BOHMIAN DISPOSITIONS

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Abstract: This paper argues for a broadly dispositionalist approach to the ontology of Bohmian mechanics. It first distinguishes the 'minimal' and the 'causal' versions of Bohm's Theory, and then briefly reviews some of the claims advanced on behalf of the 'causal' version by its proponents. A number of ontological or interpretive accounts of the wave function in Bohmian mechanics are then addressed in detail, including i) configuration space, ii) multi-field, iii) nomological, and iv) dispositional approaches. The main objection to each account is reviewed, namely i) the 'problem of perception', ii) the 'problem of communication', iii) the 'problem of temporal laws', and iv) the 'problem of under-determination'. It is then shown that a version of dispositionalism overcomes the under-determination problem while providing neat solutions to the other three problems. A pragmatic argument is thus furnished for the use of dispositions in the interpretation of the theory more generally. The paper ends in a more speculative note by suggesting ways in which a dispositionalist interpretation of the wave function is in addition able to shed light upon some of the claims of the proponents of the causal version of Bohmian mechanics.

1. The 'Minimal' Elements of Bohmian Mechanics

Bohm's Theory or, as I shall call it here, Bohmian Mechanics (BM) is nowadays often described in terms of what is known as the 'minimal' version of the theory. According to this version, BM is a first order theory that describes at all times the positions and velocities of each of the particles in an N-particle system. However, this is not the original 'causal' version of the theory that was famously introduced by David Bohm himself in a couple of well-known papers in 1952, and later developed together with collaborators such as Basil Hiley. Now, let me first of all list and briefly explain the uncontroversial or neutral first four postulates of BM. I shall offer some explanation for them before I go on to describe the additional fifth postulate that distinguishes the 'causal' from the 'minimal' versions of BM. I refer to them as the *state description*, *dynamical*, *equilibrium* and *guidance* postulates, and they are as follows.

1. The State Description Postulate: The state description of an n-particle system is given by (Ψ, Q) where Ψ (q, t) is the quantum state with q = (q_1, q_2,..., q_n) $\in \Re^{3n}$, and Q = (Q_1, Q_2,..., Q_n) is the set of particle positions with $Q_k \in \Re^3$ as the actual position of the k^{th} particle.

Concerning this first postulate, it is well known that BM is a hidden variable theory, ascribing to all elementary particles a position at all times. This is additional information that is not encoded in the quantum state or wavefunction. Hence the first postulate of the theory already states that a full state description of a Bohmian particle, or system of particles, is given by a precise specification of both wavefunction and hidden state. (Therefore the description within the theory of the entire Universe at any given time is provided by the complete or universal wavefunction together with the complete quantum state for all the particles contained in the Universe).

2. The Dynamical Postulate: The quantum state Ψ (q, t) evolves according to the Schrödinger equation: $i\hbar \frac{d|\Psi\rangle}{dt} = \hat{H}|\Psi\rangle$, where H is the Hamiltonian: $\hat{H} = -\sum_{k=1}^{N} \frac{\hbar}{2m_k} \nabla_k^2 + V(q)$.

The dynamical postulate simply asserts that the time evolution of the quantum state is uniquely given by the unitary Schrödinger equation. This is the altogether orthodox dynamical rule for the evolution of the quantum wavefunction where *V (q)* is the classical potential, which takes value 0 for a free particle. However, critically, in BM – and unlike what is the case in collapse interpretations of quantum mechanics – this dynamical rule has no exceptions, ever. There is no collapse of the wavefunction, not even when measurement interactions take place, or under any other circumstances. The dynamical postulate is unexceptionally always true in any version of BM under any interpretation.

3. The Equilibrium Postulate: The quantum equilibrium configuration probability distribution ρ for an ensemble of systems each having quantum state Ψ is given by: $\rho = |\Psi|^2$.

The equilibrium postulate guarantees that the orthodox quantum mechanical probabilities, derived from Born's rule, accurately reflect our ignorance over the initial state of the system. In other words the postulate enables an epistemological reading of the probability distributions over the appropriate quantities, and in particular, the uncertainty relations. (Since in BM the underlying dynamics is entirely deterministic, the uncertainty relations may only be derived in such a way, as the result of epistemic limitations on the initial state of the system). It should also be noted that the relation established by the postulate is equivariant. That is, once the probability distribution ρ takes the value given by the

square modulus of the amplitude of the wave-function $|\Psi(t)|^2$ at any given time t in the evolution of the n-particle system described and (as long as the evolution of the system is given by the Schrödinger equation, and the distribution of particle positions is given by the guidance equation described in postulate 4) then it is always so given at any other time. There are in addition arguments to the effect that at the initial time in the evolution of the universe, t_0, the probability distribution over positions must be given by the equilibrium postulate if it is *typical* for the $|\Psi(t_0)|^2$ where $\Psi(t_0)$ is the initial state of the universe (Allori et al., 2008, p. 356).

4. <u>The Guidance Postulate</u>: The particles move on trajectories given by their positions and velocities as determined by the equation:

$$v_k^{\Psi}(Q) \equiv \frac{dQ_k}{dt} = \frac{\hbar}{m_k}\mathrm{Im}\frac{\nabla_k \Psi}{\Psi}, \text{ with } \nabla_k = \frac{\partial}{\partial q_k}.$$

This notorious fourth postulate establishes a law for the motion of particles, via a description of their kinematics. It does so by describing a velocity field associated to each particle, in terms of its position, once again as a function of the quantum wavefunction. This is a first order equation in that it involves exclusively first order differential equations with respect to the positions of the particles. (In BM, the positions of the particles, as they figure in the quantum state, are the only genuine magnitude that particles can be said to possess.) Notice that what this means in practice is that the only initial conditions that need to be fixed, in addition to the wave-function, in order to determine the values of V_k^{Ψ} at all times are the initial positions of the particles, i.e. the full configuration state of the particles ab initio, Q_k at time t_0. No further initial conditions are required; and the initial particle configuration state suffices to fix via the guidance equation all future relevant states of the particles.

2. The 'Causal' and 'Minimal' Versions of Bohm's Theory Distinguished

We may now distinguish the 'minimal' and 'causal' versions of the theory as follows. The so-called 'minimal' version accepts only these four postulates and nothing else as the axioms of BM. As a result, since only a first order equation of motion for velocity is adopted among the axioms, this version of the theory is sometimes known as the first order or kinematical version of BM. As described, the minimal version of BM is merely a presentation of the theory; in particular its ontological commitments and assumptions are very minimal and concern only the properties of position and velocity. Other than that, there are no further assumptions regarding what sort of entities in the world are represented by these four equations. [1]

[1] Other, that is, than the very minimal assumption that whatever particles exist must have determinate positions and velocities, i.e. that there are trajectories. But there are no assumptions, for instance, regarding what a particle consists in, what the background space of motion may be, whether the trajectories inhabit 3-

The original 'causal' version of the theory introduced by Bohm, however, subtly puts the emphasis beyond the kinematics of the fourth postulate and the guidance equation. Thus, according to Bohm's own presentation of the theory, there exists, besides the wave-function, a so-called 'quantum potential', ultimately determined by the wave-function, and which is said to play a fundamental causal and explanatory role. As Bohm himself states in his reminiscences regarding his original introduction of the theory, "the basic assumption was that the electron *is* a particle, acted on not only by the classical potential V, but also by the quantum potential, Q" (Bohm, 1987, p. 35). Once all the appropriate equations describing the dynamical laws for the position of particles, wave-function, and quantum potential are taken into account it is possible to provide "an in principle complete causal determination of the behaviour of these elements in terms of all the relevant equations" (ibid, 1987, p. 35). This seems to be the reason why Bohm and his collaborators often refer to their version of the theory as the 'causal' version, or 'causal interpretation' of quantum mechanics.

The minimal version, as we saw, is essentially a first order theory: it contains only variables for position and velocity. The causal version, however, is a second order theory, containing variables for accelerations, forces, or a quantum potential in addition. These differences in ontology are significant, but they are not dramatic. On the contrary, a variety of interpretations of the theory are available in both its minimal and causal versions. Correspondingly, for each of these two approaches to the presentation of the theory, a particular interpretation of the ontology may be provided, which depends on how the wave-function is understood, and what a relationship is taken to exist between the wave-function and the system's properties at any given time. In the next few sections I review four different ontologies that may be provided for the theory on either the minimal or causal version. I also review some of the problems associated with each of these ontologies.

