have spacelike separation must commute, if one also makes the physically realistic assumption that (3) an individual particle cannot serve as an infinite source of energy, then it can be shown that such a particle has zero probability of being found in any bounded spatial region, no matter how large: measurements cannot be localized in principle.[48] In short, the supposed "particle" doesn't exist anywhere in space, and therefore, to be honest, it doesn't really exist at all. Halvorson and Clifton have extended this proof and closed some loopholes by showing that the Hegerfeldt-Malament result still holds if the assumption that there is no preferred reference frame is dropped, and if the assumption of sharply localized particles is dropped.[49] They have also shown that the necessary conditions for a particle interpretation of localized field observables cannot be satisfied in relativistic quantum field theory. In short, once relativity is taken into account, there can be no intelligible notion of microscopic material objects. Particle talk has a pragmatic utility in relation to macroscopic appearances, but it has no basis in microphysical reality.

Algebraic Quantum Field Theory (AQFT)

The realization that particle talk has no basis in microphysical reality is strengthened by a consideration of algebraic quantum field theory. AQFT originated with the efforts of Rudolf Haag in the 1960s, building on the work in axiomatic quantum field theory begun by Arthur Wightman in the late 1950s. It grows out of two convictions: that the algebraic structure of the set of quantum-theoretic observables should be given priority, and that field values must be localized in a way that makes sense from an operational perspective. What algebraic QFT does is to single out sets of axioms that apply quite generally to quantum field models that are "physically reasonable," and then use these postulates as the basis for a extended structural explorations.[50]

In the usual Hilbert Space formulation of quantum mechanics, observables are represented by self-adjoint (Hermitian) operators on Hilbert Space, and quantum states are represented by one-dimensional subspaces of Hilbert Space. Because of the priority given to algebraic structure, AQFT sets the background Hilbert Space to one side and focuses on the operator algebra associated with the observables instead.

To get the basic idea here, we need some background definitions. Let $\mathcal{B}(\mathcal{H})$ be the set of all bounded linear operators on $\mathcal{H}$ and let $A \subset \mathcal{B}(\mathcal{H})$. If $A,B \in \mathcal{A}$ and $\alpha,\beta \in \mathbf{C}$, then $\mathcal{A}$ is called an *algebra* just in case $\alpha A + \beta B \in \mathcal{A}$ and $AB \in \mathcal{A}$. Furthermore, if for every operator $A \in \mathcal{A}$, its adjoint $A^* \in \mathcal{A}$, then $\mathcal{A}$ is called a **-algebra*. In general, the operator algebras of observables in AQFT are *-algebras. We now need the following definition: a *linear form* ω over $\mathcal{A}$ is a mapping $\omega\colon \mathcal{A} \rightarrow \mathbf{C}$ with $\omega(\alpha A + \beta B) = \alpha\omega(A) + \beta\omega(B)$. This linear form is called *real* just in case $\omega(A^*) = \overline{\omega}(A)$, where the bar denotes the complex conjugate; it is called *positive* just in case $\omega(A^*A) \geq 0$; and it is called *normalized* just in case $\|\omega\| = 1$. The physical states of AQFT can now be identified with all the normalized positive linear forms ω over $\mathcal{A}$. It can then be shown that each ω defines a Hilbert Space $\mathcal{H}_\omega$ and a representation π_ω of $\mathcal{A}$ by linear operators acting on $\mathcal{H}_\omega$; this is known as the Gelfand-Naimark-Segal (GNS) construction, and it allows one to obtain the Hilbert Space representation from a given *-algebra. From a mathematical standpoint, then, the canonical and the algebraic approaches to QFT are obtainable from each other, and in this loose sense, equivalent. From a physical standpoint, however, the algebraic approach, by taking the *observables* as primitives, seems more directly relevant to the task of empirical and ontological interpretation.

