Bohmian Mechanics

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Contents

1 Introduction

The purpose of this paper is to discuss the de Broglie-Bohm interpretation of quantum mechanics. The de Broglie-Bohm interpretation was first discovered by Louis de Broglie in 1927 but he soon abandoned the theory. The theory was rediscovered and extended in the early 1950s by David Bohm. The interpretation is also known by many other names such as pilot-wave theory, the causal interpretation, and the ontological formulation but it is commonly referred to as Bohmian mechanics. The idea of Bohmian mechanics is that in addition to the wavefunction, there is a hidden variable[1], denoted by $Q(t)$, that evolves deterministically. This means that Bohmian mechanics is a deterministic hidden variable type theory and thus is non-local by Bell's Theorem. In this essay I will briefly introduce the mathematical foundation of Bohmian mechanics as a stepping stone to discussing what Bohmian mechanics has to say about quantum theory. This will include a discussion of the how Bohmian mechanics handles the measurement problem and describes probability in quantum mechanics. In addition I will discuss how Bohmian mechanics handles the quantum-classical divide and how non-locality plays a role in the theory. Finally I will give some common criticisms of the theory and my own personal thoughts on Bohmian mechanics.

2 Mathematical Formulation of Bohmian Mechanics

The purpose of this initial section is to introduce the foundations of Bohmian mechanics from a mathematical point of view. I do not want to dwell on deriving much of the formalism of orthodox quantum mechanics[2] from the Bohmian picture as it is time consuming and there is plenty of literature on the subject [1][2][3]. Instead I shall touch on a few mathematical equations that will be needed to discuss more of the interpretational aspect of Bohmian mechanics. Let us consider the basic formulation of Bohmian mechanics for N spinless non-relativistic particles. Bohmian mechanics can be formulated in terms of two equations: the Schrödinger equation and the guiding equation. The Schrödinger equation is the standard Schrödinger equation that we all learnt when we first encounter quantum mechanics and appears unaltered in the Bohmian formalism

$$i\hbar\frac{\partial\psi_t}{\partial t} = H\psi_t \tag{1}$$

[1]This is a misnomer and will be expound upon later.
[2]The standard textbook interpretation pioneered by von Neumann and Dirac.

The H is the Hamiltonian of the system and has the same interpretation as in non-relativistic quantum mechanics.

$$H = -\sum_{k=1}^{N} \frac{\hbar^2}{2m_k} \nabla_k^2 + V$$

The ψ_t is the wavefunction and is a function of position and time: $\psi_t = \psi(q,t), q = (\mathbf{q}_1, \ldots, \mathbf{q}_N) \in \mathbb{R}^{3N}$. It is important to point out that the wavefunction lives in configuration space[4]. In orthodox quantum mechanics, we are finished. The dynamics are all contained in Schrödinger's equation. This is where Bohmian mechanics deviates from this viewpoint. Let us denote the configuration $Q(t) = (\mathbf{Q}_1(t), \ldots, \mathbf{Q}_N(t)) \in \mathbb{R}^{3N}$ where the $\mathbf{Q}_k(t)$ are interpreted as positions and hence must be real numbers. The equation describing the evolution of the positions is given by a second equation, called the guiding equation.

$$\frac{d\mathbf{Q}_k}{dt} = \frac{\hbar}{m_k} \mathrm{Im} \frac{\nabla_k \psi_t}{\psi_t}(Q(t)) \tag{2}$$

(2) is a series of first order ODEs that can be solved to obtain the particle trajectories. The theory of ODEs tells us that the integral curves of (2) never cross and that the solutions of these equations are unique. An alternate way to write this formula is to define $v^\psi = (\mathbf{v}_1^\psi, \ldots, \mathbf{v}_N^\psi)$ to be the right hand side of the guiding equation. This is a vector field over configuration space $\mathbb{R}^{3N}$[5]. We thus have

$$\frac{dQ(t)}{dt} = v^{\psi_t}(Q(t))$$

It is also important to note that there are many equivalent ways of writing the guiding equation and I have stuck to the one that I've found is clearest and most commonly used.

