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DISCUSSION: WHY BOHM'S THEORY SOLVES THE MEASUREMENT PROBLEM*

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Abraham Stone recently has published an argument purporting to show that David Bohm's interpretation of quantum mechanics fails to solve the measurement problem. Stone's analysis is not correct, as he has failed to take account of the conditions under which the theorems he cites are proven. An explicit presentation of a Bohmian measurement illustrates the flaw in his reasoning.

Given that David Bohm's interpretation of quantum mechanics was rather roundly ignored by the philosophical community for some time, it is gratifying to find a discussion of it recently in the pages of this journal. Unfortunately, Abraham Stone's "Does the Bohm Theory Solve the Measurement Problem?" (1994) contains some severe misunderstandings and misstatements regarding the theory. This note is intended to set the record straight.

Stone makes two sorts of observations about Bohm's theory. One is that the particle trajectories postulated by the theory may not be unique (i.e., other trajectories, given by a different dynamics, could give the same empirical predictions). That claim will not be considered in this note. It is irrelevant to the stated subject of the paper, since the fact that other theories might solve the measurement problem in no way impeaches the capacity of Bohmian mechanics to do so. The more radical claim contained in Stone's paper is that Bohm fails to solve the problem at all. That assertion rests on a manifold of confusions. Let me briefly review the relevant background.

Since Bohm's theory posits no real collapse of the universal wave function, and since the uncollapsed universal wave function is never actually employed in making any experimental predictions, the theory faces the task of showing when, why, and how it is legitimate to ascribe wave functions to subsystems of the universe and to use those wave functions to make statistical predictions (via Born's rule). This problem is solved by the notion of the *effective* wave function of a subsystem. Stone follows Dürr, Goldstein and Zanghi (1992) in his discussion, and we can do no

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better than to directly quote their paper. Suppose we isolate some set of particles in the universe as the x-system, and regard the remainder of the universe (the "environment") as the y-system. Then the universal wave-function, which is defined over the configuration space of all the particles, can be written $\Psi(x,y)$ and the actual configuration of the particles as (X, Y).

> [W] e say that a subsystem . . . has **effective wave function** ψ (at a given time) if the universal wave function $\Psi = \Psi(x,y)$ and the actual coordinates $Q = (X, Y)$ (at that time) satisfy
>
> $\Psi(x,y) = \psi(x)\Phi(y) + \Psi^{\perp}(x,y)$
>
> with Φ and $\Psi^{\perp}$ having macroscopically disjoint y-supports, and
>
> $Y \in \text{supp } \Phi$.
>
> Here, by the macroscopic disjointness of the y-supports of Φ and $\Psi^{\perp}$ we mean not only that their supports are disjoint, but that there is a macroscopic function of y whose values for y in the support of Φ differ by a *macroscopic* amount from its values for y in the support of $\Psi^{\perp}$. (ibid., 864)

Since Bohm's equation for the trajectories of particles is local *in configuration space*, when the two conditions listed above obtain, the value of $\Psi^{\perp}(x,y)$ plays no role in determining the contemporaneous change in particle positions (since Y is not in its support). The trajectories of particles at that time are determined entirely by the part $\psi(x)\Phi(y)$, which (by assumption) factorizes into a function of x and a function of y. Dürr, Goldstein and Zanghi then show, in some detail, why Bohm's theory makes the same predictions for the x-system as one would get using the usual quantum mechanical formalism on $\psi(x)$. They further show that it is impossible to improve on those predictions for the following reason. In order to improve on the prediction, one would have to know more about the actual positions X of the x-system particles than can be inferred from the effective wave-function $\psi(x)$. But no amount of investigation of the environment (the y-system) *at that time* can provide more information about the positions of the x-particles. That is, *when the two conditions stated above hold*, conditionalizing on the effective wave function $\psi(x)$ screens off the positions of the x- particles from all further information about $\Phi(y)$ or about Y.

