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FOR WHOM THE BELL ARGUMENTS TOLL

ABSTRACT. We will formulate two Bell arguments. Together they show that if the probabilities given by quantum mechanics are approximately correct, then the properties exhibited by certain physical systems must be nontrivially dependent on the *types* of measurements performed *and* either *nonlocally* connected or *holistically* related to distant events. Although a number of related arguments have appeared since John Bell's original paper (1964), they tend to be either highly technical or to lack full generality. The following arguments depend on the weakest of premises, and the structure of the arguments is simpler than most (without any loss of rigor or generality). The technical simplicity is due in part to a novel version of the generalized Bell inequality. The arguments are self contained and presuppose no knowledge of quantum mechanics. We will also offer a Dutch Book argument for measurement type dependence.

1. INTRODUCTION

The analysis of certain quantum systems suggests that the physical world exhibits at least some of the following nonclassical features:

1. MEASUREMENT-DEPENDENCE: The properties that certain kinds of physical systems exhibit when they are measured depend in a nontrivial way on the *type* of measurement performed.
2. INDETERMINISM: The outcomes produced by maximally precise measurements on certain physical systems cannot be the product of deterministically evolving systems deterministically interacting with the measuring device – the properties exhibited by measurement are the product of an essentially stochastic process.
3. NONLOCALITY: The correlations between outcomes of measurements on distant parts of certain physical systems are the product of nearly instantaneous *causal influences* between the parts across great distances.
4. HOLISM: The correlations between outcomes of measurements on distant parts of certain physical systems are due to irreducible systemic relationships among parts – relationships that are neither due to influences between parts, nor to local fields, nor to properties they carry from their common causal past.

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The *Bell arguments* concerning EPR-Bohm systems are the most compelling arguments for such claims.[1] At the core of every Bell argument is a relationship among probabilities for certain quantum events, a relationship that the argument shows to be incompatible with classical features like locality or determinism. John Bell (1964) first devised an argument of this form. He argued that the existence of *local hidden variables* would be incompatible with the probabilities quantum mechanics gives for EPR-Bohm systems.

Since Bell's original paper, a number of related arguments have appeared (e.g. Bell 1966, 1971; Clauser and Horne 1974; Hellman 1982, 1987; Jarrett 1984, 1989; Redhead 1987; Stapp 1971; van Fraassen 1982). Versions of the argument have been offered in support of a variety of claims. Some support the claim that EPR-Bohm systems are *either* nonlocally connected *or* indeterministic (Hellman 1982, Redhead 1987). Other versions indicate that EPR-Bohm systems are *either* nonlocal *or* indefinite – that they have no definite, measurement independent properties. It is often claimed that Bell arguments imply one must abandon *either* locality *or* realism, where 'realism' means definiteness (Clauser and Shimony 1978) (Davies and Brown 1986). The following versions of the argument show these to be false dichotomies. Not that any of these claims are false per se, but when combined, the following Bell arguments warrant a stronger conclusion. We will present two Bell arguments that, taken together, toll against measurement independence, *and* either against locality or in support of holism – regardless of whether the EPR-Bohm systems are deterministic, and regardless of whether they have definite values.

Bell arguments always take the form of a reductio. A collection of assumptions is shown to lead to a contradiction, and one is invited to give up the least plausible among them. Some investigators have hinted that the fault may lie with classical logic and probability theory. Others have suggested that there may be something fishy about the classical ontology of particles or waves located in space and time and the role this conception plays in the Bell arguments. Our versions will show just how little classical probability is involved, and will not depend on any ontological *presuppositions* about the composition of quantum systems.

A number of Bell arguments in the literature have employed one or more of the following claims, and one may have hoped to avoid their astounding conclusions by rejecting one of them. The main arguments in this paper will *not* assume the truth of any of these claims. We will not assume that:

(1) there exists a *perfect* or *exact correlation* between outcomes of measurements of precisely the same *type* on both parts of an EPR-Bohm system;
(2) the probabilities associated with systems satisfy the axioms of *classical probability theory*;
(3) there are *joint probabilities* for incompatible (or complementary) properties associated with measurements that cannot simultaneously be performed on the same part of a system;
(4) the quantum systems in question are composed of individual particles, or waves (or any particular story about the *ontology* of quantum systems);
(5) definite, measurement independent properties or dispositions of systems either stay fixed in their initial state (from creation), or they evolve in a deterministic fashion from their initial state.

Bell arguments often proceed with one or more of these assumptions either stated explicitly or lurking in the background. And one is left wondering whether the startling conclusions could be avoided by rejecting them. The following arguments have no such loopholes.

Our first argument is loosely related to Bell's original rendition, and to a version by Redhead (1987 pp. 82–90),[2] but our version of the argument is somewhat simpler. This argument will establish that the outcomes of measurements on EPR-Bohm systems must be nontrivially measurement dependent. Our second argument is similar to Bell's (1971), Clauser and Home's (1974), and Jarrett's (1984, 1989), but is simpler, and is not as dependent on classical probability theory as earlier versions of the argument appear to be. It will establish that the outcomes of measurements must either be nonlocally or holistically connected. Both of the following Bell arguments employ a novel version of the *generalized Bell inequality*.

We will also introduce a *Dutch Book* argument that bolsters the claim for measurement dependence. Whereas our first argument shows that *percentages for sequences* of measurement independent outcomes must conflict with quantum probabilities, the dutch book argument shows that the quantum probabilities applied to *a single system* are incompatible with measurement independence.

We will proceed as follows. In Section 2 we describe the features of EPR-Bohm systems required for our arguments. Section 3 develops the Bell argument for measurement dependence. It shows that, even if the properties of EPR-Bohm systems are nonlocally connected, they cannot be *totally measurement independent* if the outcomes occur with the likelihoods predicted by quantum mechanics. Section 4 contains a second Bell argument which establishes that the distant parts of these systems must, nevertheless, either be nonlocally connected or holistically related. These arguments depend only on the assumption that the probabilities predicted by quantum mechanics for measurement outcomes on EPR-Bohm systems are approximately correct,[3] and on a couple of uncontroversial probabilistic equivalences for the argument of Section 4. Section 5 presents the dutch book argument for measurement dependence. In the concluding section we briefly address implications of the Bell arguments for microphysical reductionism.

2. SYSTEMS AND MEASUREMENTS

The arguments in this paper will not depend on the details of quantum theory, or on any particular account of the ontology or composition of quantum systems. In order to emphasize this point, we will describe the relevant EPR-Bohm systems in almost purely operational terms. A variety of real quantum systems fit this description.

Imagine the following sort of situation. From time to time some regions of space are occupied by *systems*. One knows of the presence of such systems only by *measuring* them. One can measure systems for a variety of properties. The outcomes of a measurement may indicate a property that the system already possesses at (or just before) the moment of measurement, or they may be the product of an interaction (either deterministic or stochastic) between the system and the measuring device – one cannot say for sure, pre-theoretically.

At the moment it is generated, a system occupies a very small region of space. After a short time the system will have two parts at spatially distant locations, both of which may be measured. Whether such a system is spatially disconnected, or whether it occupies some continuous region of the intervening space, one cannot say. But suppose that there is some specific, reliable method for producing such systems.

We will call such systems ψ-systems. Each *ψ-system* has two spatially distant parts at some time after its creation, which we designate 'L' and

'R' (for *Left* and *Right*). The L part of the system can be measured in either of two ways (for either of two different properties, if you like), A or B. We will write 'A_L' to indicate that the L part of the system is measured by a device configured for an A measurement on the system, and 'B_L' to indicate that the L part of the system is measured by a device configured for a B measurement. One can never perform both A_L and B_L measurements on the same system simultaneously. And, since one cannot be sure, pre-theoretically, that making one of these measurements does not *disturb the system*, one cannot confidently determine what the result of the other measurement would have been.

The R part of a ψ-system can also be measured in just one of two ways, which we designate 'C' and 'D'. We write 'C_R' to indicate that a C measurement is made on the R part of the system, and 'D_R' to indicate that a D measurement is made.

The outcome of any of the four *types* of measurement (A_L or B_L, and C_R or D_R) on ψ-systems is bivalent. For example, if one performs an A measurement on the left wing, the resulting outcome can have only one of two values, which we designate '+' and '−'. Similar notation applies for B, C, and D. The + and − outcomes for the various *types* of measurements (A_L, B_L, C_R, and D_R) *need not* indicate the same kinds of properties. For example, A_L could be a bivalent *position* measurement in which space is divided into two exclusive regions. Then, A_L^+ would represent a *location detection* in one region, and A_L^- a location detection in the other. B_L might be a bivalent *momentum* measurement (e.g. the measuring device registers whether the momentum is above or below a certain threshold). So the '+' in A_L^+, B_L^+, C_R^+, and D_R^+ *may* indicate one of two positions for A_L measurements, one of two momenta for B_L measurements, and something else entirely for C_R and for D_R measurements.[4]

When a ψ-system is created in such a way as to have L and R parts (which may be subject to A, B, C, and D measurements), we will say that the system is in the state ψ. One may think of ψ as the state quantum mechanics assigns to such systems, or one may take ψ as a purely operational description of similarly created or prepared systems. One could also take the state of the system to be evolving in time, so that ψ should be a function of time. However, this complication would add nothing essential to our analysis. One may take ψ to represent either the initial state of the system or the (time evolved) state at the time just before any measurements are made, it will not matter.

In general one can only know that a ψ-system has been created by detecting one of its parts – i.e. when one of its parts encounters a measuring device and registers an outcome. But one can arrange the locations of a ψ-system generator and the measuring devices so that the parts of any generated ψ-system will encounter the separate measuring devices at about the same time. The devices are placed far enough apart to insure that no information about either the measurement *setting* of one device or its outcome has time to affect the other part of the system, *unless* such information moves much faster than the speed of light, i.e. superluminally. The L device is randomly and continually reset between A_L and B_L measurement configurations to insure that the measurement configuration of the L device at the time the L part is measured could not have previously influenced the R part of a system by subluminal means. The R device is also randomly and continually reset between C_R and D_R configurations.[5]

Now suppose that some well confirmed scientific theory (e.g. quantum mechanics) predicts the following probabilities for outcomes of compatible measurements on parts of ψ-systems:[6]

TP (Theoretical Probabilities):

$$P(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi) = \tfrac{1}{2}$$
$$P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi) = \tfrac{1}{8}$$
$$P(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi) = \tfrac{1}{8}$$
$$P(B_L^- \,\&\, D_R^+ \mid B_L \,\&\, D_R \,\&\, \psi) = \tfrac{1}{8}.$$

These are conditional probabilities. For example, '$P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi) = \frac{1}{8}$' says that *given* any ψ-system measured for A_L on the L part and for D_R on the R part, the probability of the joint outcome $(A_L^+ \,\&\, D_R^-)$ is $\frac{1}{8}$.

