Bohmian Philosophy of Mind?

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1. Introduction

Bohm's theory is in many ways an attractive solution to the measurement problem in quantum mechanics. It provides an intuitive explanation for the distinctive quantum phenomena of interference and entanglement without the need for any problematic "collapse" of the wave function. But it faces several serious difficulties. First, the dynamical law via which the wave function "pushes around" the Bohmian particles is explicitly non-local, against the spirit of special relativity (Bell 1987, 115). Second, the Bohmian particles can be seen as *redundant* in the context of an Everettian solution to the measurement problem (Brown and Wallace 2005). And third, the Bohmian solution to the measurement problem apparently depends on an implausible and problematic account of mental awareness (Stone 1994; Brown and Wallace 2005).

I do not wish to minimize the significance of the first two difficulties; they are serious threats to the tenability of Bohm's theory. But the third difficulty, I think, rests on a confusion concerning the way in which Bohmian particles encode the outcomes of measurements. In particular, my concern here is to respond to the accusations of Stone (1994) and Brown and Wallace (2005) that Bohm's theory requires a mysterious kind of direct awareness of the positions of the Bohmian particles in our brains, and also to the claim of Brown and Wallace (2005) that such direct awareness threatens the quantum no-signaling theorem.

2. The case against Bohm

The background to the critique I wish to discuss is an influential discussion of Bohm's theory by Dürr, Goldstein and Zanghì (1992). Dürr et al. derive a result they call "absolute uncertainty", which says that "the quantum equilibrium hypothesis $\rho = |\psi|^2$ conveys the most detailed knowledge possible concerning the present configuration of a subsystem (of which the "observer" or "knower" is not a part)" (1992, 882). The Bohmian particle configuration is always precisely defined, so it might seem that it should be possible to find out what that particle configuration is. Dürr et al.'s "absolute uncertainty" result apparently says that we *can't* find out: "no devices whatsoever, based on any present or future technology, will provide us with the corresponding knowledge. *In a Bohmian universe such knowledge is absolutely unattainable!*" (1992, 882). The best we can do is to assign a probability distribution ρ to the possible particle configurations given by the squared wave function amplitude $|\psi|^2$.

Dürr et al. intend this result as a *defense*, not a criticism, of Bohm's theory. Indeed, it is central to the empirical adequacy of Bohm's theory that the probability distribution over particle configurations is $|\psi|^2$, in accordance with the Born rule. Nevertheless, the "absolute unattainability" of knowledge of the particle configuration is the source of a recurring objection to Bohm's theory.

The original source of the objection is Stone (1994). Stone argues that the Bohmian particle configuration contains no information. In a sense, of course, the Bohmian particle configuration certainly *does* contain information, namely the precise values of three coordinates for each particle in the system. But if we take "information" to mean "*accessible* information", then arguably the Dürr et al. result entails that the Bohmian particle configuration contains no information over and above the wave function distribution, since that result seems to imply that we can't *find out* the particle configuration with any greater accuracy than $|\psi|^2$. Hence Stone concludes that "we will never have an empirical way to decide between the many competing stories about the Bohm trajectories" (1994, 264). Since learning that one among the many possible Bohm trajectories is actual is central to the Bohmian solution to the measurement problem, Stone concludes that Bohm's theory fails to solve the measurement problem.

It is worth noting, though, that Dürr et al.'s result includes the caveat that the observer is not part of the system. In a footnote, they expand on this exception: "There is one situation where we may, in fact, know more about configurations than what is conveyed by the quantum equilibrium hypothesis $\rho = |\psi|^2$: when we ourselves are part of the system!" (1992, 903). Stone takes this to mean that "while detailed knowledge of the configurational states of external systems is forever unattainable to us, we can nevertheless have knowledge of (perhaps we should say 'have our knowledge in') the configuration of our own particles" (1994, 264). Here we get the first inkling of the suggestion that Bohm's theory requires a distinctive account of mental awareness—that *direct awareness* of the particle configuration in our own brains can bypass the prohibition on knowing the particle configuration, and hence provide a route via which Bohm's theory can solve the measurement problem.