Stone correctly reports this result:

> If, as we are assuming, all "information" in the environment is encoded in the positions of its particles, then the most the environment can ever "know" about a system, **prior to measuring it**, is the *probability* that the measurement in question will come out a certain way—the probability given by Born's rule. (op. cit., 263, boldface emphasis added)

After repeating this result again several times, Stone continues:

> By now we know clearly that something is wrong. Besides the obvious questions about the physical nature of particles whose positions carry no information[!], the whole course of our argument seems to contain a basic flaw. We assumed that anything worth calling "information"—in particular, any recording of the outcome of the measurement—was stored in the configurations of the Bohm particles. But we have just proven that these configurations cannot store *any information at all.* (ibid., 264)

This passage contains Stone's argument that Bohm's theory does not solve the measurement problem.

The obvious answer to his complaint is that no one ever showed that in Bohm's theory particle positions cannot store information about other particle positions, only that *at the beginning of a measurement* the positions of particles in the environment store no more information about the particles in the measured system *than is reflected in the effective wave function.* At the *beginning* of a z-spin measurement on an x-spin up electron, nothing in the environment can determine whether the incoming electron's position is such as to yield an up or down result. We *get* that information exactly by coupling the position of the incoming particle to the position of (say) a macroscopic pointer. The Bohmian account of such a coupling is perfectly straightforward: the dynamics, when applied to the measurement situation, implies that for certain initial electron positions the pointer will go one way, for others, another (see Albert 1992, chapter 7 for a clear analysis). *At the end of the measurement, the positions of particles in the pointer contain information (in the usual sense of information) about the initial position of the electron.* A measurement device exactly *creates* correlations between positions of particles, such that one can infer from the final state of the positions of particles in the measuring device what the initial state of the measured system was. Bohmian particle positions (in a measurement situation) carry exactly the information that we want them to.

Let us go through a measurement in detail. Suppose the environment can itself be divided into a measuring device and the rest of the universe such that $\Phi(y) = \chi_{\text{ready}}(\mathrm{u})\xi(\mathrm{v})$, where $\chi_{\text{ready}}(\mathrm{u})$ is the wave function of a measuring device in its ready state and $\xi(\mathrm{v})$ is the wave function of the rest of the universe. The actual coordinates Y similarly split into the positions U of the particles in the measuring device and the positions V of the rest of the universe. Of course, U is in the support of $\chi_{\text{ready}}(\mathrm{u})$ and V is in the support of $\xi(\mathrm{v})$ since Y is in the support of $\Phi(y)$. So the initial wave function of the universe is $\psi(x)\chi_{\text{ready}}(\mathrm{u})\xi(\mathrm{v}) + \Psi^{\perp}(x,u,v)$, with U and

V in the supports of $\chi_{\text{ready}}(\mathrm{u})$ and $\xi(\mathrm{v})$. The effective wave function of the x-system is $\psi(x)$.

Now suppose (for simplicity) that $\psi(x)$ is non-zero in two separated regions (with equal amplitude), and the measuring device is constructed to determine which region the particle is in. It might contain two detectors and a pointer, hooked up such that if one detector is triggered the pointer swings to the right, and if the other is triggered the pointer swings to the left. So

$$\psi(x) = 1/\sqrt{2}\psi_{\text{right}}(x) + 1/\sqrt{2}\psi_{\text{left}}(x),$$

where a particle in the support of $\psi_{\text{right}}(x)$ will cause the pointer to swing to the right and one in the support of $\psi_{\text{left}}(x)$ will cause it to swing to the left. In terms of wave functions, this means that $\psi_{\text{right}}(x)\chi_{\text{ready}}(\mathrm{u})$ will evolve (via Schrödinger's equation) to $\psi_{\text{right}}(x)\chi_{\text{right}}(\mathrm{u})$ and $\psi_{\text{left}}(x)\chi_{\text{ready}}(\mathrm{u})$ will evolve to $\psi_{\text{left}}(x)\chi_{\text{left}}(\mathrm{u})$, where $\chi_{\text{right}}(\mathrm{u})$ and $\chi_{\text{left}}(\mathrm{u})$ are the wave functions of a pointer pointing to the right and left respectively. So the initial wave function

$$\{1/\sqrt{2}\psi_{\text{right}}(x) + 1/\sqrt{2}\psi_{\text{left}}(x)\}\ \chi_{\text{ready}}(\mathrm{u})\xi(\mathrm{v}) + \Psi^{\perp}(x,u,v)$$

will evolve into

$$\{1/\sqrt{2}\psi_{\text{right}}(x)\chi_{\text{right}}(\mathrm{u}) + 1/\sqrt{2}\psi_{\text{left}}(x)\chi_{\text{left}}(\mathrm{u})\}\ \xi'(\mathrm{v}) + \Psi'^{\perp}(x,u,v).$$

