SLAC-PUB-4729
September 1988
(T/Noyes)

ON THE COMPUTER SIMULATION OF THE EPR-BOHM EXPERIMENT*

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ABSTRACT

We argue that supraluminal correlation without supraluminal signaling is a *necessary* consequence of any finite and discrete model for physics. Every day, the commercial and military practice of using encrypted communication based on correlated, pseudo-random signals illustrates this possibility. All that is needed are two levels of computational complexity which preclude using a smaller system to detect departures from "randomness" in the larger system. Hence, the experimental realizations of the EPR-Bohm experiment leave open the question of whether the world of experience is "random" or pseudo-random. The latter possibility could be demonstrated experimentally if a complexity parameter related to the arm length and switching time in an Aspect-type realization of the EPR-Bohm experiment is sufficiently small compared to the number of reliable total counts which can be obtained in practice.

GENERAL ARGUMENT

In any finite and discrete theory such as ours [1], any question as to whether a finite ensemble has a specific attribute can be answered "NO" or "YES." Thus, *with respect to any particular attribute* and a well-defined (strictly constructive) computational procedure, we can define an *attribute distance* relative to some reference ensemble by the number of computational steps it takes to bring the ensemble into local isomorphism with the reference ensemble. If we call the number of steps which

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

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Submitted to Bell's Theorem, Quantum Theory and Conceptions of the Universe, Physics Department George Mason University, Fairfax, Virginia, October 21-22, 1988.

increase the distance I and the number of steps which decrease the distance D, the attribute distance is $I - D$. If we take as our unit of time the computational step, this gives us the *attribute velocity* as $I - D/I + D$, which is obviously bounded by ± 1 ($I + D$ has to be greater than zero in a discrete and finite theory). Thus, any attribute and any computational procedure specify a limiting velocity.

If we use such a theory to model physics, we must specify which attributes in the theory are to correspond to those physical attributes which specify a physical object. In general, these will specify different limiting velocities. Clearly the transmission of *causal* (*i.e.,* physically effective) information between two physical objects will be limited by the minimum of these maximum velocities and can be identified with c, the physical limiting velocity. However, if we talk about the correlation or synchronization of a more limited set of attributes — for example, spin — this need not be limited by the velocity of light. We conclude on general grounds that in any finite and discrete model for physics we can anticipate the occurrence of phenomena like the supraluminal correlations predicted by quantum mechanics and observed in EPR–Bohm type experiments [2]. This should come as no surprise to *computer scientists* who know that in complex systems synchronization and correlation are not limited by the computational information bandwidth (transfer velocity).

To see how this fact can be used to make an explicit computer model of supraluminal correlation, we start by quoting Ref. [2], p. 49:

"Consider (1) a system composed of a Universal Turing machine with a finite memory, and (2) a binary number generator G. Such a system is incapable of deciding whether or not the number generator produces repeating binary strings of length n whenever the memory is smaller than an amount m equal to $n + \log_2 n$.

"Suppose that the Turing machine takes as input a particular substring of length n output by G, and we wish it to determine whether or not the number generator G is producing this substring repeatedly .... The Turing machine must consume an amount of memory equal to n in order to store the string; then, the computational space cost C_s for any computation on the substring, including direct comparison with a second substring, is at least as great as C_s for a count of the number of symbols n in the substring ($\log_2 n$). Thus, $n + \log_2 n$ sets a lower bound on the computational space cost $C_s(0)$ for any algorithm which may be selected to make this decision.

"It follows that the system cannot decide whether or not the target string has been produced if it has memory less than $n + \log_2 n$. But this means (that) this system cannot distinguish between number generators which produce repeating strings and (those which produce) random numbers. Clearly (we have assumed that) the symbols in the repeating strings will occur with equal probability, as required for a random distribution. However, since this system cannot detect that a given string is repeating, it cannot detect that some string of cyclicity n is repeating. Thus, for systems with less than $n + \log_2 n$ memory, a generator producing repeating strings of minimal cyclicity n cannot be distinguished from a generator producing random numbers."