Stone immediately objects to this suggestion: "What physical model of brain processes can possibly underlie this statement? Suppose I consider a single neuron of my brain as "the system" and the rest of my brain as part of the "environment". Since the "environment" does not contain information about the "system" configuration (beyond what is available from its wave function), whatever knowledge this neuron may have stored up in the configuration of its particles is "absolutely unattainable" to the rest of my brain!" (1994, 264). That is, Dürr et al.'s result entails that any "direct awareness" of the particle configuration by one part of my brain would be completely inaccessible by the rest of my brain. Stone is surely right to think that any such hermetically sealed "awareness" couldn't in principle fulfill the functions of *genuine* awareness in guiding belief and action.

So with or without the proposed exception for direct awareness, Stone concludes that Bohm's theory is incapable of solving the measurement problem. But is this criticism correct? Maudlin takes issue with Stone's attack, arguing that "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* (1995, 481). That is, Maudlin accuses Stone of misinterpreting Dürr et al.'s result, reading a prohibition on finding out the particle position *prior to* a measurement as an *absolute* prohibition.

How, then, does Maudlin think that we can find out the position of a Bohmian particle? Simply by correlating its position to the positions of *other* Bohmian particles: **"**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" (1995, 483). And how do we find out the positions of *those* particles? "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" (1995, 483). Hence we gain information about the Bohmian particle configuration: "If getting the state of our brain correlated with previously unknown external conditions is not getting information about the world, then nothing is" (1995, 483).

Maudlin concludes that "Bohm's theory solves the measurement problem completely and without remainder" (1995, 483). But not everyone is convinced. After all, Maudlin's solution to Stone's worry about the accessibility of particle positions is to insist that we can know them via *other* particle positions; but if particle positions *in general* are inaccessible, this is no help. Perhaps, then, it is the particle positions *in our brains* that are doing the work here in giving us access.

This is how Brown and Wallace interpret Maudlin: "Maudlin seems to be taking it for granted that our conscious perceptions supervene directly and exclusively on the configuration of (some subset) of the corpuscles associated with our brain" (2005, 534). But why think that we are directly aware of the configuration of particles in some part of our brain? After all, this seems to lead us right back Stone's concerns that such "awareness" would be inaccessible to the rest of our brain. Furthermore, it seems to involve us in "the assumption that consciousness is some sort of bare physical property (like, say, charge)," which "makes consciousness completely divorced from any assumptions rooted in the study of the brain" (2005, 536). Finally, "a violation of the no-signaling theorem is possible in principle were we to 'know' the configuration of corpuscles in our brain with a greater level of accuracy than that defined by the wave function" (2005, 535).

In sum, then, the gist of the critique of Bohm's theory is this: Bohmian particle positions, which are key to solving the measurement problem, are in general unknowable. In fact, the *only* way we might know them is via direct awareness in our brains. But this is a heterodox and highly implausible account of the nature of awareness, and what's more, it threatens the no-signaling theorem, which is important for the reconciliation of quantum mechanics and special relativity.

3. How to send a superluminal signal

Let us consider the last point more carefully. Why would knowing the Bohmian particle configuration allow one to send a superluminal signal, and why does it matter? Consider two spin-1/2 particles in the entangled state $2^{-1/2}(|\uparrow\rangle_A\,|\downarrow\rangle_B - |\downarrow\rangle_A\,|\uparrow\rangle_B)$. Suppose that Alice takes particle A and Bob takes particle B, and they perform spin measurements on their respective particles at space-like separated locations. As Bell (1987, 14) showed, the results of their measurements will exhibit correlations that can't be explained by positing local, intrinsic properties of the individual particles. It seems that quantum entanglement involves us in some kind of non-locality or non-separability or holism—some kind of "direct link" between the two particles, no matter how far apart they are.

Nevertheless, it can be shown that according to standard quantum mechanics, there is nothing that Alice can do to her particle that could be used to send a signal to Bob. This is important because it suggests the possibility of a peaceful coexistence of quantum mechanics and special relativity: while a "direct link" between space-like separated events may be in tension with the spirit of special relativity, there is arguably no outright violation of special relativity absent a superluminal signal.