We now need to consider the concept of locality embodied in AQFT. It would be nice if a field value $\psi(\mathbf{x})$ could be assigned to any spacetime point $\mathbf{x}$, but this is not realistic from an operational standpoint because it's always the case that we only have access to some finite spatiotemporal region $\mathcal{O}$. The approach taken in AQFT, therefore, is to use some smooth test function *f* of compact support (that is, it vanishes outside of $\mathcal{O}$) which spreads the field thereby localized over a corresponding space. The collection of all such smeared fields generates an algebra $\mathcal{A}(\mathcal{O})$, thus replacing $\mathbf{x} \rightarrow \psi(\mathbf{x})$ with the alternate correspondence $\mathcal{O} \rightarrow \mathcal{A}(\mathcal{O})$. Another definition is needed at this point: a *-algebra that is closed (contains all the limits of uniformly converging Cauchy sequences) in the topology (neighborhood) induced by the operator norm

$$\| \mathrm{A} \| = \sup_{\Psi \in H} [\| \mathrm{A}\Psi \| / \| \Psi \|],$$

and where the involution * and the norm $\|\cdot\|$ are related by $\| \mathrm{A} * \mathrm{A} \| = \| \mathrm{A}^2 \|$ is called a *C*-algebra*. Provided suitable physical conditions obtain, the algebra $\mathcal{A}(\mathcal{O})$ may be treated as the C*-algebra of all bounded operators associated with $\mathcal{O}$, so the notion of locality embodied in AQFT is that of local operators representing observables in some finite spatiotemporal region $\mathcal{O}$.

Let's expand on this idea a bit. In the formalism of AQFT, the totality of spacetime can be covered by a net of local algebras

(17) $$\mathcal{A}_{loc} = \cup_{\mathcal{O}} \mathcal{A}(\mathcal{O})$$

that obeys the isotony condition $\mathcal{A}(\mathcal{O}_2) \supset \mathcal{A}(\mathcal{O}_1)$ if $\mathcal{O}_2 \supset \mathcal{O}_1$. This means that the total algebra of all observables is the union taken over all bounded regions. The notion of local operators in AQFT is in conformity with microcausality, namely the restriction that no physical effect can propagate faster than light, and expressed by the condition:

(18) $[\mathrm{A}_1, \mathrm{A}_2] = 0$ if $\mathrm{A}_i \in \mathcal{A}_{loc}(\mathcal{O}_i)$ for $i = 1, 2$, and $\mathcal{O}_1$ and $\mathcal{O}_2$ are *spacelike* separated.

This limns the elementary mathematical structure of AQFT. One extremely important result in AQFT is the *Reeh-Schlieder theorem*, which states, roughly speaking, that any state can be created from the vacuum. It is here that all of the familiar quantum nonlocalities reassert themselves, despite AQFT's strenuous attempt to enforce locality. Nonetheless, the abstract approach taken by AQFT allows a wide variety of formal proofs that have interesting ontological implications, as well as providing a tool that has proven very useful in statistical mechanics.

AQFT: Reeh-Schlieder trumps Newton-Wigner

For spacelike separations, relativistic causality demands that physical effects respect the speed of light as the limiting propagation velocity, which means that all field operators with spacelike separation must commute. This is known as the *microcausality* requirement. But problems arise when we try to construct the requisite Lorentz invariant theory of localized quanta. Mathematically, what a localization scheme does is define a correspondence between real linear subspaces of a one-particle Hilbert Space (which are associated with operators representing observables) and regions in physical space. In the standard localization scheme it can be shown that perfectly localized eigenstates of the local number operator do not exist because the local number operators associated with two arbitrary volumes, overlapping or not, do not commute.