For the Bohmian, this is it! All of Bohmian mechanics follows from Eq. (1) and (2)[2]. From these two equations, and one additional postulate to be discussed in the section on probability, we can recover all the predictions made by standard orthodox quantum mechanics. I did not discuss the origins of the guiding equation, however it is possible to reason in the Bohmian picture that this equation must arise naturally[6]. Perhaps the most eloquent result that can be derived in this formalism is the double-slit experiment. Unfortunately, given the purpose of this essay, it is not possible to spend time discussing the derivation and its interpretation so instead I refer the reader to [5] for a discussion and derivation.

Now Bohmian mechanics is not simply limited to non-relativistic quantum theory. We can use the formalism to derive various other properties of nature such as relativistic quantum effects like spin and quantum statistics. It is also possible to develop quantum field theory in the Bohmian picture. While these ideas are very interesting, I only mention that they can be done and derivations can be found in [1][3][6][7]. Finally, I should mention that there are other formulations of Bohmian mechanics using stochastic mechanics or replacing point particles with strings or fields [7]. Again I will not dwell or develop any of these ideas.

3 The Meaning of Bohmian Mechanics

I think the most concise way of demonstrating the interpretation of Bohmian mechanics is to compare and contrast it with the orthodox interpretation of von Neumann and Dirac. Consider initially the orthodox interpretation. It states that the wavefunction is complete or, to quote von Neumann, "*everything which can be said about the state of a system must be derived from its wavefunction*" where state is meant to be the ontic, what exists, state otherwise we have a tautology [8]. Contrast this with Bohmian mechanics which states that the wavefunction is not a complete property of the system. Instead, in Bohmian mechanics the ontology is given in terms of point particles and the wave function. The primitive ontology, the part of ontology representing matter, consists solely of the point particles [7].

Now what is meant when we say point particles? Bohmian mechanics takes point particles as we do in classical theories. There are some subtleties to this as discussed in [9] but I avoid them here. These are the so-called 'hidden variables' of Bohmian mechanics, however the term is a misnomer [5]. The reason for this misnomer is that the positions of particles are not really hidden. They are the actual positions of the particles. The identification of the 'hidden variable' aspect arises since the evolution is not governed by the Schrödinger equation and thus are 'hidden' when compared to orhtodox quantum mechanics. John Bell, himself a proponent of Bohmian mechanics, states it best: "*...it is not the wavefunction one finds an image of the visible world... but in the complementary 'hidden' variables*"[6].

So given this primitive ontology, how do we recover macroscopic objects? How do we recover tables and chairs? To derive a table or a chair we simply look at the trajectories of particles in space-time at a certain time. If we freeze at this time and look at the particle configuration we see that they correspond to macroscopic objects such as tables and chairs. In other words, when we look at objects we see table configurations and chair configurations. This idea of definite particle configurations is important when we discuss the measurement problem in Bohmian mechanics.

Now above I stated that it is possible to extend Bohmian mechanics to explain quantum statistical mechanics and one may ask does this not contract the Bohmian idea of particles? In normal quantum statistics we have that particles are indistinguishable, but in Bohmian mechanics we have assigned a definite trajectory to particles so it seems like I could easily identify a single particle and follow its evolution through Eq. (2) thus contradicting the whole idea of indistinguishable particles! Bohmian mechanics indeed has an answer in the form of the symmetrisation postulate[1][7]. The basic idea is that the labelling of the particles is unimportant and leads to the standard results of quantum statistical mechanics.

However, let us not dismiss the wavefunction entirely. One of the names of Bohmian mechanics is the pilot-wave theory. The reason for this is if we look back at Eq. (1) and (2) we see that the Schrödinger equation remains the same. This equation can always be solved. Now the guiding equation tells us how the positions of the particles are moved based off their position and the wavefunction. Thus the wavefunction plays the role of a "pilot" or a "guide" for the particles. Hence we have a literal wave-particle duality[1].

It is clear that Bohmian mechanics is an objective interpretation as can be seen by the preceding discussion. The orthodox interpretation is also objective through its interpretation of the wavefunction. However in the orthodox view, if we take the wavefunction to be ontic we immediately run into problems such the collapse of the wavefunction and the measurement problem. Yet Bohmian mechanics also is objective but is able to do away with these problems. I will discuss how Bohmian mechanics solves these problems below.