It is important, however, to distinguish from the very start these ontological readings or interpretations of the 'minimal' and 'causal' versions of the theory from the versions themselves. All of them are often referred to as 'interpretations' of Bohm's Theory (or even, 'interpretations of quantum mechanics'), yet only the fully ontologically interpreted versions can properly speaking be the 'interpretations' traditionally conceived by philosophers. That is, to provide an interpretation of a theory is to provide a description of what the world would be like were the theory true (or, more precisely in the appropriate conditional form: what the world is like if the theory is true). The underdetermination of interpretation by theory suggests that there is no unique 'reading off' strategy to extract the ontology from any version of the theory.

Now it has been pointed out how the minimal and causal versions of Bohmian mechanics differ minimally in ontology. This difference is indeed minimal, since neither version by itself describes how the world is ultimately

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dimensional or a higher dimensional configuration space and, of course, whether there are additional entities over and above the particles.

furnished ontologically, but to the contrary leaves the fundamental ontological options wide open. [2] Thus, the causal version merely adds a fifth axiom, namely the so-called "quantum potential equation of motion" (QPE), which describes second order quantities, in the sense that the equation involves first order derivatives of the particles' velocities, i.e. second order differential equations with respect to the particles' positions:

5. The Quantum Potential Postulate: The force acting on each particle at position k with velocity v_k is given by the quantum potential equation of motion (QPE): $\vec{F} = m_k \frac{dv_k}{dt} = -\nabla(V + U)$, where $U = \frac{-\hbar}{2m_k} \frac{\nabla^2 R}{R}$ is the quantum potential for a particle in the state $\Psi = R \cdot e^{\frac{-iS}{\hbar}}$.

This fifth postulate establishes the nature of the forces acting upon the particles, which as mentioned are taken in this approach to determine and explain their motion. The QPE is a second-order differential equation on the particles' positions, which leads its proponents to refer to this presentation of the theory as the 2nd order or 'causal' interpretation – although in line with the distinctions already introduced in this paper, it is best to describe it as the 'causal version' of the theory. Notice that defining forces in this manner is equivalent to setting down a formula for the potentials acting on the particles, since the gradient of some potential W implicitly defines the force as: $\vec{F} \equiv -\nabla(W)$.

Yet, consistency with the former four equations, including the Schrödinger equation, demands that the form of these potentials include a term unlike anything one finds in classical mechanics, and named for that reason by Bohm and Hiley (1993) the *quantum potential*. One of the immediate consequences of the formal definition of the quantum potential above, is the fact that for an N-particle system, the potential depends on the real part of the n-particle wavefunction, and what this means is that the force locally acting upon each particle essentially depends, via the quantum potential, upon the physical quantities (including positions) of all the remaining particles regardless of their distance. The quantum potential thereby nicely represents the non-local character of interactions that is characteristic of Bohmian mechanics. [3]

There are putatively further explanatory and heuristic advantages to this 'causal' version of the theory. Its proponents argue that just as in classical mechanics, the quantum potential equation allows us to define a force field at each

[2] Thus only pragmatic reasons may lead us to embrace one or another combination of version and ontology – there can be no logical compulsion – and some of these pragmatic reasons are rehearsed later on in this paper in arguing for a particular such combination.

[3] This is obviously not to say that the 'minimal' version is local, but the non-locality takes the form of non-supervenience there (see Esfeld et al. (2013, pp. 79ff.), for a discussion).

point that a particle may occupy, given its mass and velocity at that point, as the product of the mass and first order time derivative of the velocity, i.e. the particle's acceleration at that point. We then have putatively defined, by means of this analogy, a dynamical equation describing the 'forces' that 'cause' particles to accelerate in or out of inertial constant motion. Hence it is tempting to think of the causal version as importing the explanatory framework of classical mechanical dynamics into the quantum realm. However, note that this framework is brought to bear merely as a consequence of the emphasis upon the appropriate equation since, as has already been noted, the 'causal' version of the theory differs merely in presentation. It does not in itself provide an ontological interpretation of the terms that appear in the equations. Thus the bringing of a 'classical' explanatory framework to bear is an entirely presentational, heuristic or pragmatic matter, and does not in itself require the ontology of classical physics. On the contrary the defenders of the 'causal' version make it abundantly clear that whatever the correct interpretation of this version of the theory, it will certainly not import a fully classical ontology. In particular the quantum potential does not fade off with distance, it depends on the shape and not the amplitude of the wavefunction, and in the many particle system case has instead built-in a notoriously sui generis kind of non-locality (see e.g. Bohm, ibid, pp. 36-37; Hiley and Peat, 1987, p. 15; Holland, 1993, pp. 89-90). [4]

Nothing much may seem to hinge upon the explicit postulation of the fifth axiom, since it can be derived from the gradient of the guidance equation (GE) given the Schrödinger equation in the many particle system case too (Holland, 1993: pp. 279-280). Moreover, the two equations have essentially the same solutions given the equilibrium postulate, so there is no additional empirical content to the theory under the causal interpretation. One may then wonder why advocates of the causal interpretation should want to elevate the quantum potential equation (QPE) in postulate 5 to the status of an axiom. There are two types of consideration. Firstly, one reason adduced is that, in line with the above considerations, this is a convenient move to emphasize the explanatory power of the theory, since the QPE makes explicit the role of the quantum potential. And it may be supposed that forces and potentials play an explanatory dynamical role in BM similar to the role that they play in classical mechanics. This view seems implicit in the following quotes from Holland, who writes with respect to classical mechanical notions, that "Newton's laws (or their refinements in the Lagrangian, Hamiltonian, and Hamilton-Jacobi formalisms) allow us not only to predict the results of experiments on fields and particles, but also to provide an explanation of these results in terms of a definite world view – that of mass points pursuing well-defined trajectories in space and time and interacting via preassigned potentials" (Holland, 1993, p. 27). He then goes on to state with respect to the 'causal' version of Bohm's theory: "The purpose of the causal interpretation [sic] is to offer an explanation of quantum phenomena […] The introduction of the quantum potential as a causal agent has explanatory power which one unnecessarily foregoes by concentrating on just [the guidance equation (GE)]" (ibid, p. 78).

[4] The proponents of the 'minimal' interpretation of course also emphasize the strong differences with classical mechanical concepts (see e.g. Dürr, Goldstein and Zanghi, 1996, p. 25ff.), but this is to be expected in their case.

Secondly, there is a way to present the causal version as fundamentally postulating only the Quantum Potential Equation (QPE) along with the other three basic principles. Thus Solé (2013, p. 368) proposes that in the causal version of the theory (QPE) is fundamental, and the Guidance Equation (GE) is merely a restriction on the initial conditions of the system. So, on this understanding of the causal version, Bohmian mechanics is fundamentally given by only the axioms 1-3 and 5, and 4 does not have the character of a postulate but only a boundary or initial condition, which restricts the class of solutions offered by (QPE). And it is this latter equation that on its own provides for the motion of the particles, the only genuine *equation of motion*.

It is clear in either case that the (QPE) must be doing some significant explanatory work. In the latter case it is providing the dynamics entirely on its own, while in the former case it is supposedly adding some explanatory value (otherwise it would not be presented as an axiom). And while I have nothing to say in favour of bringing it explicitly as an axiom of the theory, I do think that Holland has some point here regarding the explanatory resources of the quantum potential equation. Moreover it is unfortunate that this good point is often dismissed by the defenders of the minimal version of the theory along with the axiomatics, since it is an independent point. In the final section of the essay I elaborate a few suggestions regarding ways in which the explanatory and heuristic resources that the equation provides may be best appreciated on a dispositionalist interpretation of the theory. At this stage, it suffices to stress that that the minimal ontological difference between the 'minimal' and 'causal' versions of the theory is significant. On the minimal version all there is available for explanation are the positions and velocities of the particles, i.e. their trajectories. But this is arguably what stands in need of explanation (Belousek, 2003, p.135ff.). The QPE is derivable as an axiom but on the minimal version it is merely redundant mathematical artifice. On this view there are no 'accelerations', 'forces' or 'potentials' proper to speak of. The primitive ontology of the theory (Allori et. al., 2008) is just the set of particle positions and velocities. On the 'causal' version of the theory, by contrast, there are in addition 'accelerations', 'forces' and 'potentials' which are causally or at least explanatorily relevant to those particle trajectories. The primitive ontology of the causal version of Bohmian mechanics is correspondingly larger.