But this microcausality misdemeanor is small in comparison to the implications of the Reeh-Schlieder theorem, which entails that local operations applied to the vacuum state can produce any state of the entire field, a flagrant violation of microcausality. Much as Newton-

Wigner states in the heuristic formulation of quantum field theory were introduced in an attempt to construct states of perfect localization for a Lorentz invariant theory, Irving Segal and quite recently Gordon Fleming have suggested an alternative "Newton-Wigner" localization scheme in algebraic quantum field theory that aims to avoid the Reeh-Schlieder theorem by reworking the correspondence between spatial regions and subalgebras of observables.[51] For the free Klein-Gordon (bosonic) field in the heuristic formulation, it has been shown that the Newton-Wigner localization is the best that can be done under the condition of Lorentz invariance, in the sense that any other position localization scheme would be even more badly behaved. In respect of Segal's and Fleming's efforts in algebraic quantum field theory, however, Hans Halvorson has shown that their alternative localization scheme only avoids the Reeh-Schlieder theorem in a trivial sense.[52] In particular, it remains the case that "NW-local fields allow the possibility of arbitrary spacelike distant effects from actions localized in an arbitrarily small region of space over an arbitrarily short period of time" rather than instantaneously, so it is still the case that "NW-local operators fail to commute at spacelike separation."[53]

The significance of all this, of course, is that "NW-local" position operators are not, in fact, localized, and when microcausality is egregiously violated in this fashion, nonlocal phenomena that have no physical explanation are manifested. Since the Newton-Wigner scheme is the best that can be done, the proper conclusion is that relativistic quantum field theory describes natural phenomena for which we have no physical explanation. More specifically, there are measurement-outcome correlations in nature that require a causal explanation but for which no physical explanation is in principle possible, and the nonlocalizability of field quanta entails that they fail the criterion of material individuality. So the most fundamental constituents of the so called "material world" are not material substances, and, as we have seen, their mereological fusion through environmental decoherence does not generate—and hence does not explain—macroscopic material *substances*, only macroscopic material *appearances*.

One might be inclined to wonder whether a field ontology could substitute for a particle ontology at this juncture and rescue philosophical naturalism in the process. Quite aside from the impossibility of constructing metaphysically coherent identity conditions and a viable notion of physical substance out of acausally fluctuating quantum fields, David Baker has suggested that the very considerations rendering a particle interpretation of quantum field theory untenable also preclude a field ontology.[54] More specifically, Baker argues that the regnant candidate for a field ontology, which relies on the notion of a wave-functional space, falters because it is unitarily equivalent to the Fock Space occupation number representation. In light of this equivalence, he contends that the most powerful arguments against particle ontologies count equally against field ontologies.

The general solution that Baker adopts for this difficulty—interpreting QFT ontology in terms of some suitable algebra of observables—is not new; a critical discussion of the standard options in this regard has been given by Laura Ruetsche.[55] But the crucial point to be made here is that by switching to an ontology constituted by an algebra of *observables*, we are moving away from material substances altogether to an ontology of mathematically limned phenomenological structures *without* substance; and need it be said that phenomenological structure *sans* substance is not something physical? Naturalistic metaphysics is a nonstarter at the most fundamental level of physical theory, pure and simple. Since there must be some explanation for the world of our experience, the correct explanation will therefore have to be one that is not physical and so transcends the explanatory resources of naturalism, whatever that might mean.

4.5 Structural Realism Comes (Partially) to the Rescue

To begin work on this conundrum, let's start with the eminently reasonable assumption that there is a way that the world is, that we can get it right or wrong, and that science is a useful tool in helping us to get it right. In particular, when physical theory backed by experiment demonstrates that the world must satisfy certain formal structural constraints—for example, quantizability, nonlocality as encapsulated in the Bell theorems, nonlocalizability as indicated by the Hegerfeldt-Malament and Reeh-Schlieder theorems, Lorentz symmetries in spacetime, internal symmetries like isospin, various conserved quantities as implied by Noether's theorem, and so on—then this formal feature of the world may be taken as strong evidence for a certain metaphysical state of affairs. At a minimum, such states of affairs entail that the structural constraints empirically observed to hold and represented by a given theory will be preserved (though perhaps in a different representation) by any future theoretical development; thus far structural realism.

Whether this structural realism has further ontological consequences pertaining to the actual furniture of the world (entity realism) is a matter of debate among structural realists. The epistemic structural realist believes that there are epistemically inaccessible material objects forever hidden behind the structures of physical theory and that all we can know are the structures.[56] The ontic structural realist eliminates material objects completely—it is not just that we only know structures, but rather that all that exists to be known are the structures.[57] Both these versions of structural realism are deficient, though in different ways.