This fact is the basis for modern commercial and military encryption systems [3].

As a practical example, suppose you are in Tokyo and have a colleague in London, in these space-like separated regions (*i.e.,* your separation remains space-like in any Galilean frame connected to your common frame by a Lorentz transformation) each of you receive simultaneously an encrypted message from your home office in Chicago. The encryption uses a pseudo–random sequence of bits that cannot be decoded without using a more powerful computer than the computer in Chicago needed to send the message, yet you and your colleague, having the appropriate key number, need only a simple wallet card computer to decode it. Modern computer times are such that each of you has the information in a time less than the velocity of light would allow you to communicate with each other. This gives a more accurate correlation than implied by quantum mechanics, but is in no way mysterious. To simulate quantum mechanics, all we need do is to introduce a specific noise function into the detectors without destroying the correlations.

PROPOSED COMPUTER SIMULATION

An actual computer experiment along these lines was started by MJM [4] and HPN. It has not been completed, but some results already obtained are interesting. The first step was to construct a model for a polarization detector for polarized particles, which gives a count with probability $\cos^2 x$ where $x = \pi k/N, 0 \leq k \leq N$ is the discretized angle that the beam polarization makes with the 100% transmission angle of the detector. The guts of the programming for this is a pseudo-random number generator routine $Pick(B)$ which returns any integer $0 \leq b \leq B$ with frequency $1/(B+1)$. Given this routine, Manthey's coding only takes three lines:

$$b := Pick\ (B)$$

$$y := \cos\ x$$

$$\text{if } b \leq B \times y \times y \text{ then detector} := 1, \text{ elsedetector} := 0 \quad .$$

We checked that this routine does indeed give a number of ones divided by the number of trials which reproduces the function $\cos^2 x$ to the accuracy to be expected from the number of trials; we tested this with $B = 500$ for nine equally spaced values of $0 \leq x \leq \pi/2$ and 500 trials for each x. Given two detectors, which can obviously be set at different angles with respect to each other and the beam polarization θ by defining the detector setting as θ_d and taking $x = \theta - \theta_d$, the simulation of an experiment in which two polarized signals with the same polarization are set to two distant detectors is also easy,. The same routine (Pick) can be used to generate two beams with pseudo-random polarization θ but 100% correlated (*i.e.,* the same value of k for both); since we have simulated a polarimeter rather than a Stern–Guerlach detector we cannot tell the difference between correlated and anticorrelated; the counting statistics will be the same whether we are modeling spin 1/2 or spin 1 polarization. Given the beam polarization θ and the two detector settings θ_1, θ_2, the probability of getting a count in detector 1 is $\cos^2(\theta - \theta_1)$ and so on, so the four joint probabilities for having two coincidence counts, a count only in detector 1, a count only in detector 2, or no counts, are, respectively,

$$\begin{aligned}
d_{11} &= \cos^2(\theta - \theta_1)\cos^2(\theta - \theta_2) \\
d_{10} &= \cos^2(\theta - \theta_1)\sin^2(\theta - \theta_2) \\
d_{01} &= \sin^2(\theta - \theta_1)\cos^2(\theta - \theta_2) \\
d_{01} &= \sin^2(\theta - \theta_1)\sin^2(\theta - \theta_2)
\end{aligned}$$

and add to unity as they should. The correlation between the two detectors [5] is $d_{11} - d_{10} - d_{01} + d_{11}$ and hence our model so far is expected to give $\cos\ 2(\theta - \theta_1)\cos\ 2(\theta - \theta_2) = 1/2\cos\ 2(\theta_1 - \theta_2) + 1/2\cos\ 2(2\theta - \theta_1 - \theta_2)$. Consequently, if our source emits all polarizations with equal probability, the second term will average out and the calculation will give only half the quantum mechanical prediction [5] of $\cos\ 2(\theta_1 - \theta_2)$.