We'll leave the notion of probability uninterpreted. These probabilities might be relative frequencies, or propensities, or might satisfy some sort of subjectivist or logical interpretation. They may or may not be classical. We will not presuppose any particular position on these interpretational issues. Indeed, we will not even assume that the numerical values that the theory assigns are precisely right. We only suppose the Approximate Correctness of the Theoretical Predictions:

ACTP: The theoretical predictions given in **TP** for values of the probabilities of outcomes (for measurements on ψ-systems) are correct within a margin of error of ± 0.03 (e.g., $0.095 \leq P(A_L^+ \ \& \ D_R^- \mid A_L \ \& \ D_R \ \& \ \psi) \leq 0.155$).

The precise probability values predicted in **TP** and the value for the margin of error are really incidental. The important feature of **ACTP** is that the numerical values it assigns entail a *Contra-Bell Inequality*:[7]

$$
\begin{aligned}
&P(A_L^+ \ \& \ C_R^- \mid A_L \ \& \ C_R \ \& \ \psi) \\
&\quad > P(A_L^+ \ \& \ D_R^- \mid A_L \ \& \ D_R \ \& \ \psi) \\
&\quad + P(B_L^+ \ \& \ C_R^- \mid B_L \ \& \ C_R \ \& \ \psi) \\
&\quad + P(B_L^- \ \& \ D_R^+ \mid B_L \ \& \ D_R \ \& \ \psi),
\end{aligned}
$$

[since, $(\frac{1}{2} - 0.03) = 0.47 > 0.465 = (\frac{1}{8} + 0.03) + (\frac{1}{8} + 0.03) + (\frac{1}{8} + 0.03)$].

The essence of the argument in the next section is that *Contra-Bell* requires the probabilities of L and R measurement outcomes to depend nontrivially on the *type* of measurement performed. The section after shows that *Contra-Bell* requires that outcomes depend on either the type of distant measurement performed, or the *outcome* of the distant measurement. This will imply either a violation of locality or the existence of holistic systemic properties.

3. MEASUREMENT DEPENDENCE

Do the *types* of measurements performed on a ψ-system influence the outcomes? There is a trivial sense in which the answer is *yes*. One cannot get *outcome* A_L^+ (or A_L^-) if B_L is performed. Let's phrase the question more precisely. At the time a measurement is about to be performed on a part of a ψ-system,

(1) is there a definite or determinate property of the L part of the system that will produce the outcome A_L^+ (or A_L^-) if A_L is performed, and also a definite property for B_L; *or*

(2) does the L part of the system have a definite disposition to produce an A_L^+ outcome (or A_L^- outcome) for an A_L measurement, and also a definite disposition for some particular B_L outcome; *or*

(3) is there at least, for each ψ-system, either a true conditional claim of the form '*if* A_L *is* (*or had been*) *performed, then* A_L^+ *will* (*would have*) *result*(*ed*)' or a true conditional claim asserting '*if* A_L *is* (*or had been*) *performed, then* A_L^- *will*

(*would have*) *result*(*ed*)', and also a similar true conditional for B_L?

If one answers *yes* to any of these questions, then one is asserting the existence of Passive Measurement Definite Values (**PM-DVs**). One is claiming that each ψ-system has some Definite Value (**DV**) – some definite property, or disposition, or at least that there is some true conditional statement associated with each possible *type* of measurement. Measurement is passive in that it simply reveals some independently existing property, or disposition, or truth. On the other hand, if the answer to all of the above questions is *no*, then outcomes must *depend nontrivially* on the types of measurements performed.

In this section we will show that the existence of **PM-DVs** is inconsistent with the approximate correctness of the probabilities predicted by the theory (i.e. **ACTP**). We will also eliminate a certain sort of Active Measurement **DV** account. Before proceeding to the argument, we will spell out the possible **PM-DV** accounts in a bit more detail, and describe the possible alternatives to them. All possible interpretations may be classified with regard to whether measurement plays an active or a passive role, and with regard to whether interpretations attribute to ψ-systems definite or indefinite values for unmeasured properties (see Figure 1).

3.1

According to the first of the **PM-DV** accounts, at the times when each part of a ψ-system is measured, either the system or each of its parts possesses a complete collection of definite properties, and the measurements simply reveal some of them. The L part of a system, for instance, possesses definite properties for both the A_L and B_L measurements. When considering this sort of interpretation we let underlined expressions like '$\underline{A}_L^+$' and '$\underline{B}_L^-$' represent the definite properties of the L part of a system at the moment of measurement, properties which produce outcome A_L^+ if measurement A_L is performed and outcome B_L^- if B_L is performed. For example, the *passive-measurement disturbance* accounts are of this kind – i.e. accounts that say a particle always has a precise position and momentum (though they are not simultaneously measurable), and any position measurement not only registers the pre-

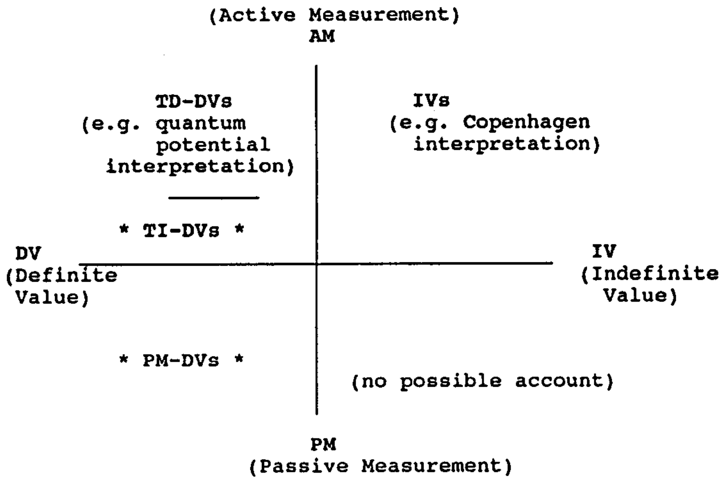

Fig. 1. Possible interpretations: Definiteness vs. Measurement-Dependence. (The interpretations enclosed between '*' are refuted by the Bell argument of this section.)

existing position, it also randomly disturbs the pre-existing momentum, making simultaneous position and momentum unknowable.

PM-DV interpretations of the second sort assert that, regardless of whether ψ-systems possess *definite properties* responsible for the measurement outcomes, each system does have a definite or determinate disposition to exhibit a particular outcome, say A_L^+, if A_L is measured, and the definite disposition to exhibit, say B_L^-, if B_L is measured. The existence of these dispositions in a particular system depends in no way on the *types* of measurements actually performed. Measurement simply reveals whatever disposition is present at that moment. When considering dispositional interpretations we let expressions like '$\underline{A}_L^+$' and '$\underline{B}_L^-$' represent these dispositions.

The third sort of **PM-DV** view holds that, whether or not a system possesses such properties or dispositions, there is at least some complete collection of true conditional statements about that system – e.g., 'if A_L were measured, then A_L^+ would result', and 'if B_L were measured, then B_L^- would result'. The truth values of these conditionals is supposed to depend in no way on what *types* of measurements are actually performed. When considering this interpretation we let '$\underline{A}_L^+$' and '$\underline{B}_L^-$' represent these *truths*.[8] The conditional in question may be read as a subjunctive (or counterfactual) or as an indicative conditional; for our purposes it won't matter.

The **PM-DV** interpretations appear to be the only possible accounts in which the *type* of measurement performed plays the completely trivial role of exposing something that is already present. All remaining **DV** interpretations are Active Measurement (**AM**) accounts. They hold that systems always possess a complete collection of properties, but that upon measurement, a given system will change definite values, perhaps due to the interaction with the measuring device. On these interpretations, the outcome of a measurement reveals one of the new properties that result from the measurement interaction. **AM-DV** interpretations may be either deterministic or stochastic.

It will be convenient to relegate all *deterministic* **DV** interpretations for which outcomes do not depend on the *type* of *distant* measurement performed to the class of **PM-DV** interpretations. For, if all measurement outcomes are *deterministically* produced by the measurement of a system, then the system must have had a definite disposition (or there must at least have been some true conditional about the system), prior to the measurement, that *predetermined* the outcomes any measurements would produce. In that case one may view the measurement process as revealing the preexisting disposition (or true conditional assertion). If these determining dispositions (or conditionals) for outcomes do not draw on information about the *distant measurement type*, then they fit the description of the **PM-DV** interpretations. Thus, the only deterministic **DV** interpretations that will count among the **AM-DV** (Active Measurement **DV**) views are those on which the *type* of *distant* measurement performed plays an essential role in determining the measurement outcomes.

Also, notice that only a definite *property* version of the stochastic (indeterministic) Active Measurement **DV** interpretations makes sense. For, if ψ-systems have definite *dispositions* just prior to measurement (or if there are true determinate conditionals), then the measurement should faithfully reveal the disposition (or true conditional) already present, and the outcome is not produced by a stochastic change after all, In what sense could there *be* definite dispositions (or true conditionals) if the promised outcome is not forthcoming upon maximally precise measurement?

Divide the **AM-DV** accounts into two kinds. Those of the first kind hold that the *type* of measurement performed has an influence on which new properties will evolve. We call these Measurement-Type Dependent **DV**s (**TD-DV**s). All other **AM-DV** accounts must hold that although the measurement is associated with a change in properties, the *type* of measurement performed has *no* relevance in determining which new properties will occur. We call these Measurement-Type Independent **DV**s (**TI-DV**s). For **TI-DV**s, measurement brings about a change in properties, but the *type* of measurement performed only affects which of the new properties is *revealed* by the measurement.

Since all *determisitic* **AM-DV**s are dependent on the distant measurement *type*, they are all **TD-DV**s. So, all **TI-DV**s are indeterministic. Of course there are coherent indeterministic **TD-DV** accounts, too. The following Bell argument applies to **TI-DV**s (as well as **PM-DV**s). In the context of the following argument, as it applies to **TI-DV**s, underlined expressions like '$\underline{A}_L^+$' represent the property produced by the stochastic measurement process, the property reported by outcome A_L^+ if A_L is the type of measurement performed. For any *stochastic* **DV** account either $\underline{A}_L^+$ or $\underline{A}_L^-$ must exist as a **DV** produced by the measurement, even when B_L is the measurement performed.