Insofar as Bohm's theory is empirically equivalent to standard quantum mechanics, the no-signaling theorem is retained. So as long as Alice can know no more about her particle than is given by the Born rule, then she cannot send a signal to Bob. But suppose that Alice *can* know the location of her particle in its wave packet with greater precision than $|\psi|^2$: then she can send a signal.

To see how this is possible, consider how the state of the system evolves as Alice and Bob make their measurements. The easiest way for each of them to measure the spin of their particle is to pass it through an inhomogeneous magnetic field oriented along some chosen axis, and then run it into a fluorescent screen that lights up at the point of contact. If Alice and Bob orient their magnets in the same direction—say along the *z*-axis—the measurements can be represented as in Fig. 1. For a two-particle system, the wave function inhabits a six-dimensional configuration space, but for picturability, we can focus on the *z*-coordinate of Alice's particle, plotted vertically, and the *z*-coordinate of Bob's particle, plotted horizontally. The circle represents the region of configuration space in which the wave function amplitude is large, and the point represents the positions of the two Bohmian particles.

Consider a frame of reference in which Alice's measurement occurs first. As her wave packet passes through the magnetic field, it splits into two components based on its spin—a spin-up wave packet displaced upwards, and a spin-down wave packet displaced downwards. The Bohmian particle follows one of the components, depending on its initial position: if it is above the midpoint of the initial wave packet in Alice's *z*-coordinate, it moves upwards, and otherwise it moves downwards.[1]

Now Bob passes his wave packet though a magnetic field. Given the entangled nature of the original state, the wave packet that is spin-up for Alice's particle is spin-down for Bob's particle, and vice versa. Hence there is no further splitting of the wave packets in configuration space: the packet that was deflected upwards in Alice's *z*-coordinate is deflected downwards in Bob's *z*-coordinate, and vice versa. The Bohmian particle is carried along with the packet it occupies. Hence if Alice's particle is above the midpoint in the initial wave packet, as shown in Fig. 1, then Alice gets the result "spin-up" for her measurement and Bob gets the result "spin-down".

Fig. 2 shows what happens if Alice rotates her measuring device by 180°. Now the spin-up component of Alice's wave packet is displaced downwards, and the spin-down component is displaced upwards. But as before, if the Bohmian particle is above the midpoint of the initial wave packet in Alice's *z*-coordinate, it moves upwards, and otherwise it moves downwards.[2]

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[1] For a single particle, this is because otherwise Bohmian trajectories starting below the midpoint and above the midpoint would intersect each other, and intersecting trajectories are prohibited in a deterministic theory. For two particles in a six-dimensional configuration space, there is no danger of the trajectories intersecting, but the additional degrees of freedom corresponding to Bob's particle are irrelevant to the motion of Alice's particle.

[2] By the same argument as before.

When Bob passes his wave packet through the magnetic field, the packet that was deflected upwards in Alice's *z*-coordinate is deflected downwards in Bob's *z*-coordinate, and vice versa, and the Bohmian particle goes with it. Hence if Alice's particle is above the midpoint in the initial wave packet, as shown in Fig. 2, then Alice gets the result "spin-down" for her measurement and Bob gets the result "spin-up".

Note that for the same initial state (wave packet plus Bohmian particle position), the results of the measurements depend on the orientation of Alice's measuring device. One way up, Alice gets "spin-up" and Bob gets "spin-down". The other way up, Alice gets "spin-down" and Bob gets "spin-up". This is an illustration of the contextuality of spin in Bohm's theory: the result of a spin measurement depends on how that spin is measured. But if Alice can locate her particle with greater accuracy than $|\psi|^2$, it also provides a way for Alice to send a superluminal signal to Bob. All she needs to do is to observe whether her particle is above or below the midpoint of her wave packet. If it is above the midpoint, then to send the signal "spin-up" to Bob she rotates her measuring device, and to send "spin-down" she leaves it as it is. If her particle is below the midpoint, she reverses this strategy.