True, the fundamental ontology of BM remains an essentially open matter in both causal and minimal versions of the theory, [5] since we still need to establish on either account what counts as 'particles', what is represented by the wavefunction, and how the two relate. But the minimal ontological differences between the two versions of the theory already make a difference to their explanatory resources. Belousek (2003) claims that the minimal version of Bohmian mechanics is in fact not properly speaking explanatory at all, since it merely describes motion but does not relate it to any further entities or processes that can provide an explanation of

[5] The idea that BM is not itself an 'interpretation' of quantum mechanics, but a theory of its own – and one open to a plurality of interpretations just like orthodox quantum mechanics, or Newtonian classical mechanics – goes back at least to Fine (1996).

these motions. On his view, only the 'causal' version is explanatory, at least in ambition. One need not go as far as denying that the minimal version is explanatory, in some thin sense of explanation as 'covering' or 'describing' events. However, it will be maintained in this paper that the added ontology built into the 'causal' version can certainly provide some additional explanatory power, going beyond the mere description of motion.

3. Configuration Space Realism, and the 'Problem of Perception'

In this and the next few sections I analyse four different interpretative approaches to Bohmian mechanics in general, together with some of the most significant objections to each. These interpretations go further than the minimal ontologies discussed in the previous section, since they do inform us regarding the meaning of particle, position, wave-function, and their interrelations. The first interpretation that I intend to discuss is what is nowadays known as configuration space realism. According to this view a realist understanding of quantum mechanics will 'depict the history of the world as playing itself out' in configuration space. [6] This is because, since the wavefunction inhabits configuration space, realism about the wavefunction demands that we accept that this is the space that we all 'live in'. [7] Now, for an N-particle system, configuration space is 3N dimensional. In BM the Schrödinger equation has no exceptions, and physical interactions, including those that constitute measurements, only serve to integrate systems into an ever more complex entangled system. We may then refer to the set of all interacting world particles as the World system; this is ultimately a W-particle system described by a universal wavefunction defined over 3W dimensions. Now, this universal wavefunction describes the motion of one particle in a huge 3W dimensional configuration space, and we may refer to it as the World particle. Configuration space realism is the view that the wavefunction is real – and this entails ultimately the reality of the world particle in the 3W dimensional configuration space that we supposedly 'live in'.

What sort of space is configuration space? Certainly, 'space' is a loaded term in this context, since its most common understanding relates precisely to the three-dimensional Euclidean space of classical physics, and this is ostensibly not the configuration space of N-particles except for a one single particle system. So whatever this realism amounts to, it is certainly no ordinary or 'common-sense' realism regarding the objects of our immediate or everyday perception. Now 'common sense' realism about the objects of our ordinary or classical perception is predicated on their 'living in' three-dimensional space (or, at best, four-dimensional spacetime in the case of relativistic phenomena). This is the arena of all our perceptual experience – including that perceptual experience within experimental physics that provides the background to all our experimental results. Scientific knowledge itself – including whatever reasons we have to suppose

[6] Albert, 1996, p. 277; compare the more subtle formulation in Albert, 2013, p. 53, which emphasises the crucial fact that the space of the wavefunction is not strictly identical to 'our' space, but merely isomorphic to it.
[7] Albert, 1996, p. 277.

something like Bohmian or quantum mechanics to provide us with an accurate theoretical representation of our world – depends upon this sort of ordinary perceptual experience in plain 3 dimensional space.

Hence the view that what is ultimately real is the 3W-dimensional configuration space of the universal wavefunction has much explaining to do. For whatever warrant we may have for this view, it ultimately derives from our perception of experimental results in (what appears to us to be) something very unlike 3W dimensional space. The problem of reconciling the appearances with what lies at the level of fundamental reality according to configuration space realism is known as the *problem of perception* (Solé, 2013, p. 366; see also Belot, 2011, p. 73-74). There are a number of strategies defenders of configuration space realism have developed in order to answer this problem, but none has convinced the critics of configuration space realism (such as e.g. Monton, 2013). One prominent such strategy is to show that the appearances emerge in the classical limit as $\hbar \to 0$ (Albert, 2013, defends a version of the strategy). However, this confronts many difficulties, since it is not obvious at all that the actual objects that make our ordinary experience are in any way a limiting case of the world particle in configuration space. True, the laws of classical mechanics emerge in the limit, but this in no way explains how the objects themselves (such as tables and chairs) are 'composed by' any combination of properties of the configuration space (see e.g. the essays in Ney and Albert, 2013, which review different accounts of reduction and emergence in this context). The problem of perception undermines the very empirical grounds that support both quantum mechanics and BM. As a consequence it undermines the very configuration space realism that gives rise to the problem in the first place. For if the three dimensional appearances that constitute empirical data are to all effects and purposes 'illusory', then there are no non-illusory grounds upon which to suppose these theories are empirically adequate, never mind true, as descriptions of reality. So no 'interpretation' of any of these theories has any genuine warrant for us to suppose that they describe anything like the real space we inhabit.

4. Multifield Realism, and the 'Problem of Communication'.

Configuration space realism interprets the wavefunction realistically as an object in configuration space. But this is not the only option available for interpreting BM in such terms. [8] We may consider the multifield option – this postulates a multitude of fields in 3d space, corresponding to each physical particle. Each of these fields is determined by the wavefunction in configuration

[8] Belot (2012) helpfully divides realistic interpretations of the wavefunction in general – including in BM into three kinds: i) object, ii) law and iii) property interpretations, depending on whether they take the wavefunction to be the description of a real object, a genuine law, or an actual property. In my terms, both configuration space and multifield realism are interpretations of kind i), the nomological approach is an interpretation of type ii) and dispositionalism is of type iii).

space, as follows. [9] For an N-particle system wavefunction Ψ defined over 3N dimensions (x_1^1, x_1^2, x_1^3, x_2^1, x_2^2, x_2^3, … x_N^1, x_N^2, x_N^3) a restricted function gives values over the coordinates in 3D space of each particle only. Crucially some information regarding entangled states will get lost in the restricted functions (corresponding to the phase of the wavefunction in polar coordinates), so it is imperative to perform the calculation afresh each time. In other words the wavefunction in configuration space continues to determine the dynamics, in accordance to the Schrodinger Equation and the dynamical postulate, and the positions of each particle continue to depend on the wavefunction in accordance to the Guidance Equation (GE). Yet, at each instant in time, a field is defined in 3-D space corresponding to each particle.

The great advantage of multi-field realism over configuration space realism is that it solves, or at least accommodates, the *problem of perception*. On this view it is not just configuration space that is real, but physical 3-D space as well, with the individual particle fields defined in it. The wavefunction in configuration space encodes information regarding the dynamics of both particle positions and fields in 3D space. It plays the role of a global 'invisible hand' without diminishing the ontological weight of the particles and corresponding fields in ordinary 3D space. There is no *problem of perception* because there is, on this approach, no need to explain how the objects of ordinary perception emerge from configuration space. The objects are already there ab initio, in the description of 3D space, -- albeit with the addition of a field defined presumably at each possible particle position.

However, the multifield approach has yet a different problem, namely the so-called *problem of communication* (Solé, 2013, p. 367; Belot, 2012, p. 72). According to this view, the multi-fields are defined at each instant by the wave-function in configuration space, and the question is how the wave-function 'communicates' to physical 3D space in order to fix each of the fields and the positions of the particles for any system of N particles. Note that this is generally a problem for any account on which the wave-function in configuration space 'dictates' features of physical 3D space that are responsible for the motion of particles, whether it be a multifield, forces acting in the space, a quantum potential located in that space, or directly the motions of the 3D particles themselves. Also, note that the communication is curiously one way: while the wavefunction fixes the physical properties, including position, of particles in 3D space, these have no effect back onto the wavefunction, which essentially ignores which are the actual particle trajectories amongst all the possible trajectories compatible with the dynamics. So it is not possible to understand the communication as a physical interaction between two different kinds of field. [10] By what sort of mechanism does

[9] Belot (2012) here defers to Forrest (1988, Ch. 5), which gives a general account of the equivalent of multi-fields but for dispositional properties or propensities! I come back to the issue in the main text, but for now one gets the idea: There is always a way to define a truncated version of the wavefunction for each particle regardless of whether the properties of the particles are interpreted to be dispositional or categorical.