The active and passive measurement accounts exhaust the **DV** interpretations. The only alternative to **DV** accounts is Indefinite Value (**IV**) interpretations. They say that a ψ-system does not possess *definite* values or dispositions for every possible outcome prior to measurement, and that there is no complete collection of true conditionals about which outcome each measurement would produce. Rather, the only *measurable properties* a system possesses are propensities or probabilistic dispositions to produce particular outcomes if a certain measurement is performed. On views of this sort nothing can be said about what the unmeasured values would have been beyond *citing the probability* that a specific *type* of measurement would have resulted in one of its associated outcomes. So, **IV** interpretations are inherently *measurement-type dependent*. And because measurement-type doesn't *determine* outcomes, **IV** accounts are clearly stochastic. **IV** interpretations are unaffected by the following Bell argument.

The following argument shows that if the theoretical predictions for probabilities of outcomes are correct within a margin of error of $+0.03$ (i.e. **ACTP** holds), then no interpretation on which outcomes are *independent of measurement-type* can yield the correct probabilities. Thus, all **PM-DV** and **TI-DV** interpretations are ruled out. Only **TD-DV** and **IV** interpretations are consistent with the theoretical predictions.

Bohr's Copenhagen interpretation of quantum mechanics is an **IV** account (Bohr 1934, 1935), and Bohm and Hiley's (1984) quantum potential interpretation of quantum mechanics employs **TD-DVs**. So there are extant instances of each of the two classes of interpretations that survive the following Bell argument.

3.2

The Bell argument against **PM-DVs** and **TI-DVs** is a *reductio*. Assume the Approximate Correctness of the Theoretical Predictions (**ACTP**) and assume that there are either **PM-DVs** or **TI-DVs**. Consider any assortment of n ψ-systems measured in any assortment of ways. Though one cannot *measure* all definite values of a single system, still they must all exist if any **DV** account holds. Let $\#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^+ \mathbin{\&} \underline{C}_R^- \mathbin{\&} \underline{D}_R^+ \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)$ be the number among the n systems, prepared in state ψ and measured in various ways, that possess (or take on) $\underline{A}_L^+$ and $\underline{B}_L^+$ and $\underline{C}_R^-$ and $\underline{D}_R^+$ at the respective moments that the L and R parts are measured. Here M_L and M_R simply say that some measurement is made on L and on R, respectively. For the sake of argument we do not deny the possible relevance of the fact that some measurement is performed. Indeed, '$(M_L \mathbin{\&} M_R)$' may carry as much detail about the measurement set-up as you please, short of specifying which of the two *types* of L and R measurements are performed. Now, if **PM-DVs** or **TI-DVs** exist, then the actual numbers of systems with various combinations of these **DVs** must add up as follows:

$$\begin{aligned}
&\#_n(\underline{A}_L^+ \mathbin{\&} \underline{C}_R^- \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)\\
&\quad = \#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^+ \mathbin{\&} \underline{C}_R^- \mathbin{\&} \underline{D}_R^+ \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)\\
&\qquad + \#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^+ \mathbin{\&} \underline{C}_R^- \mathbin{\&} \underline{D}_R^- \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)\\
&\qquad + \#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^- \mathbin{\&} \underline{C}_R^- \mathbin{\&} \underline{D}_R^+ \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)\\
&\qquad + \#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^- \mathbin{\&} \underline{C}_R^- \mathbin{\&} \underline{D}_R^- \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi).
\end{aligned}$$

That is, the total number of systems that have both $\underline{A}_L^+$ and $\underline{C}_R^-$ among the n systems must be the sum of all the systems that have $\underline{A}_L^+$ and $\underline{C}_R^-$ in combination with each of the various B_L and D_R values.

Similarly,

$$\begin{aligned}
&\#_n(\underline{A}_L^+ \mathbin{\&} \underline{D}_R^- \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)\\
&\quad = \#_n(\underline{A}_L^+ \mathbin{\&} \underline{B}_L^+ \mathbin{\&} \underline{C}_R^+ \mathbin{\&} \underline{D}_R^- \mid M_L \mathbin{\&} M_R \mathbin{\&} \psi)
\end{aligned}$$

$$
\begin{aligned}
&+ \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^+ \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&+ \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^+ \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&+ \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi).
\end{aligned}
$$

$$
\begin{aligned}
&\#_n(\underline{B}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\quad = \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^+ \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^+ \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^- \,\&\, \underline{B}_L^+ \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^- \,\&\, \underline{B}_L^+ \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi).
\end{aligned}
$$

$$
\begin{aligned}
&\#_n(\underline{B}_L^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\quad = \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^+ \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^+ \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^- \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^+ \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{A}_L^- \,\&\, \underline{B}_L^- \,\&\, \underline{C}_R^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi).
\end{aligned}
$$

By comparing terms on the right-hand sides of each of these equations it is easy to verify that

$$
\begin{aligned}
&\#_n(\underline{A}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\quad \leqslant \#_n(\underline{A}_L^+ \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{B}_L^+ \,\&\, \underline{C}_L^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \#_n(\underline{B}_L^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi).
\end{aligned}
$$

since each term on the right-hand side of the first *equality* occurs on the right-hand side of one of the other three *equalities*.

Divide both sides of the *inequality* by n, and let $\%_n = \#_n \div n$. Then we have, for any systems in state ψ,

$$
\begin{aligned}
(1)\qquad &\%_n(\underline{A}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\quad \leqslant \%_n(\underline{A}_L^+ \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \%_n(\underline{B}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi)\\
&\qquad + \%_n(\underline{B}_L^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi).
\end{aligned}
$$

This is a Bell inequality. If there are **PM-DVs** or **TI-DVs**, then any collection of n systems must possess (or produce) percentages of **DVs** that satisfy this inequality.

One cannot actually count how many of the n systems have

($\underline{A}_L^+$ & $\underline{C}_R^-$) unless one measures them all for (A_L & C_R). In general some number, n_1, of the n systems is measured so that the values of A_L and C_R may be observed. Similarly, let n_2, n_3 and n_4 be the number among the n systems that are measured for (A_L & D_R), (B_L & C_R), and (B_L & D_R), respectively. We assume each of the n systems is measured in one of these ways, so $n_1 + n_2 + n_3 + n_4 = n$. We will represent the observed percentages for systems measured in each of these ways by the expressions:

$$\%_{n1}(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi),$$
$$\%_{n2}(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi),$$
$$\%_{n3}(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi),$$
$$\%_{n4}(B_L^- \,\&\, D_R^+ \mid B_L \,\&\, D_R \,\&\, \psi).$$

For instance, '$\%_{n1}(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi)$' represents the percent of the n_1 systems (measured for A_L and C_R) that have joint outcomes A_L^+ and C_R^-, joint outcomes that indicate the presence of the **DVs** $\underline{A}_L^+$ and $\underline{C}_R^-$.

Now there are two important considerations raised by the Bell inequality, Equation (1). The first is a purely theoretical point; the second regards an empirical issue.

The theoretical point is this. Regardless of how the observed percentages turn out, whenever any three of the *theoretical percentages* of **PVs** or **TI-DVs** in Equation (1) are within 0.03 of the theoretically predicted probabilities in **TP**, the fourth must be more than 0.03 away from its theoretically predicted value.

If the theoretical probabilities given in **TP** represent the probabilities of outcomes due to definite values, and if the **DVs** do not depend on the *type* of measurement performed (i.e. they are **PM-DVs** or **TI-DVs**), then the following equalities should hold:

(2)
$$P(\underline{A}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi) = P(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi) = \tfrac{1}{2}$$
$$P(\underline{A}_L^+ \,\&\, \underline{D}_R^- \mid M_L \,\&\, M_R \,\&\, \psi) = P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi) = \tfrac{1}{8}$$
$$P(\underline{B}_L^+ \,\&\, \underline{C}_R^- \mid M_L \,\&\, M_R \,\&\, \psi) = P(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi) = \tfrac{1}{8}$$
$$P(\underline{B}_L^- \,\&\, \underline{D}_R^+ \mid M_L \,\&\, M_R \,\&\, \psi)$$

$$= P(\underline{B}_L^- \ \& \ \underline{D}_R^+ \mid B_L \ \& \ D_R \ \& \ \psi) = \tfrac{1}{8}.$$

These equalities just say that the probabilities for the occurrence of the **DV**s responsible for the outcomes are the same as the theoretical probabilities for the outcomes – outcomes that merely report the **DV**s present.

The equalities in (2) are clearly incompatible with the previous inequality, (1), regarding percentages for n systems. Just observe that $\frac{1}{2} > (0.5 - 0.03) = 0.47 > 0.465 = (\frac{1}{8} + 0.03) + (\frac{1}{8} + 0.03) + (\frac{1}{8} + 0.03)$. So, for *any* given sequence of n systems, whenever any three of the percentages in (1) come within 0.03 of their associated theoretical probabilities in (2), the fourth percentage *must* fall more than 0.03 away from its theoretical probability. Thus, if any **PV-DV** or **TI-DV** account is true, **ACTP** must be violated by the theoretical percentages of **DV**s.

The second, empirical point is this. If the *observed percentages* of outcomes, $\%_{n1}(A_L^+ \ \& \ C_R^- \mid A_L \ \& \ C_R \ \& \ \psi)$, etc., all closely approach their theoretically predicted values, $P(A_L^+ \ \& \ C_R^- \mid A_L \ \& \ C_R \ \& \ \psi) = \frac{1}{2}$, etc., then at least one of the observed percentages must be significantly different from the actual percent, $\%_n(\underline{A}_L^+ \ \& \ \underline{C}_R^- \mid M_L \ \& \ M_R \ \& \ \psi)$, etc, of **DV**s present in all n systems. For example, if all observed percentages are within 0.01 of the values in **TP**, then at least one observed percentage must differ from the corresponding actual percentage (of which it is a subsample) by more than 0.02. A difference this large between the observed percentages and the actual percentages is extremely unlikely to occur if n and the n_i are sufficiently large – extremely unlikely unless the *types* of measurements performed select nonrepresentative subsamples of all measured systems in state ψ. But, if measurement-*types* do select nonrepresentative subsamples, then the theoretical probabilities to which they converge should be essentially dependent on measurement-type after all. Observed percentages in experiments tend to bear out the theoretical predictions (see note 3). So the experimental data weighs against the existence of **PM-DV**s and **TI-DV**s.

No account that endorses independence of the *type* of measurement is consistent with **ACTP**, and experiment supports **ACTP**. Both **PM-DV** interpretations and **TI-DV** interpretations endorse such independence, so both must fail. Only the essentially measurement-type dependent interpretations, **TD-DV**s and **IV**s, are consistent with the approximate correctness of the theoretical probabilities.