Perhaps, though, Alice is only directly aware of the positions of particles in her own brain. Even so, if it can be arranged that Alice's particle in the above experiment is embedded in her brain in the relevant way, then she can use her direct awareness of the position of this particle to send a signal to Bob. That is, it looks like Brown and Wallace are correct that direct awareness of the positions of the Bohmian particles threatens the no-signaling theorem, and hence the possibility of peaceful coexistence of quantum mechanics and special relativity.

4. Awareness as a red herring

Stone (1994, 264) and Brown and Wallace (2005, 534) each complain that making direct awareness *exceptional* in this way—allowing that one can be directly aware of the position of a Bohmian particle even though no other physical process can locate a Bohmian particle with greater accuracy than $|\psi|^2$—threatens standard assumptions about the nature of mind. If minds are physically instantiated, how can they operate in ways that other physical systems cannot? In particular, how can a particle embedded in Alice's *brain* be used to send a superluminal signal, when a similar set-up outside her brain cannot? It all looks decidedly spooky.

However, I think all this talk about what Alice is directly aware of is a distraction. There is a perfectly straightforward sense in which the positions of Bohmian particles encode *accessible information* about the outcomes of measurements, contra Stone. And the ability to access this information wouldn't give a system (or a person) the ability to send a superluminal signal, contra Brown and Wallace.

Let's start with the first point: Bohmian particles encode accessible information. As mentioned previously, there is a trivial sense in which the Bohmian particle configuration contains information that is not contained in the wave function. Consider the initial position of the Bohmian particle in Fig. 1. The wave function is entirely symmetric around the midpoint of Alice and Bob's *z*-coordinates, but the particle configuration breaks the symmetry. Furthermore, the particle configuration is *predictive* of the result of the spin measurement: if Alice's particle is above the midpoint in her *z*-coordinate, Alice gets spin-up and Bob gets spin-down, whereas if the particle is below the midpoint, Alice gets spin-down and Bob gets spin-up.

Finally, at the end of the measurement, the particle configuration is *perfectly indicative* of—one might even say *constitutive of*—the outcome.

Hence there is an obvious sense in which the particle configuration contains information about measurement outcomes, information that is accessible via measurements. Why think otherwise? There are a number of concerns one might have. First, the above story depends on Alice performing her measurement *before* Bob, but given that the measurement locations are space-like separated, there is (according to special relativity) no fact about which measurement is performed first. This is an entirely reasonable criticism of Bohm's theory: the dynamics of the theory are explicitly non-local, and require an absolute standard of simultaneity in order to be well-defined. But given that this prerequisite of the Bohmian dynamics is satisfied, it makes sense to say that Alice's measurement occurs first.

Second, the above story is relative to an orientation of Alice's measuring device: if she rotates her device by 180°, the particle configuration contains *different* information about the measurement outcomes. This is an expression of the well-known *contextuality* of properties other than position in Bohm's theory: spin is not an intrinsic property of a particle, but is defined only relative to a measurement context. Even so, *granted* this contextuality, the particle configuration contains accessible information about the (contextually defined) spin properties of the particles.

Finally, and most importantly for present concerns, it might be objected that the above story begs the question, in that it assumes that the particle configuration at the end of the measurement—the one I said was constitutive of the outcome—is *accessible*. Doesn't the Dürr et al. "absolute uncertainty" result show that knowledge of the particle configuration is "absolutely unattainable"? I could spin out the story further, but the objection would recur. If the particles are detected by running them into a fluorescent screen, then the position of the measured spin-1/2 particle is reflected in the positions of the electrons in the excited atoms at the impact point. If the light from the excited atoms is detected, then the positions of the particles in the display of the photon detector reflect the position of the measured spin-1/2 particle. At each stage, the position (and hence the spin) of our original Bohmian particle becomes correlated with the positions of more and more Bohmian particles in the environment. But if the positions of Bohmian particles are in general inaccessible, how does this help?

The answer, I think, is to appeal to functionalism. The spin of the original particle is correlated with the positions of the particles in the photon detector. The positions of those particles can in turn be used to control further physical systems in any way whatsoever. That is, the Bohmian particles in the photon detector can access the spin of the original particle on any reasonable functional characterization of what it takes to access an aspect of the physical world.