We have seen that quantum theory is incompatible with the existence of material substances, even those of a relationally holistic sort. Given that this is the case, the epistemic structural realist is just wrong that there is a world of inaccessible material individuals hidden behind the structures that quantum theory imposes upon the world. The situation would therefore seem to default to ontic structural realism. But while the ontic structural realist is correct that there are no material objects behind the structures, his position is deficient too because there can be no structures simpliciter without an underlying reality that is enstructured; we cannot build castles in the air. It would seem, then, that we're in a sort of Catch-22 situation. The challenge to making sense of quantum physics is to give an account of what the world is like when it has an objective structure that does not depend on material substances. What investigations of the completeness of quantum theory have taught us, therefore, is rather than quantum theory being incomplete, it is material reality (so-called) that is incomplete. The realm that we call the "physical" or "material" or "natural" is not self-sufficient but dependent upon a more basic reality that is not physical, a reality that remedies its causal incompleteness and explains its insubstantiality, and on which its continued existence depends.

In light of this realization, the rather startling picture that begins to seem plausible is that preserving and explaining the objective structure of appearances in light of quantum theory requires reviving a type of phenomenalism in which our perception of the physical universe is constituted by sense-data conforming to certain structural constraints, but in which there is *no material reality giving rise to (causing) these sensory perceptions*. What we are left with is an ontology of (ultimately immaterial) minds experiencing and generating mental events and processes that, when sensory in nature, have a formal character limned by the fundamental symmetries and structures revealed in physical theory. The fact that these sensory perceptions are not mostly of our own individual or collective human making points to the falsity of any solipsistic or social constructivist conclusion, but it also implies the need for a transcendent source and ground of our experience. Although I will not explore the hypothesis at length in this context, I contend that there is one quite reasonable way to ground this ontology and obviate any puzzlement: metaphysical objectivity and epistemic intersubjectivity are maintained in the context of an occasionalistic theistic metaphysics that looks a lot like the immaterialism defended by George Berkeley and Jonathan Edwards and in which the only true causation is agent causation. The difference in the present case is that this explanatory hypothesis is grounded by ontological deduction from fundamental physical theory and experiment, rather than by epistemological analysis (Berkeley) or philosophico-theological argument (Edwards).

4.6 Quantum Theory and Physical Law

This may seem a bridge too far for many, but let's work our way to it along another path by considering the implications of quantum theory for physical law. There are various conceptions of natural laws that try to give an account of them as natural necessities of one variety or another. These nomological theories are called necessitarian, for obvious reasons. The causal power account sees laws of nature as grounded in the essential natures of things, that nature ultimately inhering in their material substance. Laws of interaction among material things depend upon the essential natures of the things interacting with each other and on the forces or fields mediating these interactions. Spelling this out often involves some notion of a causal power essentially possessed by an object, the possession of which follows from some other property the object has in virtue of being an instance of some natural kind.[58] Another necessitarian approach characterizes laws of nature in terms of universally quantified counterfactual conditionals of the form "*All* things of type T, were they subjected to conditions C, *would* manifest property P."[59] For example: all pure water at sea level, were it heated above 100 degrees Celsius, would boil. Note that the necessity here is implicitly embodied in the inviolable universality of the phenomenon. Lastly, there is a species of necessitarianism that explains laws of nature in terms of relations among universals. On this last account, natural laws are correlations among the properties or behavior patterns of different things in the world, the necessity of these correlations being explained by the existence of "necessary" second-order relationships among universal categories, and the behavior of individual things mirroring the necessity of the relationships among the universal categories to which they belong.[60]