[10] Finally, also note that the same problem of communication would affect a version of configuration space realism where only the universal wavefunction is

the wavefunction fix, or determine, the physical properties of fields and particles in 3D space? How does the wavefunction in configuration space *guide* the particles in physical space? At the very least, the theory seems to lack the resources to tell a story here, and without a story it remains a mystery how the wavefunction determines the multifields. As regards an ontological interpretation, this is a major problem since it fails to describe how values of physical properties emerge from the underlying wavefunction.

5. The Nomological Interpretation and the 'Problem of Temporal Laws".

Yet another interpretative option is to suppose that the wavefunction has the character not of a space or a field, but of a *law*. This would be a 'nomological' interpretation of the wavefunction. On this view the wavefunction does not represent any real object in 3N-dimensional configuration space, 3-dimensional physical space, or any other space. It does not represent an object – whether a field, a wave, or an extended particle. It rather represents a law – one that describes the motion of real physical particles in 3-d space via the Guidance Equation (GE). [11]

Now, as has been pointed out by Gordon Belot (2012), the objections to nomological interpretations of the wavefunction fall into two types. There is first of all an issue regarding the modal character of laws; an issue that comes to the fore when considering the relative status of the wavefunction (and the guidance postulate and GE) with respect to the dynamical postulate. The dynamical postulate establishes that the Schrödinger equation is the law that unexceptionally governs the temporal evolution of the wavefunction. Thus if the wavefunction is a law, it must be a second order, or subsidiary, law since at any given time the wavefunction is delivered as the outcome of the Schrödinger equation, which itself has undisputedly the character of a law. Hence, although at any given time the wavefunction has via the guidance postulate a nomological role vis a vis the positions and velocities of the particles, it itself is the result of the application of another higher order law, given in the dynamical postulate. In other words, whatever nomological force or necessity the wavefunction possesses over the particle trajectories, it is subsidiary to the nomological force or necessity of the Schrödinger equation.

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reified, but not the universal particle. On such views, there is a real wavefunction in 3N space, which effectively fixes the particle positions of each particle in 3D space – with the same difficulty to explain how the interaction occurs. (Belot, 2012, p. 77).

[11] I suppose that the wavefunction could also be taken to represent a law describing the motion of the world particle in configuration space; but this combination of nomological and configuration space realism would seem to inherit the disadvantages of both types of realism while acquiring none of their relative advantages. And, at any rate, this is not how the proponents of the nomological interpretation read it – see Durr et al. (1997), or Goldstein and Zanghi (2013).

The existence of a modal hierarchy need not be an altogether insurmountable problem. It certainly does not seem to be so in general when the appropriate nesting relations obtain. In such cases we often distinguish phenomenological and theoretical laws, and have no problem in assuming that the necessity of the phenomenological laws is derived from, or subsidiary to, the necessity of the theoretical laws. As examples, consider the relation between the laws of geometrical and physical optics, or between Kepler's three planetary laws and the laws of Newtonian mechanics. In both cases it is at least arguable that the dependence does not impugn the nomological force or character of the subsidiary law but, if anything, explains it. Hence we gain some understanding of why Kepler's laws are indeed laws when we learn that they can be derived from Newton's laws, and similarly for the optics case.

However, in the context of the interpretation of BM, this solution is not so clearly applicable. Is the defender of the nomological interpretation of the wavefunction happy to accept that its necessity is secondary just like Kepler's laws or the laws of geometric optics? Is he or she prepared to accept that the wavefunction is a phenomenological but not a fundamental law? This may moreover be seen to be a particular problem for defenders of the nomological interpretation of the minimal version of BM. For a standard way to cash out the difference between phenomenological and fundamental laws is precisely by appealing to explanatory power. The fundamental laws explain the phenomenological ones (as in the case of the relationship between Newton and Kepler) by displaying the second order causes (forces) of the first order motions (trajectories) that appear in the phenomenological laws. Yet the minimal version of BM contains only first order properties, and the conjunction of the (GE) and the Schrödinger equation therefore cannot explain the wavefunction in this way. The fundamental laws contain no second order properties (such as forces) that may explain causally the first order properties in the phenomenological laws. The causal version obviously overcomes this problem very simply, since on this version of the theory the fundamental laws include the (QPE), which does refer to second order properties akin to Newtonian forces; hence the relation is explanatory in the prescribed sense.

I shall not delve further into the question here, because I think that there is yet a more powerful objection against the nomological approach. At any rate the onus seems to be on the defender of the approach to come up with an account of the wavefunction as a law that does not make its nomological force entirely subservient to, or dependent upon, that of the Schrödinger equation. [12] An interesting proposal to achieve this is by means of the concept of the 'effective wavefunction' of a quantum subsystem of the universe (Durr et al., 1996, p. 39). Suppose then that the actual state of the universe at time t is given by Q_t and Ψ_t. For a subsystem, the x-system, with generic configuration x, we may write, q = (x, y) where y is the generic configuration of the environment of the x-system, i.e. the rest of the Universe. Suppose that the actual configuration at time t is given by $Q_t = (X_t, Y_t)$; then roughly the effective wave function of the x-system at time t is

[12] Or, more precisely, one that does not make it subservient to the conjunction of the Schrödinger and Guidance equations.

given by $\Psi_t(x) = \Psi_t(x, Y_t)$. The point then is that this effective wavefunction is not subservient to the conjunction of the GE and the Schrödinger equation (GE), as applied to it in isolation, since it rather depends on the complete universal wavefunction and its evolution. A nomological interpretation of the effective wavefunction is therefore more attractive, but not yet free of problems. [13]

The even deeper problem is that the modal force of any quantum wavefunction –its status and content as a law, and the prescriptions that it exerts upon the properties of the physical particles – is always relative to a particular instant in time. This fact also follows from the dynamical postulate, but it is distinct and independent from the earlier objection regarding the phenomenological character of the wavefunction, since it concerns strictly the fact that the wavefunction is a time dependent entity. We may refer to this distinct problem as the problem of time-indexicality. It arises out of a consideration of the time-dependent Schrödinger equation, which determines the wavefunction at each instant in time. This means that the wavefunction is essentially determined afresh each time, in accordance with the unitary evolution sanctioned by the Schrödinger equation. And this would be fine if the wavefunction merely described the state of an entity or its properties, which of course would vary with time, but it seems completely at odds with any 'nomological' character of the wavefunction. In other words we typically understand physical laws as determining the time evolution of the objects in its domain but not as subject themselves to any temporal evolution. [14]

The argument is not merely one of conceptual novelty with respect to the character usually ascribed to laws. It further threatens logical contradiction. It is extremely hard to see how the law can determine – as it must for a law - the temporal evolution of the objects in its domain if the law itself is subject to constant temporal evaluation. For what would it mean for the law at time t to prescribe a certain future state at time t' of some object in its domain when the law itself may be a completely different one by the time t', and therefore establish a completely different prescription at that time? How can such a law be said to have any modal force? Perhaps this makes sense if the prescription at time t merely describes an expected regularity, at time t, given past behaviour up to t. But if the

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[13] These problems are related to the fact that the effective wavefunction is not exactly as above, which is rather a representation of a 'conditional wave function' that does not obey Schrödinger's equation (Dürr et al.,, 1996, p. 39), but I gloss over them since I regard the problem of time-indexicality to be the more acute one anyway.

[14] At any rate, this is certainly how we understand dynamical laws – such as Newton's laws and the Schrödinger equation. So much seems uncontroversial, and it is enough to make the point in the main text above, but it may be objected that there are also physical laws which do not have this dynamical character – perhaps purely geometrical laws that describe the internal constitution of solids. And perhaps the wavefunction understood as a law has this different character. However, it seems to me that the same problem reappears here too – even if the laws don't prescribe the temporal evolution of the objects in their domain, it is nonetheless bizarre to think that they themselves are time-indexed or time-dependent things.

prescription merely amounts to a statement of regularity, it can hardly be said to be nomological. [15] If the law genuinely determines the state of the particles at any given time with nomological force, it must not itself vary in time on pain of potentially failing to determine uniquely such states, and thereby possibly incurring a contradiction.