3.3

The preceding argument does not rely on the assumption that the L and R parts of the systems are locally isolated or incommunicado. Even slowly evolving systems with parts in constant communication cannot possess **PM-DVs** or stochastically produce **TI-DVs** at rates compatible with the probabilities in **TP**. The violation of **ACTP** results only from the assumption that outcomes do not depend on which *types* of measurements are made. The **DVs** for these systems may be correlated through pre-established harmony (at the moment of their creation) or may nonlocally interact with one another at every moment. The possible existence of nonlocal influences or holistic properties has no direct bearing on the fact that passive measurement accounts (**PM-DVs**) and measurement-*type* independent accounts (**TI-DVs**) cannot produce the theoretically predicted statistics.

The preceding argument does, however, have an important implication regarding a connection between locality and determinism. The argument ruled against all **DV** accounts except the **TD-DVs**, and we pointed out earlier that the only deterministic **TD-DV** interpretations are those in which outcomes depend on the *type* of *distant* measurement performed. So, as a corollary to the argument, it follows that the only deterministic interpretations consistent with **ACTP** (the approximate correctness of the theoretical probabilities) are those that depend on the *distant* measurement *type*. For appropriately measured EPR-Bohm systems, such a dependence must involve either a nonlocal or holistic connection between outcomes and *distant* measurements.[9] The discussion of nonlocality and holism in the next section will make this claim more precise.

Purely local, nonholistic versions of the stochastic measurement-*type* dependent interpretations (both stochastic **TD-DVs** and **IVs**) may still appear to be live options. The next section is primarily devoted to showing that only nonlocal or holistic versions of these interpretations are consistent with the approximate correctness of the theoretical predictions.

4. NONLOCALITY AND HOLISM

Our treatment of nonlocality and holism will begin with an analysis of these two concepts. This is followed by a brief look at one way of arguing that EPR-Bohm systems are either nonlocally or holistically connected. The rest of the section is devoted to constructing a Bell argument for this claim.

4.1

We will say that the world is *Locally Subdivisible* (more simply, *local*) if for every short time interval there is some distance great enough that no two events separated by a greater distance can causally influence one another during the time interval.[10] *Locality* is the thesis that the world is locally subdivisible. Call any pair of events so separated in space and time *Locally Isolated* from each other. Nonlocality is just the thesis that the world is not local.

Locality should be distinguished from another concept with which it is closely associated. We will say that causal influences between events are *Contiguously Mediated* just in case they propagate as contiguous sequences of intervening events across space and time. If all influences between events are contiguously mediated and the world is locally subdivisible, then an event can only be *directly* affected by other events that are both nearby and in the immediate past (assuming that events can only be influenced by earlier events). Events in the more distant past can have only a mediated effect here and now, through their influence in bringing about recent, nearby events. Both locality and contiguous mediation are tied to the special theory of relativity in spirit, though perhaps not written into the letter of its laws.

Locality and contiguous mediation are logically independent theses. Unmediated influences might abide by a speed limit, so distant concurrent events could still be locally separable. On the other hand, influences that propagate instantaneously might do so by initiating a contiguous chain of instantaneous intervening events. Such influences would be contiguously mediated, but would still violate locality. The Bell argument of this section shows that if the theoretical probabilities for outcomes provided by quantum mechanics are approximately correct (i.e. if **ACTP** holds), then EPR-Bohm systems violate *locality* unless they are holistically connected. Contiguous mediation is not directly at issue.

Holism is a much less precise concept than locality. For our purposes it will suffice to contrast holism with nonlocality. A *holistic connection* between events is any real, systemic relationship among them that is neither due to causal influences between them nor to properties and dispositions carried by them from their common causal past. On the other hand, a nonlocal influence is a causal influence on which there is no speed limit. Any more precise distinction between causal influences and holistic relationships will depend on the nature of *causal influences*.

For positivists, Humeans, and other regularity accounts of causation there can be little real difference between nonlocality and holism. If there are no causal influences, then even local *processes* are merely constant correlations. Correlations between *locally isolated* systems are no different; they just occur farther apart. Without *influence*, locality itself would be of little interest were it not for the role it plays in the special theory of relativity.

Above we described the notion of *locality* in terms of causal influences. If there are no causal influences, another sense can be given to the term. In the context of the special theory of relativity, *locally isolated* pairs of events could be *defined* as those with space-like separation – i.e. pairs of events with no absolute, reference frame independent temporal order. These coincide with the pairs of events that could not be connected by influences traveling at light speed or slower (if influences existed). If the special theory is right about this, and if 'causation' is just constant succession, then the ambiguity in order of succession for isolated pairs suggests that they should not be described as *causally related*. So, the Humean may have reason to draw a distinction between *holistically* related nonlocal constant correlations, on the one hand, and *causally* related local correlations, on the other, where the distinction involves the existence of an absolute temporal order, rather than influences.

If *causal influences* are real, and causation is not merely constant correlations, then a *holistic connection* is any real systemic relationship that brings about correlations among events – correlations that are not due to causal influences between the events and are not simply the result of their separate individual properties. Holistic relationships may, of course, obtain between events that are not locally isolated, as well as those that are. Cases of holistic connectedness may be difficult to empirically establish as holistic, especially if the correlated events are not locally isolated. For correlated events that are not locally isolated it may be difficult to rule out the possibility that some unknown *hidden* causal process is at work. However, if the world is local regarding influences, then any real, repeatable correlations between pairs of locally isolated events will be strong evidence for holistic connectedness. If there are such correlations, and if they cannot be due to a common causal factor locally carried by the parts, then these correlations can only be due to a holistic systemic relationship or to a vast coincidence.

The success of the special theory of relativity provides strong grounds for thinking that there is a speed limit for causal influences. Space-like separated events have no absolute temporal order, so there is no absolute sense in which one isolated event can causally influence another, unless causal order somehow supersedes temporal order. Each event of a mutually isolated pair occurs before the other in some reference frame. So, if the special theory of relativity is correct and yet *there are repeatable correlations beween certain pairs of locally isolated events not attributable to comon factors*, then there is compelling reason to think that these correlations, at least, are due to holistic connectedness.[11] The arguments of this section will show that if certain well confirmed theoretical predictions (**TP**) from quantum mechanics are approximately correct, then *there are such correlations between pairs of locally isolated events.*

4.2

One way to argue that there must be either nonlocal influences or holistic connections is to invoke *Constant Correlations* (or anti-correlations):[12]

> **Const-Corr** (Constant Correlation): Whenever the same kind of measurement, X, is performed on both the L and R parts of a ψ-system, either the joint outcomes are (X_L^+ & X_R^+) or they are (X_L^- & X_R^-); this holds for A, B, C, and D substituted for X.

If the theoretical predictions (**TP**) for ψ-systems are approximately correct, then **Const-Corr** must either conflict with locality or endorse holism. To see why, suppose that the world is locally subdivisible, and consider the measurement events on the distant parts of ψ-systems. Each measurement event consists of the performance of one measurement (of *type* A_L, B_L, C_R, or D_R) and the registration of its outcome. It is possible to perform a measurement (and register an outcome) on each part, L and R, of a ψ-system almost simultaneously, and at locations as widely separated as needed in order to make the measurement events locally isolated from one another. The *type* of measurement each device is configured to perform can be continually and randomly reset in order to insure that neither measurement event can be influenced by the *type* of measurement performed during the other. Any such pair of measurement events should be locally isolated if the world is local.

Constant correlation guarantees that if the two measurement events on separate parts of a ψ-system should happen to employ the *same types* of measurements, their outcomes would agree. The odds against the chance occurrence of such agreements for millions of ψ-systems are astronomical. So there appear to be only three plausible explanations of the agreements. *Either*, (i) the parts of the system *agreed in advance* on which outcomes they would yield for each kind of measurement, or (ii) the parts nonlocally influence one another so as to come to agreement when measured the same way, *or* (iii) the parts exhibit a holistic correlation property possessed by the system that is not locally carried by the separate parts. But agreement in advance would entail the existence of either some kind of passive measurement definite values (**PM-DVs**) at the moment of measurement or the existence of deterministic *type*-dependent **DVs** – i.e. the *agreed values* would either be **PM-DVs** or deterministic **TD-DVs**. The Bell argument of the previous section ruled out **PM-DVs** if the theoretical predictions are approximately right (as specified in **ACTP**). And all deterministic **TD-DVs** are essentially dependent on the *type* of *distant* measurement performed, which clearly must be a non-local or holistic connection, given the measurement setup. So, if **Const-Corr** and **ACTP** hold, the events that satisfy **Const-Corr** must be either nonlocally or holistically connected after all.

The constant correlation path to nonlocality or holism has both strengths and weaknesses. Constant correlation is plausible because in quantum mechanics it arises from a conservation law, and quantum mechanics is a well confirmed theory. **Const-Corr** itself *appears* to be pretty well confirmed. But the experiments that confirm it are imperfect, since one doesn't find exact correlations in the experimental data. Detectors in measuring devices are inefficient (they miss some detections), and they may sometimes give false readings. So the raw data from experiments is processed using a statistical model of the *random errors* in detections. This leaves some room for doubt as to whether **Const-Corr** is literally true. If the percentage of real violations of **Const-**

Corr is sufficiently small, violations may mistakenly be discounted as errors. **Const-Corr** may only be a good approximation. If it is just an approximation, then the argument from **Const-Corr** collapses. The following Bell argument will establish the existence of either nonlocal causal influences or holistic connectedness without invoking **Const-Corr**.

4.3

In the remainder of this section we will explore another path to either nonlocality or holism. Our route is similar to Bell's (1971), Clauser and Home's (1974), and Jarrett's (1984, 1989), but is more direct, employs a simpler version of the generalized Bell inequality, and does not *assume* that the probabilities involved are classical. The argument will rely only on certain minimal, explicitly stated assumptions about the probabilities and the logic – assumptions that even a quantum logician should grant. We will take the conclusion of the previous Bell argument as granted: there are no passive measurement definite values and outcomes depend essentially on the *type* of measurement performed. So in the following Bell argument we need only consider those interpretations left standing by the previous Bell argument, the indeterminate value (**IV**) accounts and the measurement-*type* dependent definite value (**TD-DV**) accounts.

Our argument will proceed as a *reductio*. We will show that if the theoretical probabilities for measurement outcomes satisfy two very weak assumptions, then the conjunction of two strong theses, warranted by locality and nonholistic separability, leads to a Bell inequality. This runs contrary to the inequality given by *Contra-Bell*. But Section 2 showed that the approximate correctness of the predicted probability values, as specified in **ACTP**, implies the inequality in *Contra-Bell*. So if **ACTP** is right and the two weak assumptions hold, then one of the strong theses must be rejected. It will follow that locality must fail unless there are holistic connections. We present the two weak assumptions first.