All these necessitarian accounts, without exception, fail to work in the quantum context. The essential causal powers account, the counterfactual account, and the relation among universals account all require that physical systems and material objects objectively possess properties that are capable of being connected together in a law-like fashion. At a minimum, necessitarian and/or counterfactual physical law theorists have to maintain that quantum systems, or their components, objectively possess properties prior to measurement, whether these properties are determinate or indeterminate (probabilified dispositions), and that it is the *objective possession* of these properties that necessitates (or renders probable) their specific behavior. Bell's theorem demonstrates that this assumption leads to empirically false consequences in the case of local deterministic and local stochastic models.[61] As we have also seen, this assumption either leads to an ontological contradiction in the nonlocal stochastic case embodied by relational holism (dynamic emergence), or if an undetectable privileged reference frame is invoked, succumbs to the nonlocalizability and insubstantiality of the intended possessors of the requisite properties.

Furthermore, if we pursue the one remaining option for a purely naturalistic interpretation, the nonlocal deterministic model associated with the de Broglie-Bohm theory, we find it is fraught with insurmountable technical difficulties, and even if this were not the case, its ability to restore a straightforward ontology of material objects grounding a necessitarian nomology would be suspect. More specifically, even if we grant the non-relativistic Bohmian mechanical ontology of nonlocally correlated structureless point particles for the sake of argument, their lack of essential intrinsic properties[62] makes it impossible to generate the natural kinds required by necessitarian and, in particular, causal power accounts of natural laws.

What we are left with, therefore, is a situation in which there are no objective physical properties in which to ground necessitarian/counterfactual relations. So necessitarian theories of natural law cannot gain a purchase point in fundamental physical theory and must be set aside. All that remains is the so-called *regularist* account of natural laws, which asserts that while there are regularities present in the phenomenology of the world on a universal scale, there are no real *laws* of nature, that is, there is *no necessity* that inheres in the natural relationships among things or in the natural processes involving them. In short, nature behaves in ways we can count on, but it does so for no discernible physical reason. This state of affairs requires an explanation.

4.7 Humean Supervenience, Quantum Coincidence, and Explanatory Demand

In regard to this explanatory requirement a brief comment on the idea of "Humean supervenience" is in order, because the attitude it represents denies any demand for an explanation grounding the regularities present in nature, resting content with their brute factuality. As David Lewis, late of the Princeton University philosophy department, states the matter, Humean supervenience maintains that in a world like ours, the fundamental relations are spatiotemporal: distance relations that are both spacelike and timelike, and perhaps occupancy relations between point-sized things and spacetime points.[63] Furthermore, the fundamental properties are local qualities: perfectly natural intrinsic properties of points, or of point-sized occupants of points. Everything else supervenes on the spatiotemporal arrangement of local qualities throughout all of history—past, present, and future. The conception of physical law associated with this ontology is the descendant of a proposal by Frank Ramsey (and of John Stuart Mill before him, and of David Hume, of course, before him). Lewis again: take all axiomatic deductive systems whose theorems are true; the best system is the one that strikes the optimal balance between simplicity and strength (informativeness). A natural regularity is then a law just in case it is a *theorem* of the *best system* (which is postulated to exist whether we know anything about it or not).

Aside from the peculiarity of this view and puzzlement over why anyone would wish to hold it, the picture it offers obviously needs to be tweaked in order to deal with chance, and it needs substantial revision if it is going to be able to handle quantum nonlocality and the undoing of the causal metric of spacetime in quantum gravity. I am skeptical whether this needed tweaking is doable—in fact, I firmly believe that it is not—but for the sake of argument, let's suppose that the position is tenable. What does it amount to? Lewis claims that his account of laws should not be understood as epistemological. Rather he insists that Humean supervenience is an account of how nature—which, he asserts, consists in the Humean distribution of qualities—determines what is true about laws and chances, quite independently of what we humans (not to be confused with Humeans, though the latter are presumably a peculiar qualitative subset of the former) believe about the world.