One aspect of quantum interpretations that is very important is how do we define the quantum state. As discussed above, the orthodox interpretation takes it to be wavefunction and real while a statistical interpretation would tell us that the quantum state is only the information we have about the state. Thus, how does Bohmian mechanics define the notion of the quantum state? It provides the answer through determinism. We note immediately Eqs. (1) and (2) evolve deterministically and thus Bohmian mechanics is a deterministic theory. If we are given the initial conditions of all our particles then we can integrate and solve our equations of motion for unique trajectories. This is very different from the standard orthodox interpretation. In the orthodox interpretation we can have evolution is non-deterministic (collapse of the wavefunction) and hence we have a stark contrast between the Bohmian viewpoint and the orthodox interpretation. It is also interesting to note that is possible to formulate Bohmian mechanics using stochastic methods [6], but we will not dwell on this point here. Now given that Bohmian mechanics is deterministic, we can make the definition the state of any quantum system, at time t_0 to be $(Q(t_0), \psi_0)$ [10].

4 Measurement

I feel that is important to make clear what we mean by the measurement problem itself. It manifests itself in the orthodox interpretation. To see why, recall that the orthodox interpretation takes the wavefunction as the primitive ontology. When one takes this viewpoint, one finds the existence of the projection postulate. This postulate is that certain types of measurement that are not predicted by the Schrödinger equation. This suggests, that in addition to the unitary evolution, there exists another set of dynamical laws that describe how the wavefunction evolves. Thus, the problem arises, when does a measurement take place and which dynamical law should apply[8]? There are various ways of getting rid of the measurement problem by interpreting different statements of quantum mechanics, such as measurement and the quantum state, in different ways. For example if we take the quantum state to be the information we have about the system, the whole idea of the measurement problem goes away because when we do a measurement and get a result, we simply update the information we have about the quantum state based off this measurement. Since the quantum state is only the information we have about the thing and not an objective property, there is no problem of wavefunction collapse or the role of the observer; it's all information. On a related note, if we follow Einstein and consider quantum mechanics gives an incomplete description of nature then the measurement problem is also gone. Finally an alternative viewpoint, known as collapse models, occur if we have non-unitary evolution instead of unitary evolution[6].

So how does Bohmian mechanics deal with the measurement? Immediately it takes issue with the orthodox viewpoint that the wavefunction is the primitive ontology. As stated above, the primitive ontology are the point particles and these point particles evolve deterministically. Thus Bohmian mechanics considers both the observer and the system in consideration on equal ontological grounds which are subject to the same dynamical laws. In essence the observer and system are all just particles that evolve deterministically. This provides a stark contrast from Bohr's interpretation of the classical observer which has a strict divide between classical and quantum mechanics. When we perform a measurement on the particle, it is like any other interaction the particle may experience. Thus when we perform a measurement at any time, the pointer on our measuring device will correspond to that pointers particle configuration. To clarify, in terms of Schrödinger's cat type analogy, there are two distinct cat configurations, the alive cat and the dead cat. There is no in-between. Each corresponds to a different particle configuration. Thus, in Bohmian mechanics, when we measure the position of pointer, it means that the evolution was guided into a configuration where one configuration was preferred over the other one. In terms of the cat analogy, the alive configuration was favoured over the dead configuration of our cat. This is known as the "effective collapse" [6][11]. Thus we can see that there is no measurement problem in Bohmian mechanics. To elaborate, in the orthodox viewpoint we had problems about when a measurement takes place and what laws determine its evolution. In Bohmian mechanics, we have only deterministic laws and a measurement is just any other disturbance of the system and our system will evolve into whatever configuration is determined by these laws. Along these same lines, there is no collapse of the wavefunction since the wavefunction is not a primitive ontology and hence there is no notion of collapse.