This is essentially Maudlin's (1995, 483) answer. But Maudlin (unintentionally) muddies the water by spinning out the story in terms of a correlation with particles in an observer's *brain*. This in turn leads Brown and Wallace (2005, 534) to conclude that Maudlin is appealing to some special account of direct awareness. But as I hope to have shown here, there is no need to mention either brains or awareness: *any* system can in principle access the spin of the particle and use it to control other systems.

The appeal to functionalism is this context is something of a double-edged sword, however. The main argument of Brown and Wallace (2005) is that the *wave function* can perform all the functions that the Bohmian particle configuration can perform, and hence that the Bohmian particles are *redundant*. The difference, of course, is that the Bohmian particle configuration picks out *one* result of the spin measurement, whereas the wave function is symmetric between *all* possible results. But provided that an Everettian or many-worlds solution to the measurement problem is tenable, the Bohmian particle configuration arguably adds nothing.

As I mentioned earlier, I do not mean to dismiss this redundancy argument. If there is a response, it is that the Everettian solution to the measurement problem might *not* be tenable (Callender 2010). But for present purposes, my point is that, setting aside considerations of redundancy and of non-locality, there is no *additional* problem concerning the accessibility of the Bohmian particles.

What of Dürr et al.'s "absolute uncertainty" result, then? The key here, as Maudlin correctly notes, is that when Dürr et al. say that we can't know the particle configuration with greater precision than $\rho = |\psi|^2$, the ψ in question is the *effective* wave function. The effective wave function is the component of the wave function that is relevant to our concerns, *given* what we know. And in the context of Bohm's theory, the effective wave function is the component of the wave function that is relevant to our concerns, given what we know *of the Bohmian particle configuration*.

Consider again Alice's spin measurement. According to Bohm's theory, the wave function never collapses, so the quantum state of the world will be very complicated indeed. But given the effects of decoherence, that state will naturally decompose into a number of branches, most of which are irrelevant to the behavior of the branch containing the Bohmian particles. If the experiment has been set up correctly, the branch containing the Bohmian particles will take the form of the entangled wave packet we have been studying. This is the effective wave function at the beginning of the measurement. Dürr et al.'s result entails that at the beginning of the measurement, Alice knows no more about the Bohmian particle configuration than that it has a probability distribution given by the absolute square of this effective wave function.

But what about at the end of the measurement? Here again Maudlin inadvertently muddies the waters by stressing that Dürr et al.'s result applies to Alice at the *beginning* of the measurement, perhaps implying to some readers that at the end of the measurement we can know the particle configuration with *more* accuracy than given by the square of the effective wave function. Indeed, he adds that "if we want to know more, we couple the system to a measuring device… 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" (1995, 483). This might inadvertently suggest that particles in our brains have a special role in allowing us to know more than the square of the effective wave function.

Of course, it is entirely correct to say that at the end of the measurement we know more than at the beginning. But the crucial point is that Dürr et al.'s result applies equally at the end of the measurement—it's just that the effective wave function has *changed*. When Alice learns that the result of her measurement is spin-up, she learns that the Bohmian particle is not associated with the spin-down wave packet, and hence that she can ignore it. That is, the effective wave function changes from the entire entangled state to just one term in this state.

Does she know more than is given by the squared wave amplitude of this remaining term in the wave function? Well, maybe—it depends on the accuracy of the measurement via which she locates the particle. Perhaps she performs a very rough position measurement that only distinguishes the spin-up term from the spin-down term, and nothing more; in that case, the post-measurement effective wave function is just the spin-up term. Or perhaps the position measurement is more accurate; in that case the post-measurement effective wave function is more tightly localized. The point is that no measurement is *completely* accurate, and however tightly localized the final effective wave function turns out to be, Alice's knowledge of the position of the Bohmian particle will be distributed according to the square of this effective wave function.