To sum up, we have prima facie unearthed two difficulties for the nomological construal of the wavefunction: i) whatever modal force the wavefunction possesses it seems subservient to – i.e. dependent upon – that of the dynamical equations of the theory – including notably, on any version of the theory, the Schrödinger equation –, and ii) the time-indexed character of the wavefunction militates against understanding it nomologically, under any interpretation of 'nomological'.

6. The Dispositional interpretation and its Response to all Problems.

The fourth and final ontological interpretation I would like to discuss is a dispositionalist understanding of the wavefunction. On this view, the wavefunction is not a law, and has no nomological force. It has merely a descriptive, or representational, function concerning the state of the physical particles in 3-d space. Yet, it does not represent any distinct object per se in 3-d space – neither a field nor a wave nor even the particle itself. And it certainly does not represent the state of an ultra-particle in N-dimensional configuration space. Its function is rather to represent, in a rather indirect manner that I shall shortly describe, the properties of the 3-d particles, including crucially a series of dispositional properties over and above the particles' positions. [16]

The idea behind a dispositional reading of Bohmian ontology is in particular linked to the interpretation of the Guidance Equation (GE in postulate 4). GE lays down a velocity field at any given time t – let us denote it as X_t - since it determines for every possible particle's position Q_k in 3-d space very precisely a velocity vector $v_k^{\Psi}(Q)$, given the quantum state or wavefunction Ψ. Now, I emphasize

[15] This may indicate that the correct construal of 'nomological' in this approach is Humean - in the sense that the wavefunction is meant to be a law in the Hume-Lewis best system sense of law, as a description of regularity over the course of the actual world history that best summarizes space-time coincidences (see Esfeld et al., 2014, pp. 780ff.) for some suggestions in this regard). But the possibility of undermining futures is a problem for the Humean analysis of laws too, and a law that would correct itself in the future would be just as counterintuitive from this point of view.

[16] I will for the sake of argument assume that position is not a dispositional but a categorical property. The dispositionalist interpretation of BM would of course be further strengthened if position turned out to be a dispositional property as well (for some suggestions to the effect see Clifton and Pagonis, 1995). The argument above shows that even if position is categorical, the interpretation of other properties as dispositional already serves to solve many of the problems reviewed so far in establishing the ontology of the theory.

possible particle positions, since this field X_t is defined for any triple of values $Q_k \in \Re^3$, for every particle in any n-particle system. As far as I can see nothing prevents a strong as well as a weak reading of the modalities involved in this statement. Thus, according to the weaker reading, given any real n-particle system and its associated wavefunction Ψ, we may calculate X_t via the GE for any possible initial position of the particles, including but not limited to their actual initial position values. The field X_t then describes, for any real particle system, the velocities the particles would have, had their initial positions been different. But more strongly, we can also via GE calculate for any *possible* n-particle system its corresponding velocity field given a wavefunction state for it. In other words, the velocity field describes the dispositions of every particle configuration in any real or imaginary system of particles.

The picture that best seems to me to capture the nature of X_t is therefore entirely in analogy with a physical field. For instance, the electromagnetic field as determined by a system of charged particles describes a vector potential quantity for every point in space, which in turn determines how any hypothetical system of particles would behave, and in so doing it determines a 'dispositional' field. In a similar guise, a dispositional interpretation of BM invites the thought that every point in physical 3-d space is endowed with a 'potential velocity vector' that determines how a particle in a particular quantum state which found itself at that point would evolve in time. More precisely, the idea is that on this interpretation, an actual n-particle system in the state given by (Q_t and Ψ_t) determines, via the Guidance Equation of motion (GE) a velocity vector for every point for each of its particles. Thus if the wave-function of the n-particle system is Ψ (q, t) with $q = (q_1, q_2,\ldots, q_n) \in \Re^{3n}$, and the position state is $Q = (Q_1, Q_2,\ldots, Q_n)$ with $Q_k \in \Re^3$ as the actual position of the k^{th} particle , then the GE determines a value of a velocity for each of the particles in their respective positions. The strong and weak modalities that I have described may then be described as follows. For any actual n-system of particles with quantum state wavefunction Ψ (q, t) with $q = (q_1, q_2,\ldots, q_n) \in \Re^{3n}$ we can consider, weakly, all the different possible position states of the n-system at any given time, i.e. the different $Q_t = (Q_1, Q_2,\ldots, Q_n)$ position states at time t. Each of these will define a velocity vector field for every point in space occupied by each imaginary particle. Since we can in principle imagine any n-particle system, this procedure would exhaust the points in 3D space, thus covering up the space. Alternatively, the stronger modal reading is to imagine any arbitrary n-system particle with its own characteristic state (Q_t and Ψ_t). We may then also fill the entire 3D space with a velocity vector field associated to each point, but do so differently - obviously - for each combination of the Q_t and Ψ_t states.

The velocity field defined by the GE is therefore a catalogue of all the dispositions for the motion of particles. [17] That is, in a one-particle system, it

[17] One can also read the multifield approach dispositionally and, in fact, this is what Forrest (1988, Ch. 5) does in introducing it as a 'propensity multifield'. This would amount, in terms of the proposal advanced in the main text above, to defining a velocity field in 3d space for each particle, for every given wavefunction for the corresponding n-particle system as defined in 3-n configuration space. I don't see any substantial difference between this proposal – if read dispositionally

determines the trajectory that the particle, in a given quantum state, would follow if it found itself at a particular point in 3-d space. More generally, for a larger system of n particles in a given quantum state the velocity field defined by the GE determines the set of all particle trajectories in the system. The only difference is that, for a system of n particles, the wavefunction for the whole n-particle system must be fed into the GE in order to perform the calculation. For the whole universe, the complete wavefunction of the universe must be fed into the GE, of course, but there is no particular difficulty here, since in BM there is at no point any need to invoke external measuring devices in order to explain the actualization of these dispositional properties. Rather, on this picture – and in line with the analogy with the electromagnetic field –, the dispositional velocity property defined relative to a state at each point is spontaneously actualised when a particle happens 'to reside at' that point.

This velocity vector of course depends on the positions of all the other particles in the n-system, as the (GE) makes clear. So this is a non-local quantity, which depends on the values of certain quantities of distant objects, or the corresponding related events of those quantities taking values across space-like related gaps. A comparison is instructive with the alternative account offered by Esfeld et al. (2014). On their account only the universal particle in configuration space has dispositions, and the velocity field is defined over configuration space. The actual velocities of particles in 3D space are thought instead as the manifestation of these universal particle dispositions (Esfeld et al. p. 785). I understand this to mean that there are no genuine dispositions for the individual particles taken in isolation. The only dispositions that exist are those represented by the universal wavefunction for all the particles, which concern the universal particle; these dispositions manifest themselves in the first instance in the evolution of the universal particle itself. True, these are perceived as motions of each of the individual particles in 3D space but there are no dispositions 'residing in' physical 3d space – neither in the points of 3D space nor in the 3d particles that occupy such points.

This "Esfeld" disposition, as we may call it, is a holistic property of the universal wavefunction. So the manifestations will appear to be non-local, in the sense that it will appear as if the velocity of a particular particle over here depends upon the positions of particles elsewhere. But in reality there are no dispositions in 3D space or in the 3D particles, there is only one higher rank disposition of the universal particle, which is necessarily entangled or holistic (but not non-local since there is only one universal particle with a particular location at all times). [18]

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in this way – and my own proposal above other than the nature of the position property itself (which, on the multifield approach would presumably be necessarily dispositional too).

[18] In other words, I use the terms "locality" and "separability" roughly in the sense of Howard (2008). Under this aception, locality requires separability but not viceversa. In a typical EPR experiment, for example, one can have separable particle states in both wings, but non-local connections; or one can postulate one non-separable state (or even particle), but not both. The standard understanding

By contrast, on the interpretation that I am proposing, the dispositional velocities are in the 3d particles themselves, but they depend non-locally on the properties of other particles, in particular they depend on the positions of the other particles. Although in practice there is no difference between these two views at all – and in particular they certainly do not entail different empirical predictions – there may nonetheless be differences in the types of explanatory stories they furnish.