5 Probability

If there is one thing all physicists agree on is that quantum mechanics has an aspect of probability to it. While different interpretations attempt to do away with this probability interpretation, to me it is nonetheless obvious that at its core, quantum mechanics requires some notion of probability. This is all fine and dandy, but in the orthodox picture we have non-deterministic evolution and in Bohmian mechanics we have deterministic evolution and both give us the same experimental results. The orthodox picture gives us probabilities through Born's rule but Bohmian mechanics makes no mention of probabilities anywhere in its foundation. Yet how can this be that the two interpretations give the same predictions? Along those same lines, I have not even brought up the Born rule, which is a very important rule in quantum mechanics. If Bohmian mechanics involves determinism, where does the notion of probability come in to reproduce the predictions of orthodox quantum mechanics?

A few times I have mentioned that given the initial conditions of a point particle we can predict exactly how the system will evolve. However, in reality, we cannot know the exact initial conditions of the point particles due to limitations in our measuring devices, background noise, and external sources [3] and thus we must prescribe some probability distribution $\rho_{t_0} = |\psi(t_0)|^2$ to the system. Now it follows that if initially we have some probability distribution then we have that the probability density at any time later is given by $\rho_t = |\psi(t)|^2$. To see this, we recall the conservation of probability current that is well known from the Schrödinger equation[12]

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho v)$$

It then follows from this law of conservation of probability and some algebra that we obtain the desired result known as the equivariance theorem[5] or the quantum equilibrium hypothesis[6]. This theorem provides a link between probability and the deterministic evolution of the positions. In the section on the mathematical formulation, I mentioned that there is one additional postulate that is needed to make reproduce all the predictions, This extra postulate is the quantum equilibrium hypothesis. With this postulate and the Schrödinger and guiding equations, we can recover all of orthodox quantum mechanics. In fact, one is able to see how the Heisenberg uncertainty principle is satisfied using the equilibrium hypothesis since the notion of a point particle evolving deterministic appears to undermine the notion of the Heisenberg uncertainty principle. It is also important to note that there are certain viewpoints in Bohmian mechanics that allow to equilibrium hypothesis to arise naturally by considering a classical gas[6].

However this is not an entirely convincing argument since we have that the Born rule arises from the ignorance of the initial conditions of a system. This stands in stark contrast to the orthodox viewpoint where the Born rule does not reflect our ignorance of the situation; we could know everything about the system prior to measurement yet we will still obtain an outcome with some probability given by Born's rule. Thus there must be an alternative way to derive Born's rule. To do so, one considers an ensemble of prepared particles that evolves deterministically through the same wavefunction. It then follows from a more rigorous treatment of measurement theory [3] that we are able to obtain Born's rule that has the same interpretation as the standard Born rule in the orthodox interpretation.

6 The Classical Divide and the Quantum Potential

To me the correct interpretation of quantum mechanics will provide a satisfactory answer to the question: why, if quantum mechanics underlies classical mechanics do we not see large scale quantum phenomena? To me, this is a critical question that a satisfactory interpretation of quantum mechanics should provide an answer to. Now it is well known that if we take the limit $\hbar \to 0$ we do indeed recover the Hamilton-Jacobi equation and thus classical mechanics is restored. However this is hardly a satisfactory answer to me for two reasons. Firstly, it's not a well defined limit in itself; what if we us some units where $\hbar = 1$. It disappears from Schrödinger's equations and how would one take a limit here? It is certainly not clear what taking the limit to zero means. In that regard, if are able to take the limit of $\hbar$ going to zero many equations depend on $\hbar$ being in the denominator so how do we know a priori that these also go to classical limits? Secondly, it doesn't really answer the question. It just demonstrates that classical mechanics is, in some form, contained within quantum mechanics. It doesn't explain why there are no large scale quantum phenomena.

To contrast with Bohmian answer, let us look at Bohr's interpretation and QBism as they have radically different approaches to answering this question. In relationship to Bohr has the notion that measuring devices and observers are classical. This hardly answers the questions and, to my mind, raises more questions than it answers. Where is the dividing line between classical mechanics and quantum mechanics? Why would there exist such a dichotomy? It has been demonstrated that quantum effects in buckyballs (C_{60}) and researchers are working on getting more large scale quantum effects.

On the opposite end of the spectrum, QBism has a radically different approach. QBists state that the experience is neither classical or quantum. Furthermore "*quantum mechanics is something put on top of raw, unreflected experience. It is additive to it, suggesting wholly new types of experience, while never invalidating the old.*"[13]. In fact QBist consider this question "*obstructive*". Despite finding myself drawn towards the ideas of QBism to the extent that I call myself a QBist[3], to me this is hardly a satisfactory answer and seems more like a cop-out then an explanation.