So Dürr et al.'s result applies both before and after a measurement, and in no way precludes finding out about the Bohmian particle configuration. Seen in this way, the result might look trivial: the post-measurement effective wave function reflects what you *know* of the Bohmian particle configuration, so *by definition* you can't know the configuration with greater accuracy! But it is nevertheless an important result: it shows that Bohm's theory is *consistent*. The wave function plays a peculiar dual role in Bohm's theory: a dynamical role in pushing the particles around, *and* an epistemic role in reflecting our knowledge of the particle configuration. It is important that these roles always coincide, and Dürr et al.'s result shows that they do: the relevant part of the wave function, dynamically speaking, is always also the part over which your knowledge of the particle configuration is distributed according to $\rho = |\psi|^2$.

Nevertheless, Dürr et al. let their rhetoric get away with them. Knowledge of the Bohmian particle configuration is not "absolutely unattainable"—in fact, knowledge of the particle configuration is easily attainable by a simple position measurement. Perhaps what they mean is that no measurement is *perfectly* accurate, so one can never know the Bohmian particle configuration with perfect precision. But this is hardly a surprise; it is equally true of the classical particle configuration.

Similarly, Dürr et al. are mistaken in suggesting that there is an exception to their result for knowledge of the particles in your own brain. As Stone correctly points out, in order to count as *knowledge*, such self-awareness needs to be accessible by other parts of your brain, and any physical account of this process will be subject to Dürr et al.'s result. Whatever you find out about the configuration of Bohmian particles in your own brain via such a process, you will never attain *perfect* precision, and your probability distribution over the possible particle configurations will be given by the squared amplitude of the effective wave function—the wave function *given* what you have found out.

The lack of an exception is good news for Bohm's theory, in that it avoids the criticisms of Stone and of Brown and Wallace directed at the exception. Bohm's theory does not need any special account of awareness of your own brain state. Nevertheless, you can find out about the Bohmian particle configuration, both inside and outside your brain, to any practicable degree of accuracy. What, then, of Brown and Wallace's further contention that such knowledge would allow one to send a superluminal signal?

5. No signaling

Consider again what Alice needs to do to send a superluminal signal. She needs to find out the position of the Bohmian particle relative to her wave packet, and set her measuring device accordingly. As detailed above, it is perfectly possible for her to find out whether the Bohmian particle is above or below the midpoint of the wave packet: she simply needs to perform the relevant measurement. The relevant measurement in this case is to pass the wave packet through a magnetic field and then to detect whether the particle moves up or down. If it moves up, she now knows that it was above the midpoint.

But of course by this stage it is *too late* to set her measuring device according to the initial position of the particle: she has already *measured* her particle, and in doing so, has moved it from its initial position. In other words, in order to send a superluminal signal, Alice would have to act on the particle position *before* she has accessed that position. Trivially, Alice can't do that, even though she can perfectly well find out the position of her particle to any practicable degree of accuracy. Her ability to find out the Bohmian particle configuration does not allow her to send a superluminal signal.

6. Conclusion

Stone contends that Bohm's theory doesn't solve the measurement problem, because Dürr et al.'s result means that you can never find out the Bohmian particle configuration, except perhaps via some implausible direct awareness of your own brain state. Stone's argument rests on a mistaken reading of Dürr et al.'s result, albeit one that is suggested by some of Dürr et al.'s rhetoric. Maudlin correctly identifies Stone's error, but continues to suggest (perhaps inadvertently) that there is some special role for awareness of your own brain state in finding out the particle configuration. I hope to have shown here that there is no special problem in finding out the Bohmian particle configuration, and that acquiring such information neither conflicts with Dürr et al.'s result, nor requires any special role for direct awareness of your own brain state. Finally, finding out the Bohmian particle configuration does not allow you to send a superluminal signal, as Brown and Wallace contend. In short, Bohm's theory provides a perfectly straightforward solution to the measurement problem, and one that does not require any special account of mental awareness.