The dispositional interpretation of the velocity field defined by GE provides ready-made responses to the problems that make other ontological interpretations of BM untenable. In particular, I argue in the rest of this section that the dispositional interpretation overcomes the problems of perception, communication and underdetermination, which I reviewed in the previous sections. This can be seen as a decisive advantage of the dispositional interpretation, although it is an advantage that needs to be put in context, as follows. The problems reviewed in the last sections were each of them in some way artificially compounded by the corresponding ontological interpretations. Thus the problem of perception only really makes sense with respect to configuration space realism (or some versions of the multifield interpretation). The ontology brings the problem with it as it were. Similarly, the problem of communication only really makes sense in the context of ontologies that reify some space in addition to 3-d (or perhaps 4-d spacetime) space by declaring it just as real. It is clear that such problems do not arise in the context of a theory where only 3-d (and / or spatiotemporal 4-d) space is real. In other words these problems cannot arise for either nomological or dispositional interpretations of BM. The decisive issue for the dispositionalist interpretation of BM may thus be rather whether it introduces problems of its own, and if so, whether such problems incur a heavier or lighter toll than the alternatives.

For example, the problem of perception as it arises in the context of configuration space realism is inapplicable to the dispositional interpretation of BM, since on the dispositional account 3-d physical space is the only real space. True, on this account, not all properties of systems are categorical, and therefore not all of them are reducible to the Humean mosaic of spatio-temporal coincidences. There are instead important modal properties of particles, expressed by the velocity field X_t, which do not supervene on the particles' positions. Moreover some of these dispositional properties are explicitly non-local, and hence can be understood to interact 'at a distance' with each other. I review some of the implications of this view vis. a vis. Humean metaphysics in the next section. For now it suffices to show that each and every one of the objections raised against the other ontological interpretations of the theory are naturally resolved or dissolved within the dispositional interpretation.

The problem of perception is immediately dissolved, as noted, since on the dispositionalist account the space of our perceptions of physical and measurement interactions and their consequences and results remains indeed the only real physical space. On this account reality unfolds in 3-d space completely and the

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of separability of states is as supervenience (Teller, 1989) and this fits in well with Esfeld et al.'s emphasis upon the failure of Humean supervenience

history of the world unfolds in this space in its entirety. Configuration space is, on this account, a mere mathematical space, which plays a useful role in codifying the properties of particles beyond position, in particular its dispositional properties via the wavefunction. But, as I shall argue, this higher-dimensional 3n-d space is called in only because some of these properties fail to supervene on the particle's positions in 3-d space. The wavefunction, which represents these further properties, cannot be defined in 3-d space alone. Yet, there is on the dispositional account no need to abandon the thought that reality unfolds in 3-d 'ordinary' space only. For a mathematical space to provide a helpful and efficient representation of some of the properties of the entities the theory postulates, it is not required that those entities themselves actually live in that space. The theory makes clear that 3d is the space in which particles move, and it is the space on which the dispositional velocity field X_t is defined at all times. The interactions that particles have with each other and with other systems are therefore all mediated in this space. It can hardly be surprising then, that our perceptions and measurements all seemingly take place in this space. Our 3-d perception does not call for explanation, and no circularities may arise that could undermine our confidence in the theory itself.

The problem of communication is also related to the reification of higher dimensional spaces. In any 'hybrid' theory where both 3n-d configuration space and 3-d physical space are real, the challenge is not so much to explain why perceptions seem to take place in 3-d space (since it is now possible that they actually do take place in that space) but rather to explain how an entity in a higher dimensional space 'communicates' with the particles in 3-d space in order to 'guide' them. How does the real wavefunction in 3n-d space interact with the real particles in 3-d space? Note that since on this approach both the wavefunction and the particles are independently real – each in a space of their own – for the wavefunction to physically guide the particles, there must be some type of physical interaction between entities that inhabit distinct spaces. But what is the nature of such interaction – which is conspicuously absent from the theoretical framework? The dispositional account obviously does away with the challenge, since it does away with the reality of the higher dimensional space altogether. On this view the wavefunction is not an entity in its own right, and is incapable of physical or causal interaction with anything. It rather merely represents the dispositional properties of the 3-d particles. The higher dimensional space of the wavefunction may be a mere mathematical convenience. As a matter of fact, in a context in which the dispositional velocity field fails to supervene on the positions it is more than a mere convenience, it becomes a necessity. For notice that if those dispositional properties fail to supervene on the particle's positions then necessarily those properties cannot be represented in 3-d space (or any of its subspaces): Since all possible positions exhaust 3-d space, it follows that 3-d space can by definition not suffice to represent any properties that fail to supervene on such positions. In a context of non-supervenience, the recourse to a higher dimensional space is not only unsurprising but entirely to be expected.

Finally, the problem of time indexicality is a problem for the nomological interpretation of the wavefunction. It is hard to see how it would apply to any of the other interpretations canvassed, since it is only when applied to laws that this

sort of time dependence is perplexing. That is, time-dependent *laws* are perplexing, but time-dependent states, properties, or their values are not only non-perplexing, but seem entirely natural. As a consequence no interpretation that relinquishes the thought that the wavefunction is a law - for instance by asserting instead that it is an entity - can suffer from this difficulty. On the dispositional interpretation, the wavefunction is a mathematical tool that encodes the dispositional properties of particles at any time, given their initial positions. It is only to be expected that particles' properties – including their dispositional properties – will be time-dependent in the usual manner, so there is no difficulty at all with this. Nor is there of course, any difficulty with the wavefunction dependence upon the Schrodinger equation expressed in the second dynamical postulate. This merely expresses the fact that the Schrodinger equation governs the time evolution of the dispositional field and therefore of the ensuing dispositional properties. The guidance equation (GE) already guarantees the equivalent fact for the particles' positions anyway.

7. Problems for the Dispositional Interpretation.

The dispositional interpretation therefore solves – or rather dissolves – all the problems that make other interpretations untenable. However, it is important to remind ourselves that these problems were created by the interpretations in the first place. That is, the problem of perception only arises in the context of configuration space realism, the problem of communication only arises in the context of some hybrid realism regarding both configuration space and 3-d space, while the problem of time-indexicality only really arises for the nomological interpretation of the wavefunction. It is of course important to note that these problems all disappear on a dispositional interpretation, but we may still wonder whether the dispositional interpretation will not generate its own problems on a par with these. In this last section I would like to argue that this is not so – the dispositional interpretation does not generate additional problems. Since we should always prefer an interpretation that poses no problem of its own while resolving those of its competitors, we should prefer the dispositional interpretation to any of its present day competitors.

Some of the possible problems with the dispositional interpretation are related to challenges and difficulties with dispositional properties in general, and I will not discuss them in much detail here. The objections at this level are typically of two sorts. First, there are the usual objections from those Humeans who endorse the thesis of Humean supervenience, according to which all genuine properties ultimate supervene on the Humean mosaic, i.e. the set of spatiotemporal local coincidences (see Lewis, 1986, p. ix). Any properties that prima facie do not so supervene on the Humean mosaic are condemned by such Humeans on either empiricist grounds, or grounds of parsimony. Dispositional properties are suspect since they do not appear to correspond to any of the events in the Humean mosaic. Thus, generally, to have a disposition at time t to e.g. a certain position at some time t', is to manifest that position if appropriately tested at t'. But the disposition is possessed at time t, with $t \neq t'$ generally, so the possession of the disposition at time t corresponds to no event in the Humean mosaic at that time. Nevertheless, one may suppose that dispositions supervene on the totality of the Humean

mosaic. This would certainly be the case if dispositions supervene on categorical properties in general. However, that the dispositional can be reduced to the categorical, even under such a weak notion as supervenience, is disputable. It is moreover particularly dubious at the level of the fundamental ontology of quantum mechanics since, at this level, there are no deeper or more fundamental properties to appeal to in order to carry out the reduction. So, on any committed Humean supervenience account, dispositional properties remain suspect, and so does Bohmian ontology under the dispositional interpretation of the velocity field as expounded here. The objection is thus genuine in this context, but there is no space to deal with it more fully here – other than point to the obvious retort that Humean supervenience may after all be rejected altogether.