Clearly, we must examine the situation with more care. What we have modeled so far is a source that emits two photons from an *incoherent* source which are forced to have the same polarization. Clearly, except for the digital photo-detection, this is a "classical" situation and contains no surprizes. We have imposed distant time correlation, but not the distant quantum mechanical wave function correlation which requires that once we "forced a dichotomous choice" on one quantum the other must exhibit precisely the (same or opposite depending on the spin state we model) polarization even when detected in a space-like separated region. As Bell has proved, simply by introducing a "hidden variable" in such a way as to produce perfect correlation for $\theta_1 - \theta_2 = 0$ and perfect anticorrelation for $\theta_1 - \theta_2 = \pi/2$, it is still not possible to reproduce the quantum mechanical prediction so long as this additional complexity does not couple the setting of one detector to the setting of the other.

We agree that Bell has not provided a rich enough model to reproduce quantum mechanics. However, if the "hidden variable" refers to the product space of the two detector settings, we claim that (for finite settings and finite time steps) it would be possible to construct detectors that would pick up from a signal θ, λ where λ refers to this product space, enough local information to produce the correlated statistics required for any choice of *pairs* of detector settings made *pseudo-randomly* at each location. We have not yet made a specific model to illustrate this contention, so as of this writing the proposition remains conjectural. But we feel that the possibility exists because of the encryption analogy discussed above.

The basic idea for our proposed model would be to make the "seed" for the local random number generator to be the same for each detector. Given the seed, the operation is, of course, deterministic. One standard way to get a seed is to use the reading of the "wall clock" in the computer. Each local detector uses a different wall clock, but if we take account of the transit time from the source down the cables to the two detectors, we can insure that the "seed" each of the space-like separated detectors picks up when the signal arrives is the same. This calibration relies on standard Einstein clock synchronization and can be cross-checked by both the calculated and the measured transmission time of the signals along the cables independently of the EPR program. The experimental protocol then becomes independent of whether or not the actual detections are space-like separated. If this can be shown to be "Lorentz *non*invariant," conventional theory is in much deeper trouble than the problems which arise in trying to reconcile quantum mechanics with relativity. We claim that it is obvious nothing in a simulation using a single computer will work differently when we introduce spatial separation of the source and the two detectors.

Some checks should obviously be performed once the program operates. The first is to check that if we shift the data table so that the detections correspond to different beams, the correlation washes out. If this check fails, we have a bug in the program! A second is to simulate Aspect's rather than Clauser's experiment by changing the detector settings after the signals have been launched and before they arrive. This can easily be done, but we predict that, so long as we seed the detectors in the way described above, we will still get the quantum mechanical result. On the other hand, if we seed the two detectors independently *without* the synchronization, the correlation should wash out. Finally, if we go from one case to the other by introducing time delays from the synchronization which produces the quantum mechanical result, we should — depending on the details of the time cycles in the pseudo-random number generator — find a transition from the quantum mechanical case to results in agreement with Bell's Theorem. This would simulate a new theory in which quantum mechanics is valid only up to a constant of nature whose existence has yet to be demonstrated.

CONCLUSION

For us, the implication is obvious that the current EPR–Bohm type experiments do not rule out a mechanistic model for quantum mechanics if the model is of sufficient computational complexity, contains the appropriate conservation laws to allow Einstein synchronization of clocks and dichotomous variables analagous to "spin." For instance, if the cycle length in which the universe is pseudo-random rather than random is the number of events which occur within the event horizon of the visible universe every $\hbar/m_p c^2$ seconds, we could never detect departures from quantum mechanics on the time scale available to us for experimentation. However, if there is some large but measurable parameter that marks the transition region between quantum mechanics and macroscopic physics, such as the number that Leggett [6] is trying to detect in macroscopic tunneling experiments between SQUIDs, it is altogether possible that sophisticated experiments of the Aspect type with very rapid switching times might also be able to give evidence for physics that goes beyond contemporary quantum mechanics. We conclude that continued attention to precision experiments of the EPR–Bohm type is fully justified.

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