> **TOTPROB** (Total Probability): For each measurement-*type* X_L (i.e. A_L or B_L) and Y_R (i.e. C_R and D_R), $P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi) + P(X_L^- \mid X_L \,\&\, M_R \,\&\, \psi) = 1$ and $P(Y_R^+ \mid M_L \,\&\, Y_R \,\&\, \psi) + P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi) = 1$.

TOTPROB is simply the requirement that when a part of a ψ-system is measured for a particular property X_L, the probabilities for the possible outcomes sum to 1.

The second weak assumption is the following:

> **COND** (Conditionalization): For X_L (either A_L or B_L) and Y_R (either C_R or D_R),
> $P(X_L^+ \ \&\ Y_R^- \mid [X_L \ \&\ Y_R \ \&\ \psi])$
> $= P(X_L^+ \mid Y_R^- \ \&\ [X_L^+ \ \&\ Y_R \ \&\ \psi])$
> $\times P(Y_R^- \mid [X_L \ \&\ Y_R \ \&\ \psi])$, (and similarly for $(X_L^- \ \&\ Y_R^+)$).

COND says that if a system is in state ψ and measurements X_L and Y_R are performed, then the probability of their joint outcomes is the product of the probability of one outcome given the other and the probability of the other outcome. **COND** is a *theorem* if the probability function P satisfies the classical axioms. We will not assume that P is classical, however, but only that P satisfies the two preceding and the two following conditions. **TOTPROB** and **COND** are clearly very weak assumptions, and quantum mechanics employs them both.

Next we present the two strong theses. Both are warranted if measurement events are locally isolated from one another and are not holistically connected.

> **DMI** (Distant Measurement Independence): For X_L and Y_R ranging over $\{A_L, B_L\}$ and $\{C_R, D_R\}$ respectively,
> $P(Y_R^- \mid X_L \ \&\ [Y_R \ \&\ \psi]) = P(Y_R^- \mid M_L \ \&\ [Y_R \ \&\ \psi])$, (and similarly with X_L and Y_R everywhere exchanged, and also with '+' and '−' everywhere exchanged).[13]

DMI says that the outcome of a measurement on one part of a ψ-system does not stochastically depend on the *type* of measurement performed on a distant part. If **DMI** were violated, then superluminal signaling would be possible. Suppose, for example, that $P(C_R^- \mid A_L \ \&\ [C_R \ \&\ \psi])$ differs measurably from $P(C_R^- \mid B_L \ \&\ [C_R \ \&\ \psi])$. Place the measuring devices as far apart as you like and half way between them place a ψ-system generator that creates a continual rapid fire sequence of systems. The generator might produce L and R beams of photons, for example, where each photon in the L beam is part of the same ψ-system as a photon in the R beam. By changing the measurements on the L parts from A_L to B_L for a few seconds, a person in control of the L device would bring about a simultaneous change in the percentages of

C_R^+ and C_R^- observed on the R parts. The beam intensity for C_R^+ relative to C_R^- would alter correspondingly. So by modulating the L device a person could send a message almost instantaneously to someone observing the C outcomes at the R device.

Superluminal signaling would involve a very strong kind of nonlocal influence, and it is inconsistent with the usual picture of space-time and causal processes associated with the special theory of relativity. Quantum mechanics itself seems to endorse **DMI**, and there is no experimental evidence that **DMI** is ever violated. So **DMI** is very likely true.

It should also be noted that deterministic **TD-DVs** need not violate **DMI**. Distant measurements may play a role in determining individual outcomes case by case. But this influence need not show up stochastically (in **DMI**) if the percentage of systems in which A_L^+ is produced for an A_L measurement and a distant C_R measurement is the same as the percentage of systems that produce outcome A_L^+ when D_R is measured instead – and if a similar condition exists for all other measurements and outcomes.

The second strong thesis employed in the Bell argument is:

> **DOI** (Distant Outcome Independence): For X_L and Y_R ranging over $\{A_L, B_L\}$ and $\{C_R, D_R\}$ respectively,
> $P(X_L^+ \mid Y^- \;\&\; [X_L \;\&\; Y_R \;\&\; \psi]) = P(X_L^+ \mid [X_L \;\&\; Y_R \;\&\; \psi])$,
> and similarly for X_L^- and Y_R^+.[14]

DOI says that the outcome of a measurement on the R part of a ψ-system is probabilistically irrelevant to the outcome of the measurement on the L part. In other words, the outcome of the R measurement event neither stochastically influences nor carries stochastically relevant information about what the L outcome will be. This is indeed a strong assumption, but an assumption that would be warranted *if* causal influences are strictly local, *and if* there are no holistic connections, *and if* the separate parts and their local environs carry no significant correlated properties from their common causal past. Certain probabilities given by quantum mechanics itself violate **DOI**.[15]

The only physically meaningful way in which **DOI** can fail in a local nonholistic world is for some *common causal* factor – arising at the creation of the ψ-system and carried thereafter by each part – to influence the parts so as to make the measurement outcomes of each stochastically indicative of the other. If such causally relevant properties do contribute to the outcomes of parts, then these properties cannot be passive measurement definite values, and the outcomes to which they contribute must depend nontrivially on the *types* of measurement performed on the parts. The previous Bell argument established that much. So any such properties can at best contribute stochastically to the outcomes. We will investigate such *common cause* accounts of the failure of **DOI** after developing the first part of the Bell argument.

The argument proceeds as follows. First we construct a Bell argument that shows that either **DOI** or **DMI** must fail. So, unless there are *common causal* factors responsible for the failure of **DOI**, either locality or nonholistic separateness must fail. We then consider *common cause* accounts, and produce an extended Bell argument that shows that they, too, must either violate locality or support holism.

The two weak assumptions about the theoretical probabilities, **TOTPROB** and **COND**, taken together with the pro-locality, anti-holistic theses, **DMI** and **DOI**, warrant the following derivation. Let 'X_L' represent either A_L or B_L, and let 'W_L' stand for the other L measurement, B_L, or A_L, respectively. Similarly, let 'Y_R' represent either C_R or D_R, and let 'Z_R' stand for the other R measurement. Then,

$$\begin{aligned}
&P(X_L^+ \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi])\\
&\quad = P(X_L^+ \mid Y_R^- \,\&\, [X_L \,\&\, Y_R \,\&\, \psi])\\
&\qquad \times P(Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi]), && \textbf{COND}\\
&\quad = P(X_L^+ \mid [X_L \,\&\, Y_R \,\&\, \psi])\\
&\qquad \times P(Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi]), && \textbf{DOI}\\
&\quad = P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi)\\
&\qquad \times P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi), && \textbf{DMI}\\
&\quad = P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi) \times P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi)\\
&\qquad \times \{P(W_L^+ \mid W_L \,\&\, M_R \,\&\, \psi) + P(W_L^- \mid W_L \,\&\, M_R \,\&\, \psi)\}\\
&\qquad \times \{P(Z_R^+ \mid M_L \,\&\, Z_R \,\&\, \psi) + P(Z_R^- \mid M_L \,\&\, Z_R \,\&\, \psi)\},\\
& && \textbf{TOTRPOB}\text{; thus,}
\end{aligned}$$

$$\begin{aligned}
(3)\quad &P(X_L^+ \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi])\\
&\quad = \{P(W_L^+ \mid W_L \,\&\, M_R \,\&\, \psi) \times (P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi)\\
&\qquad \times P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi) \times P(Z_R^+ \mid M_L \,\&\, Z_R \,\&\, \psi)\}\\
&\qquad + \{P(W_L^+ \mid W_L \,\&\, M_R \,\&\, \psi) \times P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi)\\
&\qquad \times P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi) \times P(Z_R^- \mid M_L \,\&\, Z_R \,\&\, \psi)\}\\
&\qquad + \{P(W_L^- \mid W_L \,\&\, M_R \,\&\, \psi) \times P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi)\\
&\qquad \times P(Y_R^- \mid M_L \,\&\, Y_R \,\&\, \psi) \times P(Z_R^+ \mid M_L \,\&\, Z_R \,\&\, \psi)\}\\
&\qquad + \{P(W_L^- \mid W_L \,\&\, M_R \,\&\, \psi) \times P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi)
\end{aligned}$$

$\times$ P(Y_R^- | M_L & Y_R & ψ) $\times$ P(Z_R^- | M_L & Z_R & ψ)}, by arithmetic.

Substituting 'A' or 'B' for 'X' (and 'B' or 'A' for 'W') and substituting 'C' or 'D' for 'Y' (and 'D' or 'C' for 'Z') into Equation (3) generates four equations with the structure of (3). Note that in the equation generated by (3) with 'B_L' and 'D_R' substituted for 'X' and 'Y', the '+' and '−' must be exchanged throughout (3) so that an equation for P(B_L^- & D_R^+ | B_L & D_R & ψ) is generated.

By comparing the right-hand sides of the four generated equations it is easy to verify that:

$$\begin{aligned}(4)\qquad & P(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi)\\ &\quad \leq P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi)\\ &\quad + P(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi)\\ &\quad + P(B_L^- \,\&\, D_R^+ \mid B_L \,\&\, D_R \,\&\, \psi).\end{aligned}$$

This is a Bell inequality. But, if **ACTP** holds – i.e. if the theoretically predicted values for these probabilities are correct within ±0.03 – the *Contra-Bell* inequality should hold. Therefore, **ACTP** and the weak assumptions **TOTPROB**, and **COND**, together imply that either **DMI** or **DOI** must be false.

We've already commented that if *distant measurement independence* (**DMI**) is violated, then the world must exhibit a stark kind of nonlocality, a nonlocality that permits faster than light signaling, and hence is in sharp conflict with the special theory of relativity. On the other hand, if distant outcome independence (**DOI**) is false, then *either* the world is nonlocally or holistically connected, *or else* there are stochastically relevant *hidden states* – *common causal factors* that influence the outcomes but are not represented by the state ψ of the system.[16]

If the failure of **DOI** is due to some kind of nonlocal influence between outcomes, then the kind of nonlocality engendered is not so stark as that which arises from the failure of **DMI**. The nonlocality associated with the failure of **DOI** does not by itself imply the possibility of faster than light signaling. Even if the outcome for the L part of a system is nonlocally influenced by the outcome of the R measurement, this influence may not be exploitable for superluminal *signaling*. A person at R cannot effectively modulate the R *outcomes* in a way that affects the percentages for L outcomes (see Shimony 1984). This characteristic of the connectedness engendered by **DOI** is suggestive of holism rather than nonlocality (see, e.g. Teller 1986, 1989; Cartwright 1989; and many of the papers in Cushing and McMullin, 1989).

4.4

Now let's turn to *common cause* accounts of the failure of **DOI**. They seem to offer the only hope for avoiding nonlocality and holism. We'll show that appeal to *common causes* provides no refuge.