References

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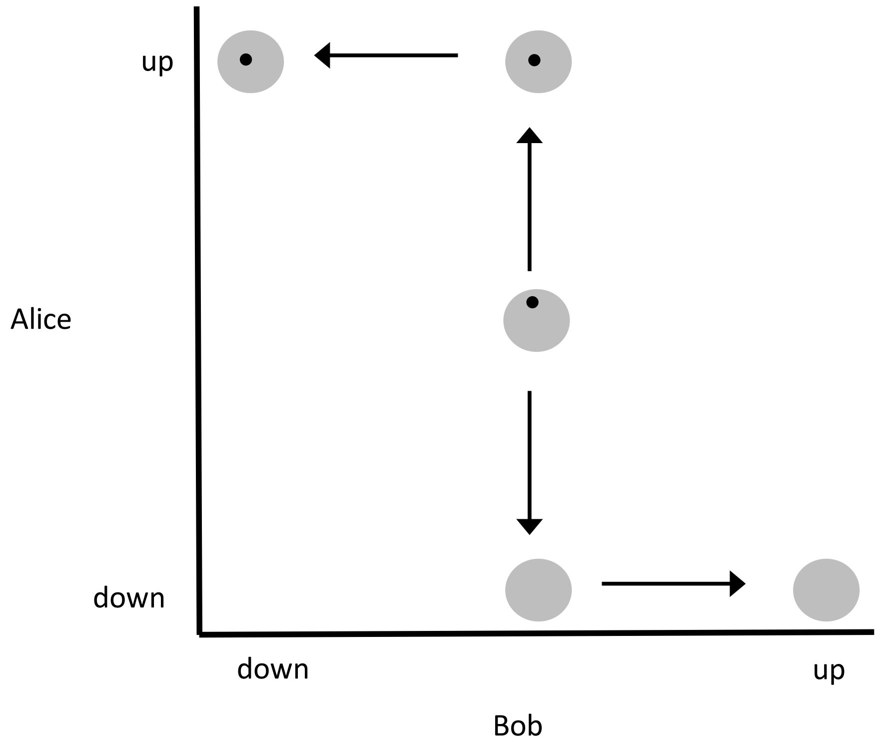

Fig. 1 Spin measurements on entangled particles

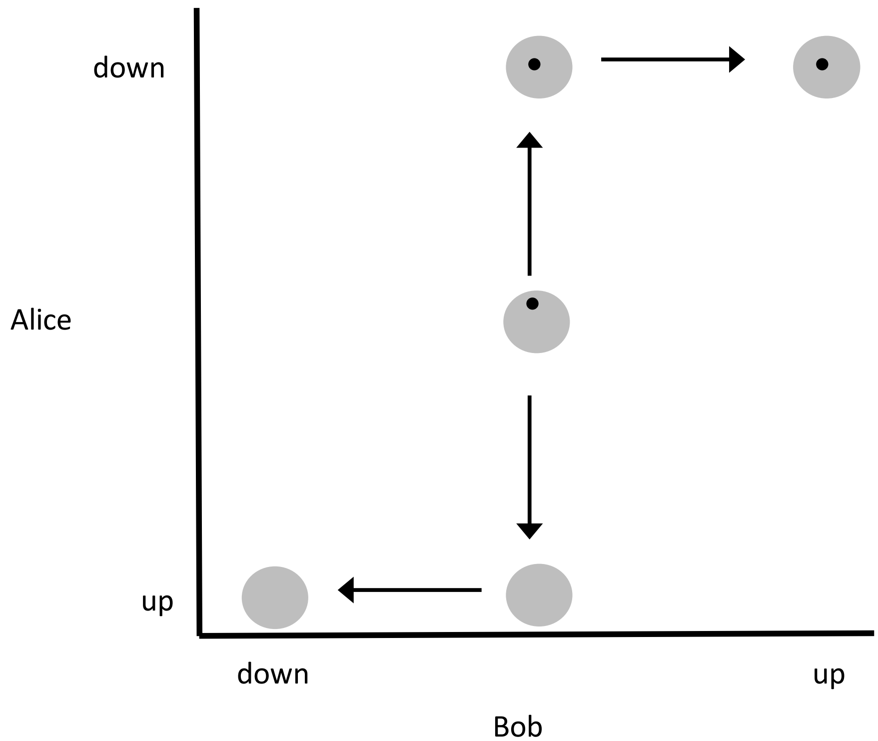

Fig 2 Alice rotates her measuring device