So how does Bohmian mechanics address this question? We first need to derive an equation that contains the so-called quantum potential. Following [1] we differentiate the guiding equation to obtain

$$\begin{aligned} m_k \frac{d^2\mathbf{Q}_k(t)}{dt^2} &= -\nabla_k (V + V_{qu})(Q(t)) \\ V_{qu} &= -\sum_{j=1}^{N} \frac{\hbar^2}{2m_j} \frac{\nabla_j^2 |\psi|}{|\psi|} \end{aligned} \tag{3}$$

Equation (3) is known as the quantum potential. The V is the well-known classical potential. We immediately notice the similarity between this equation and Newton's Second Law. However it is important to stress that the concept of force has no meaning in this equation. Tumuluka [1] states that Bohm originally published these two equations instead of the guiding equation. It appears that it postulates the existence of a quantum potential that seems very contrived and as a result has led to the notion that Bohmian mechanics as an ad hoc type interpretation. However this equation is not the proper equation to begin derivations with and is instead the guiding equation (2). As stated, this equation looks very similar to Newton's second law involving forces and one might be tempted to talk about forces again in this picture. However this viewpoint is wrong. There is no quantum force.

Now it is quite clear that Bohmian mechanics returns to quantum mechanics when the quantum potential is small compared to the classical potential. Thus the quantum potential is, in essence, a measure of the 'quantumness' of the configuration. But how do we gauge when we have classical mechanics and not quantum mechanics? A criteria given by [14] is that the de Broglie wave length λ is small compared to the characteristic length of the classical potential V. In other words $\lambda \ll L$, where L is the characteristic length scale of the classical potential. The justification that this is a necessary and sufficient condition for considering the classical limit is discussed in more detail in [14].

[3]There is still a lot with QBism that I disagree with but of all the interpretations presented in this course, it was the one agree the most with in its interpretation of quantum mechanics.

7 Non-locality

Let us recall the guiding equation from above.

$$\frac{d\mathbf{Q}_k}{dt} = \frac{\hbar}{m_k}\mathrm{Im}\frac{\nabla_k \psi}{\psi}(Q(t))$$

As we can see this equation depends upon the positions of the particles at a certain time. No further elaboration was made. However, it is quite clear that this function depends on the positions of all particles, even if they are spacelike separated. Thus Bohmian mechanics is inherently nonlocal.

This non-locality provides an explanation for Bell's Theorem which states that nonlocal hidden variable theory can reproduce quantum mechanics. Thus Bohmian mechanics must be nonlocal. As demonstrated above this is realised in the guiding equation. Now this means that Bohmian mechanics cannot be Lorentz covariant and thus seems, a priori, no way to extend to relativistic quantum mechanics. Also, it appears there will be problems with the particle picture given that in quantum field theories, particles are annihilated and created all the time. However it is possible to discuss quantum field theory in a Bohmian interpretation. However, it is highly technical and details can be found [15].

Now one may ask if it is possible to somehow exploit the nonlocality of Bohmian mechanics to transmit messages or information faster than the speed of light? The answers turns out to be a negative[11]. This has to do with the quantum equilibrium hypothesis which provides the key link between the predictions of orthodox quantum mechanics and Bohmian mechanics. Since we cannot transmit information faster than light in the orthodox interpretation, we cannot in the Bohmian viewpoint.

8 Criticisms

In this section I will discuss some two common criticisms against the Bohmian interpretation and the rebuttals from Bohmians on this attacks. A more thorough reference and discussion on these and more criticisms, along with how the founders of quantum theory viewed Bohmian mechanics, can be found in [6][11]. The two most common criticisms against Bohmian mechanics that I've found are: a return to classical notions and Ockham's razor.