Taking Lewis at his word, I conclude that what we are left with is utter mystery and befuddlement. Quantum correlations, while nonlocally coincident, are understood in terms of local properties, requiring that we postulate random devices in harmony at spacelike separation without any deeper ontological explanation. Perhaps I can engender the requisite sense of puzzlement in the following way: how could anyone accept the plausibility of Humean supervenience in this context and still accuse two students of cheating on an exam when they sat next to each other and all their essay answers were word-for-word the same? The quantum situation, given its ubiquity, is staggeringly more improbable, with the added wrinkle that no one gets to peer over someone else's shoulder, because there is no physical signal that can pass instantaneously from one location to the other, and there's no possibility of a common text in the background that would explain the coincidence. To cling to brute factuality is to embrace irrationality, and to say that irrationality is rationally unjustifiable (though perhaps psychologically explainable) is redundant: it is definitionally so. A deeper explanation is required here, and no physical explanation is possible. Incredulity is not just the proper response to Humean supervenience, it is the necessary response. When its implications are grasped, Humean supervenience serves as a reductio of itself.[64]

5. Epilogue

If we consider carefully the progress of fundamental physics throughout the twentieth century, we find that the harder we have looked, the more ephemeral material reality has gotten, until finally it looks as though nothing is there. Yet our perceptions of the world remain and they are quite evidently not all of our own making. We have seen that neither nonlocal quantum correlations nor (in light of nonlocalizability) the nature of the fundamental constituents of material reality (so-called) can be explained or properly understood if the explanatory constraints of naturalism are preserved. Moreover, we have also seen that, short of dispensing with rationality itself, quantum phenomena such as these require an explanation. The conclusion we seek therefore follows directly: naturalism (materialism, physicalism) is irremediably deficient as a worldview, and must be rejected not just as inadequate, but as fundamentally false. The argument that has guided our discussion from the start has been vindicated.

Notes

1. "What is real is not given to us, but rather set as a task, by way of a riddle."—Albert Einstein
2. Throughout this essay, I will take the nouns "naturalism," "physicalism," and "materialism," as well as their adjectival forms, to be roughly synonymous in accordance with the definition of ontological naturalism just offered, and I will use them interchangeably. The fact remains, however, that "naturalism" is a bit of a weasel word, by which I mean that it is employed in a highly malleable way designed to insulate its fundamental thesis—the causal closure of the material realm—from disconfirming evidence. So it is that various "non-reductive naturalists" attempt to combine their monism about entities with a pluralism of properties that allows for "supervenient" or "emergent" material or non-material properties involving nonlocal correlations, normativity, intentionality, consciousness, and a variety of other things that pose problems for a naturalistic worldview. The literature on supervenience and emergence in this regard is voluminous. We will touch on concepts of supervenience, emergence, and holism in our discussion of nonlocality below, taking particular care to note that their descriptive utility, such as it is, hides their explanatory *vacuity* under a patina of technical sophistication.
3. Fine 1986a, 1986b; van Fraassen 1996.
4. Van Fraassen does, however, make explicit room for a voluntarist epistemology, in a neo-Pascalian or Jamesian vein, that allows belief to transcend the empiricist sensibilities he enforces in science (see van Fraassen 2002: 81–90, 179ff, *et passim*). Fine's epistemological preference is for a contextualist pragmatism (1986a, 1986b) that eschews any notion of deep metaphysical reality in favor of "natural ontological attitudes" arising in multiple scientific contexts, without any overarching concern for inter-contextual contradictions or desire for rapprochement and reconciliation. In giving up on the traditional project of knowledge in this way, both viewpoints devolve into the rationalizations of irrationalism characteristic of "post-modernity." We can do better than this, but I contend that doing so requires eschewing naturalism, not metaphysical realism. Both Plantinga's and Koons' essays in this volume make this point quite effectively.
5. Van Fraassen 1996: 170.
6. Ibid.
7. Fine 1989b and van Fraassen 1989a.
8. Wigner 1970; cf. also Sakurai 1985: 223–32, *et passim*.
9. Adapted from Sakurai 1985: 229.
10. Fine 1982c, 1986a, 1989a, 1991; cf. Maudlin 2002: 175–87.
11. See Rowe *et al.* 2001.
12. Van Fraassen 1991: 123–25.
13. Ibid., 124–25.
14. Fine 1982a, 1982b, 1986a.
15. Wigner 1970.
16. Van Fraassen 1991: 81–93.
17. See Holland 1993; Cushing, Fine, and Goldstein, eds. 1996; Gordon 1998: 337–406.
18. See also Bedard 1999 and Dickson 2001 in this regard.
19. See Goldstein *et al.* 1996 and Goldstein *et al.* 1999 for efforts in this regard.
20. See Kyprianidis 1985; Saunders 1999: 74–75.
21. See Saunders 1999: 75–78.
22. See Saunders 1999: 80–86.
23. Teller 1986, 1989.
24. See Gordon 2002: 402–7 for a more extensive discussion of related issues.
25. McLaughlin 1997; Kim 1999, 2006; O'Connor and Wong 2005.