Suppose that each ψ-system is subject to some additional causal factor, perhaps arising with the creation of the system, that influences the outcomes of measurements in a way not captured by the state of the system, ψ. These additional factors can be represented as supplementary *hidden states* for the systems. Let $\Gamma = \{\lambda_1, \lambda_2, \ldots\}$ be the set of all possible such hidden states for ψ-systems. For the sake of simplicity we take Γ to be a countable (perhaps infinite) set of possible hidden states, but all of the following considerations are easily extendable to a continuum of hidden states (see associated endnotes). Each state λ_i is to represent a complete collection of the hidden factors in any ψ-system that possesses it, so no ψ-system possesses more than one member of Γ. A state λ_i is intended to represent all of the hidden causal factors for both the L and R parts of a ψ-system. Perhaps λ_i is separable into L and R components, and perhaps λ_{Li} and λ_{Ri} are purely local, noninteracting states of their respective parts; or perhaps they change over time and are in instantaneous nonlocal contact. Tell any story you like; it will not matter so long as the λ_i satisfy each of following six conditions.

The first condition on hidden states captures the idea that motivated the consideration of hidden stochastic states in the first place:

$$\textbf{DOI-}\boldsymbol{\Gamma}\text{:}\quad \forall\lambda_i \in \Gamma,\ P(X_L^+ \mid Y_R^- \ \&\ [X_L \ \&\ Y_R \ \&\ \psi \ \&\ \lambda_i]) = P(X_L^+ \mid [X_L \ \&\ Y_R \ \&\ \psi \ \&\ \lambda_i]).$$

DOI-Γ says that relative to any state, the outcome of an L measurement is independent of the outcome of the R measurement. The idea is that whatever relevance an R outcome has for the L outcome is due solely to the evidence it provides regarding which state, λ_i, is present. And it is the state (or causal factor) λ_i that directly influences the L outcome. If **DOI-Γ** fails, then the prima facie case in support of either onlocality or holism, due to failure of **DOI** cannot be avoided by appeal to hidden states.

The situation posed by hidden states is somewhat analogous to the relevance of past outcomes to the next in successive tosses of a bent coin. The percentage of heads in past tosses is relevant to the likelihood of heads on the next toss, but only as evidence for the degree to which the coin is biased. The bias is the common causal factor for outcomes. Given the actual degree of bias, all past tosses are irrelevant to the likelihood of heads on the next toss. The actual bias or disposition to produce heads *screens off* the next toss from the relevance of past tosses. Similarly, if the measurement event on one part of a ψ-system is locally isolated from the distant event and not holistically connected with it, but the outcome of one is relevant to the other (in violation of **DOI**), then there must be some common causal factor that gives rise to the relevance. But, relative to the common causal factor, the outcome of each measurement event will be *screened off* from the other. The members of Γ play the role of such causal factors, and **DOI-Γ** says that these stochastic states screen off the relevance of the R measurement outcome for the L outcome.

Γ is supposed to be an exhaustive collection of the hidden states that a ψ-system might possess at the time of measurement. Hence, the theoretically predicted probabilities (in **TP**) should be related to probabilities due to the stochastic hidden states as follows:

SUM-Γ: $P(X_L^+ \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi)])$
$= \Sigma_i\, P(X_L^+ \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi] \,\&\, \lambda_i)$
$\times\, P(\lambda_i \mid [X_L \,\&\, Y_R \,\&\, \psi])$ and similarly for X_L^- and Y_R^+.[17]

SUM-Γ says that the probability for an outcome relative to state ψ is equal to the average of the likelihoods of that outcome due to each of the various possible λ_i, weighted by the likelihood with which each hidden state λ_i occurs. Γ is supposed to contain all possible hidden states, and no two hidden states can both be present in an individual ψ-system; hence, if P is a classical probability function, **SUM-Γ** is a theorem. Though we are not assuming that these probabilities are classical, **SUM-Γ** is a very plausible, weak assumption. If such hidden states exist, then surely **SUM-Γ** should hold.

The hidden state that occurs for a particular 'ψ-system should not itself depend on the *types* of measurements performed on the parts of the system. Rather the hidden states together with measurements stochastically influence outcomes. Thus we have the following condition:

SMI-Γ (State Measurement Independence):
$\forall\lambda_i \in \Gamma$, $P(\lambda_i \mid X_L \,\&\, Y_R \,\&\, \psi) = P(\lambda_i \mid M_L \,\&\, M_R \,\&\, \psi)$.[18]

Weak assumptions corresponding to **TOTPROB** and **COND** should hold relative to the hidden states as well.

TOTPROB-Γ: $\forall\lambda_i \in \Gamma$,
$P(X_L^+ \mid X_L \,\&\, M_R \,\&\, \psi \,\&\, \lambda_i) + P(X_L^- \mid X_L \,\&\, M_R \,\&\, \psi \,\&\, \lambda_i) = 1$, and similarly for Y_R.

TOTPROB-Γ is just the requirement that, relative to any state λ_i, the probabilities for the possible outcomes that may result from a measurement of type X_L must sum to 1.

COND-Γ: $\forall\lambda_i \in \Gamma$, $P(X_L^+ \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi \,\&\, \lambda_i])$
$= P(X_L^+ \mid Y_R^- \,\&\, [X_L \,\&\, Y_R \,\&\, \psi \,\&\, \lambda_i])$
$\times P(Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi \,\&\, \lambda_i])$,
and similarly with '+' and '−' uniformly exchanged.

This assumption says that if a system is in state ψ together with hidden state λ_i, and measurements X_L and Y_R are performed, then the probability of their joint outcomes is the product of the probability of one outcome given the other, multiplied by the probability that the other outcome will occur. If the probability function P occurring in the theoretical probabilities (**TP**) satisfies the classical axioms, then both **TOTPROB-Γ** and **COND-Γ** are *theorems*. If the λ_i exist, then **TOTPROB-Γ** and **COND-Γ** appear to be unassailable.

The final thesis is the Γ-counterpart of distant measurement independence (**DMI**):

DMI-Γ: For X_L and Y_R ranging over $\{A_L, B_\}$and $\{C_R, D_R\}$ respectively, $P(Y_R^- \mid X_L \,\&\, [Y_R \,\&\, \psi \,\&\, \lambda_i]) = P(Y_R^- \mid M_L \,\&\, [Y_R \,\&\, \psi \,\&\, \lambda_i])$, (and similarly with X_L and Y_R everywhere exchanged, and also with '+' and '−' exchanged).

Unlike **DMI**, the failure of **DMI-Γ** would not by itself imply faster than light *signaling*, since the λ_i may be undetectable. Without knowing which λ_i from Γ is present one cannot detect the effects of changes in a distant measurement set-up. But although the possibility of faster than light *signaling* doesn't follow from the failure of **DMI-Γ**, its failure would indicate the existence of some sort of nonlocal interaction between measurements and distant outcomes. This would appear to be a case of nonlocal interaction, rather than of holistic connection, because changing the *type* of measurement on one part would have an immediate distant influence – though the effect may not be apparent unless the hidden state can be detected.

It is worth noticing that deterministic **TD-DVs** are compatible with **DOI-Γ** but not with **DMI-Γ**. Suppose each system has deterministic dispositions that, relative to the *types* of measurements performed, deterministically produces '+' or '−' on each possible measurement outcome. Since we are dealing with deterministic **TD-DVs**, these dispositions must depend in part on the *type* of distant measurement performed in determining the outcomes. Let the states in Γ represent the various possible complete collections of deterministic dispositions that a system may possess. Then, for each λ_i in Γ, $P(X_L^+ \mid Y_R^- \,\&\, [X_L \,\&\, Y_R \,\&\, \psi \,\&\, \lambda_i])$ should equal $P(X_L^+ \mid [X_L \,\&\, Y_R \,\&\, \psi \,\&\, \lambda_i])$, which should equal 1 or 0, depending on whether the measurements performed *determine* X_L^+ or X_L^- as the outcome for deterministic hidden state λ_i. But $P(Y_R^- \mid X_L \,\&\, [Y_R \,\&\, \psi \,\&\, \lambda_i])$ should be 1 and $P(Y_R^- \mid W_L \,\&\, [Y_R \,\&\, \psi \,\&\, \lambda_i])$ should be 0 for some states in Γ, since for some total deterministic states different distant measurement *types* will determine different outcomes. This observation reinforces the fact that *deterministic* **TD-DVs** must be nonlocally or holistically dependent on the distant measurement. Only *stochastic* **TD-DVs** and **IVs** have a shot at satisfying both **DOI-Γ** and **DMI-Γ**.

Now, a Bell-inequality looms once more. By the same derivation as in Equations (3), but now relativized to λ_i, we get a result analogous to (4):

(5) for each λ_i in Γ,

$$\begin{aligned} &P(A_L^+ \,\&\, C_R^- \mid A_L \,\&\, C_R \,\&\, \psi \,\&\, \lambda_i)\\ &\quad \leq P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi \,\&\, \lambda_i)\\ &\quad + P(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi \,\&\, \lambda_i)\\ &\quad + P(B_L^- \,\&\, D_R^+ \mid B_L \,\&\, D_R \,\&\, \psi \,\&\, \lambda_i). \end{aligned}$$

This inequality follows from **COND-Γ**, **DMI-Γ**, **TOTPROB-Γ**, and arithmetic. Now, multiply both sides of inequality (5) by $P(\lambda_i \mid M_L \,\&\, M_R \,\&\, \psi)$, and then sum both left and right over all λ_i.[19] Then by **SMI-Γ** and **SUM-Γ** we get the Bell inequality (4) again:

$$P(A_L^- \,\&\, C_R^+ \mid A_L \,\&\, C_R \,\&\, \psi) \leq$$

$$P(A_L^+ \,\&\, D_R^- \mid A_L \,\&\, D_R \,\&\, \psi)$$
$$+ P(B_L^+ \,\&\, C_R^- \mid B_L \,\&\, C_R \,\&\, \psi)$$
$$+ P(B_L^- \,\&\, D_R^+ \mid B_L \,\&\, D_R \,\&\, \psi).$$

Once again **ACTP** is violated. However, this time we assumed the existence of hidden states. The idea was to maintain locality and avoid holism by blaming the previous failure of **DOI** on *hidden* causal factors or states. If there are such hidden stochastic states, assumptions **TOT-PROB-Γ** and **COND-Γ** are as innocuous as their non-Γ-relative counterparts were. And clearly the hidden states present in a system, which are supposed to combine with measurements in order to produce outcomes, should not themselves depend for their existence on which measurements will be performed on the system. So **SMI-Γ** is plausible. **SUM-Γ** is the obvious way to connect hidden-state probabilities with the theoretically predicted values, and it would be a theorem if P were a classical probability function, so there is absolutely no reason to object to it. So, given the approximate correctness of the theoretically predicted probabilities (**ACTP**), either **DMI-Γ** must go, or else there is no set of hidden states, Γ, satisfying **DOI-Γ**. In the latter case there are no *hidden* causal factors, so the failure of **DOI** is unmitigated; distant outcomes either influence each other nonlocally, or else they are holistically related. But, if there are hidden states satisfying **DOI-Γ**, then **DMI-Γ** must fail. In that case ψ-systems are nonlocally or holistically influenced; the *type* of measurement performed must influence distant outcomes in a nonlocal or holistic way. In either case there must be some sort of nonlocal influence or holistic connectedness.