Typically, $\Psi'^{\perp}(x,u,v)$, (the evolution of $\Psi^{\perp}(x,u,v)$), will still have a support disjoint from $\{1/\sqrt{2}\psi_{\text{right}}(x)\chi_{\text{right}}(\mathrm{u}) + 1/\sqrt{2}\psi_{\text{left}}(x)\chi_{\text{left}}(\mathrm{u})\}\ \xi'(\mathrm{v})$, and the actual positions U and V will be in the support of $\{1/\sqrt{2}\psi_{\text{right}}(x)\chi_{\text{right}}(\mathrm{u}) + 1/\sqrt{2}\psi_{\text{left}}(x)\chi_{\text{left}}(\mathrm{u})\}\ \xi'(\mathrm{v})$. So what is the effective wave function of the x-system at the end of the measurement?

Given only the information above, we cannot say. $\{1/\sqrt{2}\psi_{\text{right}}(x)\chi_{\text{right}}(\mathrm{u}) + 1/\sqrt{2}\psi_{\text{left}}(x)\chi_{\text{left}}(\mathrm{u})\}\ \xi'(\mathrm{v})$ does not itself factorize in the right way to define any effective wave function for the x-system. But (as can be easily checked) if U is in the support of $\chi_{\text{right}}(\mathrm{u})$, then the new effective wave function is $\psi_{\text{right}}(x)$, and if U is in the support of $\chi_{\text{left}}(\mathrm{u})$ the new effective wave function is $\psi_{\text{left}}(x)$. Further, given the dynamics, if U is in the support of $\chi_{\text{right}}(\mathrm{u})$, then X is in the support of $\psi_{\text{right}}(x)$, and if U is in the support of $\chi_{\text{left}}(\mathrm{u})$ then X is in the support of $\psi_{\text{left}}(x)$. In plain English, if the pointer points to the left then the particle is to the left and the new effective wave function of the particle has its support to the left, and similarly if the pointer points to the right. The position of the pointer carries information about the position of the particle, and it is only because the pointer points where it does that a new effective wave function exists.

Where did Stone go wrong? First, he simply dropped without comment the essential qualification, "prior to measuring it," from his initial formulation. Second, he forgot that the analysis he cites only holds when the conditions for the existence of an effective wave function are met. After the measurement, the effective wave function of the measured object is *not* the (Schrödinger) time development of its initial wave function. Indeed, the point of a measurement is to take a situation where the wave functions of the system and environment factorize ($\psi(x)\Phi(y)$) to one where they are entangled. So one cannot repeat the arguments that work for the initial effective wave function to argue that after the measurement there is no information about the position of the x-system's particles contained in the y-system's positions (after one conditionalizes on the Schrödinger time development of the initial effective wave function). If one could so argue, then Stone would be right, and Bohm's theory would solve nothing. But Stone nowhere states, nor takes account of, the conditions under which Dürr et al. prove their theorems, making no mention of the effective wave function at all.

Stone seems to think that particle positions in Bohm's theory are physically meaningless. He compares them to "imaginary points" (ibid., 265), saying that it does not much matter whether they move faster than light. But far from being imaginary, the particle positions are the heart of the theory, they specify the world as we know it. Further, without them *the effective wave function cannot be defined* (note the function of Y in the definition).

If the conditions for a system having an effective wave function are satisfied at some time, we in the environment cannot, at that time, know more about the positions of particles in that system than is given by its effective wave function. If we want to know more, we couple the system to a measuring device which correlates the positions of particles in the measured system to those in the measuring system. Bohm's dynamics shows how this is done, and that the measuring device will indicate different outcomes with the right (Born) probabilities (calculated from the initial effective wave function). If we want to know what happened to the measuring device (e.g., which way the pointer went), we look at it, thereby correlating positions of particles in our brains with the pointer position. If getting the state of our brain correlated with previously unknown external conditions is not getting information about the world, then nothing is.

Bohm's theory solves the measurement problem completely and without remainder.

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