The first criticism of Bohmian mechanics is that it harkens back to the ideas and notions of classical mechanics. Related to this classical notion is the idea of the quantum potential which can be seen as a sort of ad hoc introduction to the theory. As stated above, the latter criticism can easily be alleviated if we do not start with the quantum potential, as Bohm did, but instead realise that the quantum potential is simply a consequence of the guiding equation. Indeed, some argue that the quantum potential is misleading and aides in this misunderstanding of the theory[4] since all the real evolution is done through the guiding equation and the Schrödinger equation. Now there are two arguments against this notion of returning to classical ideas. Firstly, have we really turned back to classical ideas in the first place? Bohmian mechanics possess many properties that are unseen in classical physics and are completely unclassical. Passon [6] also argues that "*the features of determinism and objectivity are 'classical', but in this respect the de Broglie-Bohm theory is as classical as the theory of relativity.*" Secondly, one can interpret Bohmian mechanics as rejecting the entire Newtonian viewpoint in the first place. In Bohmian mechanics we have that particles are guided via the wavefunction and thus the two fundamental properties are the wave function and the point particles. Newtonian mechanics involves the positions and the velocities of the particles. Velocities have no meaning in Bohmian mechanics. This, in essence, we are completely rejecting the Newtonian viewpoint and in no way returning to closely held notions of classical mechanics.

The second criticism against Bohmian mechanics that I will discuss is the idea of Ockham's razor, or, in essence, the simpler the better. To see why this is a criticism is that we have introduced the notions of point particles evolving along deterministic trajectories. We have added another equation for the dynamical evolution of quantum mechanics whereas orthodox quantum mechanics has gotten a long, from a practical application standpoint, only needing one. However, a rebuttal is that in exchange for one equation, we have removed the whole notion of probability from the theory. In addition, we no longer need to postulate the existence of an alternative measurement postulate as is required in the standard orthodox viewpoint since from the start there is no measurement problem.

9 Conclusion

How do I see Bohmian mechanics as an interpretation? As I mentioned in the essay, I consider myself most drawn towards the ideas of the QBist so it is clear that I do not subscribe this viewpoint. However, that is not to say I should dismiss the notions and ideas in the interpretation. I find that it's answer to the question about classical and quantum divide is the most satisfactory. It does leave a lot of to explained and is still, in some sense, taking limits, I think that it provides the strongest conceptual understanding of why we live in a classical world which has quantum mechanics laws underlying it.

Now I consider myself, at the end of the day, an operationalist user of quantum mechanics[4] and I think that of all the interpretations, the Bohmian viewpoint is the most developed as an interpretation. I look

[4]This is not to mean I did not enjoy the course, on the contrary; I enjoyed it a lot. I just find myself more attracted to using quantum mechanics as a tool then to debate it's foundations for a living! Unfortunately this course has also made quantum mechanics more frustrating. Sometimes I wish I could remain ignorant of the problems of quantum interpretations as there is no satisfactory answer! There is no truly turning back to the naive days of operationalism. I could try and feign ignorance but I know that it wouldn't work.

at the well formulated structure of Bohmian mechanics and see an alternate way of looking at a quantum problem akin to the Lagrangian or Hamiltonian viewpoint; both are equivalent but each is adapted to solving certain problems better. I don't necessarily believe that it tells us what is really out there, but instead gives us an alternate framework to solve problems in quantum mechanics which may be difficult or not well understood in other interpretations. To elucidate this point let us recall that Bohmian mechanics consider the point particle as a primitive ontology. I do not agree with this viewpoint. To me I see this as tacking something onto a theory that doesn't need to be there. As I explained above, I have no problems with using Bohmian mechanics as a tool for calculating various physical phenomena, but I see it only as that, a tool. As explained above, Ockham's razor has been used as criticism of the theory and, normally I don't like invoking Ockham's razor as an argument for or against a theory, but considering that a lot of the interpretational problems can be solved without tacking on extra ideas like point particles and deterministic evolution, I think it is indeed a fair criticism despite removing the notion of probability as I think we are adding more then we are taking out. Related to the simpler is better type philosophy, I found that the articles on quantum field theory in Bohmian mechanics were very technical and difficult to understand. I do, in some sense, agree with Dirac when he believed that the fundamental equations of physics should be mathematically beautiful. When I look at the standard methods of doing quantum field theory as demonstrated through either the path integral or the Hamiltonian formulation, I see a (relatively) simple mathematical theory that is not too difficult to parse. When looking at how Bohmians do it, it seems very ad hoc and very messy and not as simple as in the standard methods. One could argue, fairly, that this is due to a vast number of people working on one way of doing quantum field theory against a handful doing it in the Bohmian picture, so it is difficult to place the blame entirely on the Bohmians' shoulders. Yet I still feel that one has to walk a very precarious line that makes advancements difficult.