5. DUTCH BOOK

The Bell argument of Section 3 demonstrated that the theoretical probabilities (**TP**) require measurement outcomes for ψ-systems to depend nontrivially on the *types* of measurements performed. In this section we will take a different route to the same conclusion. We will develop a dutch book argument for measurement-*type* dependence.

In Section 3 we demonstrated that measurement-*type* independent accounts must be one of two kinds – either **PM-DV** (passive measurement definite value) or **TI-DV** (measurement-*type* independent definite value). For any of the **PM-DV** views recall that underlined expressions like $\underline{A}_L^+$ represent the *pre-measurement* values responsible for the outcome (e.g. A_L^+) of a measurement, A_L. For **TI-DV** views, we let underlined expressions like $\underline{A}_L^+$ represent **DV**s *produced* by the measurement. But the **TI-DV**s produced do not depend on the particular *type* of measurement performed. The *measurement-type* merely plays the role of exposing one of the produced **DV** – e.g. if $\underline{A}_L^+$ is one of the **DV**s produced and the *type* of measurement performed happens to be A_L, then the outcome A_L^+ results.

Suppose that in spite of our Bell argument in Section 3 someone persists in believing that one of the measurement-*type* independent accounts is viable. Let's call this person *the mark.* We will show that his view makes him vulnerable to a *dutch book.* A collection of bets on outcomes of a ψ-system, which he should be willing to accept as fair, will guarantee him a net loss. We take this as a *reductio* against his view. If the mark is open to a bit of wagering, we will show you how to take his money.

Given the mark's view that there are measurement-*type* independent **DV**s, he will surely agree with the probabilistic equivalences in Equation set (2) of Section 3. After all, they just say that the probabilities for the *occurrence* of the **DV**s (given that some measurement is made) are the same as the probabilities for the *outcomes* that result from the particular *types* of measurements. The mark will agree with this, since he believes that the outcomes of measurements simply reflect the **DV**s that are present – present before measurement for **PM-DV** views, or present as the result of measurement for **TI-DV** views. Once he is clear on the probabilities, you are ready to introduce him to the game.

You offer the mark a game of chance involving a special gambling device; this device is a ψ-system generator with appropriate measuring devices on either side.[20] The mark is to assume the role of *the house*, and will have an "advantage" (described below), as the house always does. You will place wagers against the mark on various possible **DV**s.[21] All wagers will be placed at fair betting odds, as represented by the probabilities in (2). The mark will decide which measurements to make, and he will set the measurement devices accordingly.

Point out to the mark that you will make your wagers before he decides which measurements to make. This may result in some of your wagers being placed on unmeasured **DV**s. This is where the mark, playing the role of the house, derives his advantage. Since the measurements will only *reveal* one **DV** on the left and one **DV** on the right, the game has a special rule for settling bets on the unmeasured **DV**s:

> The mark will be permitted to "guess" the values of the unmeasured **DV**s, and is invited to guess the presence of those **DV**s on which the pay-offs on the present wagers will be to his own greatest advantage. All bets will be settled on the basis of the "guessed" values together with the known values indicated by the actual measurement outcomes.

This way of settling bets on unmeasured **DV**s bends over backwards to give the mark what should be, from his point of view, an advantage. After all, on his view, the unmeasured **DV**s do have definite, though unknown, values. And since you will settle such bets as though the unknown values turned out to his greatest advantage, the mark gets every benefit of the doubt. Hence, he should agree to this arrangement. If the mark agrees, you're ready for the sting.

Here are the bets you should place. The probability for the occurrence of ($\underline{A}_L^+$ & $\underline{C}_R^+$) is $\frac{1}{2}$, so the odds against these **DV**s occurring is one to one. You should bet \$40 that this outcome *will not* occur. If it does occur (or is guessed to occur) then you will pay the mark \$40. If it doesn't occur, he will pay you \$40. You should also bet \$10 that ($\underline{A}_L^+$ & $\underline{D}_R^-$) *will* occur. Since the probability of this event is $\frac{1}{8}$, the fair betting odds *for* this event are one to seven (seven to one against). So your wager that this event will occur requires the mark to pay you \$70 if it does occur (or is guessed to occur) and requires you to pay him \$10 otherwise. At the same odds, you also bet \$10 *for* the occurrence of ($\underline{B}_L^+$ & $\underline{C}_R^-$), and \$10 *for* the occurrence of ($\underline{B}_L^-$ & $\underline{D}_R^+$). For each of these bets, you will win \$70 if the event occurs (or is guessed to occur), and you will pay the mark \$10 if it does not.

Place these bets and invite the mark to make his measurements on a single ψ-system. Once he has done so, he is to make his guesses for unmeasured values. *Whatever* the measured outcomes, and *whatever* guesses the mark makes about the unmeasured values, the mark will owe you \$10.

To see that you must win \$10, consider the following case. Suppose the mark measures (B_L & D_R). If the outcome is (B_L^- & D_R^+) then the mark clearly owes you \$70 on this bet. And, whatever he guesses about unmeasured values, you pay him at most \$40 + \$10 + \$10 = \$60 on the other three bets, netting you \$10.

Now suppose the mark measures (B_L & D_R), but the outcome is not (B_L^- & D_R^+). Then the measured outcome includes B_L^+, or D_R^-, or both. Now, notice that if the mark guesses that (A_L^+ & C_R^-) *does not* occur, then he must pay you \$40 on that bet and you pay him \$10 each on the other three bets, and you would net \$10. So, the mark better guess that ($\underline{A}_L^+$ & $\underline{C}_R^-$) *does occur*. But then, if B_L^+ was measured the mark must pay you \$70 on your bet for ($\underline{B}_L^+$ & $\underline{C}_R^-$), since $\underline{C}_R^-$ was guessed to occur, and again you net \$10. On the other hand, if D_R^- was among the measured values, then ($\underline{A}_L^+$ & $\underline{D}_R^-$) results from the guess, since $\underline{A}_L^+$ was guessed to occur, and the mark still owes you \$10.

If the mark had made measurements for any other values, a similar analysis applies. As long as the mark is willing to leave bets on unmeasured values in force, he is guaranteed a net loss.

The reasonable thing for the mark to do is call off bets on unmeasured values. If one only bets on measured outcomes, then the theoretical probabilities (**TP**) are fair betting odds, and clearly no dutch book is possible. Indeed, if the theoretical probabilities are fair betting odds, a gambler can expect to nearly break even in the long run. But given the mark's commitment to the existence of measurement-*type* independent **DV**s, he has absolutely no rationale for calling off bets on unmeasured values, especially when he gets to "guess" to his own advantage as to what those values might be.

Bets that are to be called off when some condition is not met are called conditional bets, and their associated probabilities are conditional probabilities. The theoretical probabilities for ψ-systems as given by quantum mechanics must essentially be conditional probabilities, conditional on the *types* of measurement performed. And because these probabilities *must be* conditional on the *type* of measurement performed (if dutch book is to be avoided), they are incompatible with the measurement-*type* independent views associated with **PM-DV**s and **TI-DV**s. The only remaining deterministic interpretations, deterministic **TD-DV**s, must nonlocally or holistically depend on the *type* of *distant* measurement performed. The only other survivors are the stochastic **TD-DV** and the (stochastic) **IV** accounts, and Section 4 showed that they, too, must be nonlocally or holistically connected if the theoretical predictions for probabilities given by quantum mechanics are approximately correct.

6. CONCLUSION

A number of quantum mechanical systems fit our description of EPR-Bohm systems and exhibit theoretical probabilities satisfying *Contra-Bell*. The Bell arguments presented in this paper show that no matter how one interprets quantum mechanics, if the probabilities that it specifies for outcomes of measurements on EPR-Bohm systems are approximately correct, then the properties exhibited by the measurements on parts must essentially depend on the *type* of measurement performed *and* must either interact nonlocally or be holistically connected with properties of distant parts of the same system. These systems exhibit *correlation properties* that cannot be accounted for by local properties and dispositions possessed individually by their parts. In addition, although a kind of determinism is consistent with the Bell arguments, there is little reason to think that the *deterministic versions of* **TD-DV** accounts have a stronger claim to truth than the essentially stochastic survivors. Indeed, our best current physical theories give not the slightest indication of a deterministic process underlying microphysical phenomena. Thus, the classical picture of the physical world – consisting of atoms moving through the void governed *only* by deterministic interaction between local particles and fields – appears to break in two respects. The world cannot be governed *solely* by local interaction, and the world appears to be indeterministic.

The special theory of relativity weighs against the possibility of superluminal influences. There is no absolute temporal order between a pair of locally isolated (i.e. space-like separated) events; so there is no absolute sense in which one such event occurs first and then influences the development of the other. Hence the preceding Bell arguments, together with the experimental results that confirm the correctness of the quantum mechanical probabilities, attest to the existence of a real holistic connectedness among parts of some systems. This kind of connectedness has appeared to be inherent in the formalism of quantum mechanics all along, reflected in system states that are superpositions of possible states of the parts. In some such quantum states the parts are locally isolated, but in many cases they are not. Prior to Bell arguments regarding measurements on isolated parts one might have viewed superposition states as merely an artifact of the formalism of quantum theory. The Bell results suggest that the formalism presages the existence of genuine holistic, systemic properties.

Under the influence of Bell arguments philosophers of physics are increasingly coming to the conclusion that holism plays a central role in quantum systems. Teller (1986, 1989) calls this holistic connectedness between parts of systems *relational holism*. He concludes from Bell arguments that the parts of quantum systems participate in holistic relational properties that neither reduce to nor supervene upon intrinsic properties of the parts. Cartwright (1989) holds that holistic connectedness is a kind of systemic causation. She views the quantum state of the whole system as a common cause of the correlations, a systemic common cause that is neither carried by a contiguously mediated influence (e.g. by a field) nor by the individual parts from their common past.