The other source of difficulties for dispositions in general is related to the old *virtus dormitiva* objection – their presumed lack of explanatory power or conceptual triviality. Thus Moliere famously inveighs sarcastically against the scholarly physicians who invoke the virtus dormitiva of opium in order to explain why it would put anyone to sleep. [19] If the explanandum is that someone who has ingested opium is falling sleep, it can hardly be explanatory to cite the 'dormitive power' of opium, since the disposition here merely rephrases the explanandum. But there are a few good retorts to this objection. First, it does not quite get the point of Moliere who is inveighing not against dispositions per se, but against verbose redundant explanations that merely rephrase the explanandum in pompous language (latin). The same objection could have been raised against an explanation in pompous language that merely places the explanans in a regular pattern. Moliere's sarcasm would have been just as fittingly directed to any attempt to explain e.g. why a particular object is a square by citing its 'squarity'. The dispositional nature of the property in question plays no particular role. Secondly, there are plenty of simple ordinary life counterexamples to the triviality of dispositional explanations. We seem rather disposed in ordinary life to accept the fragility of a particular glass as part of the explanation of its breakage, the solubility of a particular sugar cube as part of the explanation of its dissolving in a hot drink, etc. Nevertheless, under their usual interpretation such dispositional properties do not – in the ordinary context at hand – amount to much more the assertion of their power to bring about these effects. True, for ordinary physical dispositions, most of us tend to think they ultimately reduce to further properties (of glass, sugar, etc), which may or not be categorical. But there are other dispositions where even to suppose a reduction is problematic (behavioural and psychological dispositions, such as generosity, kindness, etc) and in the ordinary context we use them just as freely in explanatory terms. So it is hard to see how the explanatory power of the physical dispositions in any way depends on the possibility that they may reduce. At least in an ordinary context, we do not typically request to be shown a reduction in order to accept an explanation in terms of a disposition such as fragility or solubility. In other words, the virtus domitiva objection to the explanatory power of dispositions is much overrated and does not apply generally, treading as it does on features of the example at hand.

[19] In Moliere (1673, Act III, Third interlude): "Quare Opium facit dormire: ... Quia est in eo Virtus dormitiva".

I will not say more about these sorts of general objections here, which need not detain the defender of the dispositional interpretation. I will instead focus on a specific objection to Bohmian dispositions in particular. The objection is due to Gordon Belot and was inspired by some critical remarks by Albert Einstein against hidden variables. Were this objection to stand, the dispositional interpretation of BM would fail regardless of the status of dispositional properties in general. Belot (2012, pp. 77-80) endorses some of the attractions of a dispositional interpretation while simultaneously advancing this serious challenge, which I refer to as the under-determination objection. I believe possible responses to the objection can be found in propensity accounts of orthodox quantum mechanics. For this reason I indulge in the remainder of this section in a comparison with propensity accounts for orthodox quantum mechanics. The comparison will hopefully bring into relief some dispositional resources to confront the objection, while also helping to distinguish the dispositional interpretation of BM from its propensity equivalent in orthodox quantum mechanics.

The propensity interpretation of orthodox quantum mechanics is grounded upon what I have elsewhere called the 'basic dispositional template' of any dispositional interpretations. [20] Suppose that state Ψ can be written as a linear combination $\Psi = \Sigma_n c_n \left| \nu_n \right>$ of the eigenstates ν_n of the latent observable represented by Q with spectral decomposition given by $Q = \Sigma_n a_n \left| \nu_n \right>\left< \nu_n \right|$. Notably, on the orthodox eigenstate-eigenvalue link, a system in such state cannot be said to possess a value of Q. The propensity interpretation has no difficulty here, however, since it abandons the presupposition that systems only possess properties if they possess values of such properties in accordance with the e/e link. We may then assert that a system is in state Ψ if and only if it has on a measurement of Q the disposition to manifest eigenvalue a_i with probability $|c_i|^2$. More specifically, in the selective propensities interpretation, every discrete and non-degenerate observable such as Q of a system in state Ψ generates an equivalence class of states that are statistically indistinguishable from Ψ. It then becomes possible to identify the propensity of Ψ that a measurement of Q would test with the standard representative W(Q), which we may construct uniquely out of the equivalence class.

Two aspects of this propensity interpretation are relevant to our discussion here. Firstly, note that the propensity interpretation of quantum mechanics elicits probabilities for each and every one of these properties, and in fact characterizes the properties statistically, on the basis of these probabilities defined over possible outcomes. The thought is that the process whereby propensities are actualized is inherently stochastic – hence the dispositional properties of orthodox quantum mechanics are propensities. However, in Bohmian mechanics, the underlying dynamics is entirely deterministic throughout, since the Schrödinger equation has no exceptions. The quantum probabilities can only be said to emerge as a result of our ignorance of the initial state of the N-particle system. The probability distribution over the initial particle positions that describes this ignorance just so

[20] Suárez 2004, and 2007, p. 420. It is important to distinguish carefully this propensity interpretation of quantum mechanics from the – flawed – propensity interpretation of quantum probability famously defended by Karl Popper.

happens – via the equilibrium postulate 3 – to coincide with the square modulus of the wavefunction amplitude, and is thereafter preserved by the unitary dynamics of the dynamical postulate 2. In other words the probabilities in this view are epistemic, and the underlying dispositional properties are not per se propensities. [21]Bohmian dispositions are instead sure-fire dispositions, since for any particle in an N-particle system in state Ψ, the velocity field X_t defined by the GE determines a future trajectory. In other words, the particle would follow the trajectory (with certainty, i.e. probability = 1) if it found itself in that particular position. But given that we may only estimate within statistical error the probability that the particle actually finds itself in that position, this probability estimate gets carried over to the set of possible trajectories. To summarize, Bohmian dispositions are propensities only in some epistemic sense, which I now think is best not to describe under the rubric. [22]

Secondly, note that in this approach quantum propensities are represented by entire classes of quantum wavefunction states. It is not in general a requirement for a dispositional interpretation that it must identify a propensity, or dispositional property, with each and every distinct quantum state or wavefunction. This is relevant in response to Belot's under-determination objection, as follows. Belot raises and discusses Einstein's 'particle-in-a-box' thought experiment in reaction to Bohm's theory. [23] Einstein (1953, pp. 35-40) imagines a bullet of around 1 mm. in diameter, moving to and fro between two parallel walls about 1 meter apart along the x-axis. The collisions are supposed to be elastic, and the centre of mass coordinate *x* of the bullet is to specify its position. (Hence the example applies as well to any point particle). Assume a potential box of length L, where the potential is zero inside the box and goes to infinity right outside the box. Then if the particle is free, and supposing the it is confined to a length L in the unit interval [-1/2,1/2] $\in$ R, the energy eigenstates are given by the following family of wavefunctions:

$\Phi_n(x) = \sin(\pi n x)$, for n = 1, 2, 3, …

[21] It must be noted that there are accounts, such as Albert's (2000) where the initial probability distributions represent objective chances already, which get as it were transferred to later chances by the dynamics. On this account, there is determinism in the dynamical evolution of chances, yet stochastic or chancy determination of outcomes. The view is nonetheless controversial, and a full application of propensities must await a new paper.

[22] In other words I now want to reserve the term "propensity" for an essentially and irreducibly objective probabilistic disposition. See Solé (2013, p. 375) for an accurate disquisition of this point in connection with my previous defence of selective propensities for BM in Suárez (2007), for which I am grateful.

[23] In the *festschrift* for Max Born (1953), where Einstein does not explicitly address BM, which had at the time just appeared in press, but more generally any realist theory about particles' positions. He may have had in mind De Broglie's pilot wave theory in particular.

This entails via the GE that the wavefunction Ψ is stationary:  , and it can be represented as the superposition of two harmonic waves propagating in opposite directions: $\Psi = \frac{1}{2}Ae^{i(at-bx)} + \frac{1}{2}Ae^{i(at+bx)}$.

In other words, a Bohmian particle in this state in such a potential box is at rest regardless of where it finds itself in the box. Belot then argues that while this can generically be accommodated within BM, it nonetheless is hard to square with the dispositional interpretation. Instead, he claims, it shows that the quantum wavefunction is under-determined by the dispositional history of the Bohmian particle or system of particles. For here we have an example of a particle with only one dispositional history (i.e. only one value of the velocity field at any point) but a whole family of quantum wavefunctions corresponding to it. So, more generally, the under-determination of the quantum wavefunction implies that there cannot be a one-to-one correspondence between the dispositional history (or history of dispositional velocity field states X_t) and the quantum wavefunction for any n-particle system, including possibly the entire universe. And this, as Belot (ibid. p. 79) explains, "is dismaying. Under the standard approach, different Φ_n correspond to different energetic states of the system – the larger *n* is, the more dangerous it is to stick your hand in a box containing a particle in state Φ_n." What appear to be indubitably different physical states give rise to one and the same dispositional history.