Let me re-iterate the point about the comparison to Hamiltonian and Lagrangian formulation of classical mechanics because I think it's important. To me, I see that having a solid understanding of the various interpretations gives one a good idea of where to look for a possible theory of quantum gravity. Immediately I do not see how the Bohmian picture really helps in this viewpoint because of the idea of having fundamental point particles. In classical electrodynamics theory these notions of point particles causes problems and I think that in Bohmian mechanics it also will causes problems. To contrast, the QBist interpretation advocates the idea of searching for properties that are common to all objects as a more powerful direction to start a search for a quantum gravity theory. Similarly, or so I am told, the modal interpretations suggest a different approach. To me it is not immediately obvious from reading the literature of Bohmian mechanics as to where one can start in the Bohmian picture. I think that the most valid interpretation will lead, relatively, naturally to insights into quantum gravity type theories.

Now what about the idea of nonlocality? The idea of nonlocality is a fun one indeed and definitely worth playing around with but I feel that locality is too important a fundamental concept to physics to give it up immediately. To me the justification for nonlocality is unconvincing and I think the results of Bell's theorem tell us that instead of going to a nonlocal hidden variable theory we should look for a deeper theory than quantum mechanics. I cannot believe that quantum mechanics is a complete theory of nature and I believe that underlying it there is a consistent theory of quantum gravity that would provide answers to a lot of interpretational questions. However, it seems unlikely that anyone will find such a consistent theory in the near future and thus I do agree with Dr. Tumulka when he concluded his second lecture on Bohmian mechanics that there is unlikely to be any consensus on the correct interpretation of quantum mechanics any time soon. It does raise the interesting question as to whether a theory of quantum gravity would provide evidence to the correct interpretation of quantum mechanics but I feel that it will only raise more questions than it answers.

So, given all the formalism that can be developed from Bohmian mechanics, it is natural to ask the question: why aren't more physicists Bohmian? In addition, given that there exists a relatively nice structure of Bohmian mechanics, why aren't more people researching Bohmian mechanics? Despite what I said above about disliking the structure, I do feel that if more people put time into this research programme, it would allow for some of my qualms to be settled. These are both interesting question that I'm sure every espouser various non-standard interpretations hold about their interpretation. An excellent discussion of this problem is in the introduction the paper, with its title being one of these very question, by Posson [16]. I think the key point is well expressed by a quotation from David Mermin in Posson's introduction. Mermin states that

> Contemporary physicists come in two varieties. Type 1 physicists are bothered by EPR and Bell's Theorem. Type 2 (the majority) are not, but one has to distinguish two subvarieties: Type 2a physicists explain why they are no bothered. Their explanations tend either to miss the point entirely (like Born's to Einstein) or to contain physical assertions that can be shown to be false. Type 2b are not bothered and refuse to explain why.

I agree 100%. To me, the vast majority of physicists have remained uninterested or don't consider foundations to be of much importance. Thus the number of people who actually work on and espouse Bohmian mechanics is few. This is not unique to Bohmian mechanics and is a problem of all non-standard interpretations. For example, I was very surprised to learn that one can do quantum field theory using Bohmian mechanics. I'm sure most physicists are unaware of being able to do something relativistic in a theory that is nonlocal. Posson points this out stating that "*the majority of physicists has lost track of this complex debate about the measurement problem, hidden-variables, EPR, Bell, etc...*". I think this lack of interest is the main reason for the lack of Bohmian mechanics. It is unfortunate because I think that a solid understanding of quantum foundations will give a good starting point for a theory of quantum gravity as it allows ones to realise what can be said and what cannot be said in quantum mechanics. So, at the end of the day, what do I make of Bohmian mechanics? I simply see it as a tool for solving and predicting phenomena in quantum mechanics rather then an explanation of what is really going on in quantum mechanics.

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