The existence of holistic relations or systemic causes in microphysics has important implications for microphysical reductionism, and it may offer some hope of reconciling microphysics with more liberal ontologies. Microphysical reductionists often argue that *only* the most basic physical properties *possessed by individual parts* of systems can be truly causally efficacious. There can be no *higher level* or ontologically *emergent* properties – for, if there were such properties, they would either be powerless epiphenomena or, if causally empowered, they would somehow violate the microphysical laws governing the smallest parts. From these somewhat vague *observations* reductionists conclude that micro-physics is the only science that can truly claim to be about causally efficacious properties. The special sciences, as they are sometimes called, can be nothing more than epistemological placeholders for microphysics.

The classical picture offered a *compelling* presumption in favor of the claim that causation is strictly *bottom up* – that the causal powers of whole systems reside entirely in the causal powers of parts. This thesis is central to most arguments for reductionism. It contends that all physically significant processes are due to causal powers of the smallest parts acting individually on one another. If this were right, then any emergent or systemic properties must either be powerless epiphenomena or else violate basic microphysical laws. But the way in which the classical picture breaks down undermines this contention and the reductionist argument that employs it. If microphysical systems can have properties not possessed by individual parts, then so might any system composed of such parts.

Were the physical world deterministic at the microphysical level, then the reductionist might well argue that the mental or the biological are epiphenomenal at best. One might then argue that all biological entities, say, are made of microphysical stuff, so the behavior of any particular biological system is determined by deterministic microphysical events. But the success of quantum mechanics and its inherently stochastic nature call microdeterminism into question. Though a kind of nonlocal determinism can survive the Bell arguments, there is absolutely no reason to think that there is a deterministic process underlying all quantum phenomena.

Were the physical world *completely* governed by local processes, the reductionist might well argue that each biological system is made up of microphysical parts that interact, perhaps stocastically, but only with things that exist in microscopic local regions; so the biological can only be epiphenomena of local microphysical processes occurring in tiny regions. Biology reduces to molecular biology, which reduces in turn to microphysics. But the Bell arguments completely overturn this conception.

In light of the Bell arguments, the microphysical reductionist can no longer rely so casually on microdeterminism and locality to press her argument; and she must grant the ontological significance of holistic connections. For, they are a central part of *her* best account of the microphysical.

The existence of real systemic or emergent properties in the domains of the special sciences should ultimately be an empirical matter. If there are such, perhaps they *are* just systemic quantum properties of very large quantum systems. This variety of reductionism, however, need not preclude the possibility that some such properties are characteristically biological – systemic properties that only emerge in quantum systems of an appropriate organization and complexity. In any case, the reductionist presumption supported by classical determinism and locality no longer stands, and the remaining varieties of reductionism seem much less oppressive.

We'll conclude with a final observation about the implications of the Bell arguments for quantum mechanics, itself. We identified two classes of interpretations of quantum mechanics that survive the Bell arguments: measurement-Type Dependent Definite Value (**TD-DV**) interpretations, and Indefinite Value (**IV**) interpretations. Bohm's quantum potential interpretation is a **TD-DV** account, and Bohr's Copenhagen interpretation is an **IV** account. **IV** interpretations such as the Copenhagen view hold that quantum systems have no definite properties (e.g. spin, position, and momentum) until measured. But measuring devices are presumably just big quantum systems, and so have no definite properties, and register no particular outcomes, until *they* (the devices) are measured by some further device. This apparent regress gives rise to the measurement problem. All **IV** accounts are subject to the measurement problem, but **TD-DV** accounts are not. Yet both must grant the reality of either nonlocal influences or some sort of holistic connectedness. So, the **TD-DV** accounts appear, prima facie, the more plausible of the two.

NOTES

[1] Systems of this kind and their implications for 'realism' and nonlocality were first discussed by Einstein, Podolsky, and Rosen (1935). Bohm and Aharonov (1957) investigated related systems composed of photons and their polarization. We will describe the essential features of EPR-Bohm systems in Section 2.

[2] Our derivation is also related to versions developed by Belinfante (1973), Wigner (1970), and Healey (1979). Clauser and Shimony (1978) offer a version of Healey's derivation.

[3] The probabilities predicted by quantum mechanics for such measurement outcomes are pretty well confirmed by experiment (Aspect, Dalibard, and Roger, 1982; Aspect, Grangier, and Roger, 1981, 1982). So, it is reasonable to assume that they are approximately correct.

[4] For the Bohm-EPR systems usually discussed in the literature all measured properties are for components of particle spin or photon polarization along various axes.

[5] The experiment conducted by Aspect, Dalibard and Roger (1982) randomizes measurement in this way. We assume, as the experimental investigator always does, that unknown characteristics of each system to be measured do not systematically influence the type of measurement chosen for it.

[6] Quantum mechanics assigns these probability values to photon polarization measurements of correlated photons, and to spin measurements of anticorrelated spin-$\frac{1}{2}$ particles (e.g. electrons). To get these probabilities for correlated photons, A_L, B_L, C_R, and D_R must be measurements for polarization at angles (relative to some fixed axis) of 0°, 60°, 90°, and 30°, respectively; and the '+' and '−' outcomes represent polarization in the 'up' and 'down' directions, respectively. To get these probabilities for anticorrelated spin-$\frac{1}{2}$ particles the measurement angles must be doubled; the '+' and '−' outcomes represent spin 'up' and 'down', respectively, for the L particle, and 'down' and 'up', respectively, for the R particle.

We know of no quantum state that assigns these probabilities to bivalent (region) measurements of position and momentum for particle pairs. But we know of no reason why there should not be such states. If there are, then the following Bell arguments would show *directly* that a particle's position and momentum are measurement dependent and either nonlocally or holistically connected to the position and momentum of a distant particle. Otherwise, our arguments only apply *directly* to spin and polarization. But, once these claims are established for spin and polarization, there is no longer much reason to avoid them for position and momentum in accounting for the two-slit and delayed choice experiments.

[7] If one changes the angles at which photon polarization is measured to 0°, 45°, 66.5°, and 22.5° for A_L, B_L, C_R, and D_R, respectively, one may use an increased margin of error

of ± 0.05 throughout our argument. The associated probabilities assigned by quantum mechanics then become $(2 + \sqrt{2})/8$ for $(A_L^+ \ \& \ C_L^-)$ and $(2 - \sqrt{2})/8$ for each of the other three outcomes. Since, $([(2 + \sqrt{2})/8] - 0.05) > ([(2 - \sqrt{2})/8] + 0.05) + ([(2 - \sqrt{2})/8] + 0.05) + ([(2 - \sqrt{2})/8] + 0.05)$, the ± 0.05 margin of error still yields the Contra-Bell inequality. Doubling these angles will yield the same result for spin-$\frac{1}{2}$ particles.

[8] A condition called *counterfactual definiteness*, found in a number of Bell arguments for non-locality, assumes that there are true conditionals of this sort.

[9] Hellman (1982) offers a related Bell argument for this conclusion.

[10] This is only intended as a sufficient condition for the local subdivisibility of the world.

[11] Kent Peacock (private communication) suggests a model on which the idea that causal order supersedes temporal order might make sense. Suppose all causal influences are contiguously mediated, and that contiguous mediation imposes an absolute order among immediately contiguous events in some physically meaningful way. For instance, we could think of events as causally connected if and only if they are connected by a particle trajectory. Then, among time-like and light-like separated events causal order will follow temporal order. But there may be causally connected space-like separated events. If there are space-like separated causally connected events, then for such events effects would precede causes in some frames of reference. This would be an odd effect, but perhaps not much odder than holism, nonlocality, and other QM oddities. The point is that if causation is really a matter of contiguous mediation of whatever sort, then mere temporal order may be irrelevant to true causal order. No causal paradox seems to follow. See Peacock (1991) for more on this.

[12] A version of this condition is assumed in many Bell arguments. See, for example, Bell (1964), Hellman (1987), Redhead (1987), and van Fraassen (1982).

[13] Jarrett (1984, 1989) calls this condition 'locality'.

[14] Jarrett (1984, 1989) calls this condition 'completeness'. Jarrett was one of the first investigators to recognize the importance of the distinction between **DMI** and **DOI**.

[15] For correlated photons and polarization measurements at angles 0°, 60°, 90°, and 30° for A,B, C, and D measurements, respectively QM specifies:

$$P(A_L^+ \mid C_R^+ \ \& \ A_L \ \& \ C_R \ \& \ \psi) = 0 \text{ and } P(A_L^+ \mid C_R^- \ \& \ A_L \ \& \ C_R \ \& \ \psi) = 1; \text{ and } P(A_L^+ \mid D_R^+ \ \& \ A_L \ \& \ D_R \ \& \ \psi) = \tfrac{3}{4} \text{ and } P(A_L^+ \mid D_R^- \ \& \ A_L \ \& \ D_R \ \& \ \psi) = \tfrac{1}{4}.$$

Notice that *deterministic* **TD-DV**s with these probability values also violate **DOI**. If, for example, a system measured for A_L and C_R produces outcome C_R^-, this would indicate the presence of a deterministic disposition to produce C_R^- for $(A_L \ \& \ C_R)$ measurements, which in turn would indicate the presence of a deterministic disposition to produce an A_L^+ outcome for $(A_L \ \& \ C_R)$ measurements.

[16] If ψ already takes account of all of the relevant common causal factors, then, given ψ (and barring nonlocal influences and holistic connections), the R outcome should be irrelevant to the L outcome. So, **DOI** should hold.

[17] For a continuum of hidden states with probability density functions $p(\lambda \mid [X_L \ \& \ Y_R \ \& \ \psi])$,

$$P(X_L^- \,\&\, Y_R^- \mid [X_L \,\&\, Y_R \,\&\, \psi])$$
$$= \int_\Gamma P(X_L^+ \,\&\, Y_R^+ \mid [X_L \,\&\, Y_R \,\&\, \psi] \,\&\, \lambda) \times p(\lambda \mid [X_L \,\&\, Y_R \,\&\, \psi])\, d\lambda.$$

[18] In the case of a continuum of hidden states, the probability density functions satisfy

$$p(\lambda \mid X_L \,\&\, Y_R \,\&\, \psi) = p(\lambda \mid M_L \,\&\, M_R \,\&\, \psi).$$

[19] For the continuous case, multiply by the corresponding density function and integrate.
[20] Locality is not at issue here, so one need not guard against its violation by widely separating the devices and randomizing the settings, though one may certainly do so.
[21] When speaking of **DVs** with the mark use whatever interpretation he prefers – pre-measurement properties, dispositions, truth-values of conditional statements, or measurement-created properties.
[22] This paper has benefitted from discussions with friends and colleagues, and from their written comments. We particularly want to thank Jack Cohn, Ray Elugardo, RIG Hughes, and Kent Peacock. The comments from the two referees for *Synthese* were also exceptionally helpful. We owe a special debt to Chris Swoyer for numerous suggestions on successive versions of this paper.

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