26. McLauglin 1997: 39.
27. Kim 1999.
28. Loewer 2001 and Shoemaker 2002.
29. Humphreys 1997.
30. Ibid.
31. Kronz and Tiehen 2002: 344ff.
32. According to the British emergentists (see McLaughlin 1992), resultant properties are additive, like force in Newtonian mechanics, whereas emergent properties are not. This *via negativa* is taken as the definition of an emergent property and seems to be motivated by regarding forces as fundamental, then constructing a metaphysical view of emergence by analogy with the way that forces behave.
33. Teller 1986, 1989, and elsewhere.
34. Fleming 1965, 1966, 1988, 1989, 1996, 2003, 2004; Fleming and Bennett 1989.
35. Teller 1995 and elsewhere.
36. In this regard, see especially Clifton, Feldman, Halvorson, Redhead, and Wilce 1998; Halvorson and Clifton 2000.
37. Van Fraassen 1991: 434–82.
38. See Gordon 2003.
39. Jauch 1968.
40. De Muynck 1975: 340.
41. Ibid.
42. De Muynck 1975: 340–45.
43. Ibid., 342.
44. Ibid., 341.
45. Ibid., 343.
46. Ibid., 344–45.
47. Something is a material simple just in case it lacks any parts other than itself, that is to say, it has no proper parts. The condition of uniquely occupying a certain volume of space at a certain time is equivalent to saying that a material simple is impenetrable.
48. Hegerfeldt 1974, 1985, 1989, 1998a, 1998b, and Malament 1996.
49. Halvorson and Clifton 2002.
50. Haag 1996; Doplicher et al. eds. 1997; Horuzhy 1990; Clifton 1999; Kuhlmann, Lyre, and Wayne eds. 2002; Halvorson and Mueger 2007.
51. Irving Segal (1964), and quite recently Gordon Fleming (2000),
52. Halvorson 2001.
53. Halvorson 2001: 128.
54. Baker 2008.
55. Ruetsche 2002.
56. Worrall 1989; Redhead 1995; Cao 1997, 2003a, 2003b, 2003c.
57. Ladyman 1998; French 1999, 2000, 2003a, 2003b, 2005; French and Ladyman 2003a, 2003b; French and Krause 2006; Ladyman and Ross 2007.
58. See Bigelow and Pargetter 1990; Harré and Madden 1975.
59. Cf. Stalnaker 1968; Lewis 1973.
60. Armstrong 1983, 1997; Dretske 1977; Tooley 1987.
61. Bell 1987: 1–21; Redhead 1987: 71–118; Fine 1981, 1982a, 1982b; Cushing and McMullin 1989; Clifton, Feldman, Halvorson, Redhead and Wilce 1998.
62. Bedard 1999; Dickson 2001.

63. Lewis 1999: 224–47.

64. A more rigorous articulation of the argument against Humean supervenience requires a defense of the "Principle of Sufficient Reason" namely, the common-sense belief that all contingent facts have explanations. A thorough defense of this principle needs a full-length treatise and, handily, just such a treatise has been written. I am happy to recommend to the reader Alexander Pruss's book *The Principle of Sufficient Reason: A Reassessment* (Cambridge: Cambridge University Press, 2006).

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