But why should any of this bother the defender of a dispositional interpretation? After all there is nothing in the nature of dispositional interpretations that requires such a one-to-one correspondence. One has to go no further than the selective propensity interpretation of orthodox quantum mechanics above in order to find a perfectly possible account, namely one in which a dispositional state or property, or history of such states, does indeed correspond to an entire equivalence class of physical states. As long as there is a determinate manner to fix the class, whether by description or implicit definition, there is nothing fundamentally lost in considering the equivalence class vis a vis the velocity field X_t. Moreover, the one-to-many correspondence may well have its uses as I point out shortly. There is no reason as far as I can see why the defender of dispositions should in this context have to dispense with any additional state information beyond that regarding the dispositional velocity field, in particular since it turns out that this information is relevant to further dispositions, or their properties.

Belot (ibid. p. 80) adds the proviso that it may be possible to prove that only in very special cases it is not possible to reconstruct the wavefunction entirely from the complete history of the velocity dispositions; and in those very special cases one could bite the bullet and claim that there are no determinate facts regarding quantities beyond position, such as energy, etc. What I am proposing is a way around this problem by constructing equivalence classes of states with respect to each observables of interest. The solution entails the dispositional interpretation of the wavefunction – the assertion that the wavefunction describes dispositional properties – but it does not require all properties catalogued by the

wavefunction to be first-order dispositions of the particles (or, in fact, dispositions at all, since actual positions are typically understood as categorical).

8. The Explanatory Role of Bohmian Dispositions

I have argued in this paper that the dispositional interpretation of Bohmian mechanics (BM) provides natural responses to the problems that make other interpretations untenable, while yielding natural responses to other prima facie major challenges for BM. Thus my main claim in this paper, namely that a dispositional interpretation of BM is preferable, has already been argued for. Now, the dispositional interpretation of the velocity field in BM is compatible with both the causal and minimal versions of the theory, since it applies directly to the main equation of motion according to both versions of the theory, that is, the Guidance Equation (GE). So the dispositional interpretation per se does not provide an argument in favour of the causal version. Yet, in emphasizing the Quantum Potential Equation (QPE), the 'causal' version brings to the fore certain heuristic and explanatory elements that, I argue, can best be appreciated in a dispositional interpretation. Thus in this final section, I would like to outline a way of reading the second order quantities that the QPE brings to the fore in a dispositional guise.

The critical difference, from a dispositional point of view, between a first order equation such as (GE) and a second-order one such as (GPE) is that if the GE describes first-order dispositions then GPE necessarily describes second-order ones. GE establishes the dispositional velocity field for the particles, which a first order dispositional property of each of the particles. It is the disposition of the particle to move along a particular trajectory (given that the N-particle system is in state Ψ and the particle in question finds itself in a particular position). The GPE then establishes the evolution of this dispositional velocity field as a result of what it refers to as the 'quantum potential'. In a dispositional interpretation the quantum potential is nothing but a second order disposition, and the GPE then effectively describes the disposition of (first order) velocity dispositions to evolve.

It is of course true that the 'minimal' version also accepts the GPE equation – which, after all, follows from GE with additional assumptions. Yet, accepting this equation is not the same as committing to the existence of second order dispositions. For as was noted, the GPE equation is purely a formal result for the defender of the minimal version, which does not characterize any fundamental physical result. From the point of view of the minimal version ontology there are only particles and their positions and velocities (which may be interpreted dispositionally); therefore strictly speaking there cannot be second order dispositions, even under a dispositional interpretation of the velocity field.

So, here we find a significant difference in ontology between the minimal and causal versions of the theory. In particular, the defender of the 'causal' version can now appeal to some explanatory and heuristic advantages in putting the GPE explicitly upfront. First, the GPE brings out the explicit dynamical features of BM, which prescribes not just conditional trajectories, but also a dynamics for such

conditional trajectories. [24] Second, it turns out that most non-local effects in BM are encoded in this second-order dynamics, in the sense that the quantum potential is explicitly non-local since it depends on the (second order derivative of the) real amplitude of the wavefunction at all times. Thus, for example, in Einstein's thought experiment, the particle in the box is stationary according to the GE, as long as the potential walls are kept infinitely large at the extremes. The GE does not reveal how the state of the particle may change with a varying potential gradient. Only the GPE does allow that – in effect revealing the second-order dispositions that are implicit in the experimental set up. Thus, if we were to suddenly reduce the potential in one of the walls but not the other, we would ipso facto change the wavefunction, which would no longer be stationary, and the first order dispositions (velocities) of the particles. But while the minimal version has nothing illuminating to say about why this should be the case (it merely predicts that it would be the case), the causal version can say that the changes in the potentials (V and U) acting on the particles have induced changes in the velocities of the particles (i.e. the second order dispositions have changed and thereby induced a change in the first order dispositions). This is a typical feature of dispositions of many ordinary or everyday-life objects, such as the fragility typical of glass, which may be understood and explained away by an appeal to further properties (categorical but arguably also dispositional) of glass, including chemical composition and reticular shape. There is a sense in which going second order is equivalent to providing a more in-depth analysis of the reductive base of a disposition. And while this is not required in ordinary contexts for a routine explanation of a particular phenomenon of 'fragility' or 'solubility' it is required when we begin to ask questions about how the fragility or solubility of a particular object changes when we change the conditions or otherwise interact with its performance.

So, I am suggesting that dynamical interaction under experimental conditions is the key. If we just want a theoretical description of the behaviour of physical systems when left to 'their own devices' in thought experiments such as Einstein's, the minimal version does everything we could ask for. But if we are asking how a particular and concrete experimental set up may change in response to our interactions with it, the causal version comes in handy with an explanatory story of how those changes come about. Again there is no new phenomenon that the GE and the minimal version could not accurately describe; but neither is there any story to be told from the perspective of this version. While a theoretician may rest content with a thought experiment, an experimentally minded philosopher or scientist would appreciate a story that informs what happens in practice in real experiments. For the latter, the causal version does have some explanatory value

[24] Sometimes the word 'dynamics' is taken to implicitly refer to forces, as in "Newtonian dynamics" and to carry the corresponding causal connotations. More generally, however, it can be employed as in the text above to refer to any second-order derivative function of the position – and to the framework that articulates the properties that are operative at that level. Hence I am not employing the term in its most committed sense as requiring the existence of independent forces acting causally upon the particles' velocities. Rather GPE is legitimately dynamical merely on account of its formal second order character.

to offer. Any account of the dynamics of dispositional properties requires a second-order theory, in order to describe the possible changes on dispositional properties under different circumstances (counterfactual or actual). The QPE explicitly provides just that second order treatment, so it seems heuristically and pragmatically justified that it should be placed upfront, as opposed to leaving it implicit in the background. And notice that while the appeal to second order dispositions has an explanatory gain, there is little to lose philosophical since dispositions have already been accepted at the first order level. In other words, once one has taken the courageous step to accept first order dispositions (as Esfeld et al., 2014, do) there is no real gain and there may well be explanatory loss in refraining from accepting second order dispositions as well, and embracing the full causal version of Bohmian mechanics under a dispositional interpretation.

9. Conclusions

My main purpose in this essay has been to show that a dispositional interpretation of Bohmian mechanics is not only possible but, in light of the difficulties of alternative interpretations, seems desirable. The dispositional interpretation naturally dispenses with the problems and objections that other interpretations generate while creating no significant problems of its own. Of course, one may wonder whether the alternative interpretations were required in the first place. In fact one wonders whether any interpretation is really necessary. However, to the extent that the literature assumes that a realistic interpretation of Bohmian mechanics is desirable, this requires the provision of some ontology. If so, a dispositional ontology is not only relatively straightforwardly at hand. It serves in addition to furnish some understanding of claims by Bohm and his collaborators in favour of their 'causal' version - claims that would remain opaque otherwise.

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