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The Physics and Metaphysics of Primitive Stuff

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ABSTRACT

The article sets out a primitive ontology of the natural world in terms of primitive stuff—that is, stuff that has as such no physical properties at all—but that is not a bare substratum either, being individuated by metrical relations. We focus on quantum physics and employ identity-based Bohmian mechanics to illustrate this view, but point out that it applies all over physics. Properties then enter into the picture exclusively through the role that they play for the dynamics of the primitive stuff. We show that such properties can be local (classical mechanics), as well as holistic (quantum mechanics), and discuss two metaphysical options to conceive them, namely, Humeanism and modal realism in the guise of dispositionalism.

1 Introduction

There are two main options pursued in current research on the ontology of quantum physics. One option is to take the formalism of the quantum theory that one adopts to refer to the quantum state, represented by the universal wave-function, that is, the wave-function of the whole universe. Consequently, the quantum state is the physical object of the formalism of quantum physics. This option has been pursued in this quantum theory going back to Everett ([1957]) (see also Albert [1996] and the papers in Saunders *et al.* [2010] and Albert and Ney [2013] for discussion). However, since the quantum state is defined on a very high-dimensional space—namely, the configuration space of

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the universe, this option implies that one is committed to that very high-dimensional space being the space in which the fundamental physical reality is situated.

If one shrinks back from that consequence and maintains that quantum physics is about matter existing in three-dimensional space or four-dimensional space-time, one is committed to what is known as a ‘primitive ontology’ as regards that matter. The role of the quantum state, represented by the universal wave-function, is then limited to dynamics: its role guiding or governing the temporal development of the distribution of matter in physical space (see Allori *et al.* [2008]). In brief, the motivation for this primitive ontology option is to uphold within quantum physics the commitment of physics to being about matter in ordinary space, although the quantum state is defined on a very high-dimensional space (see, for example, Monton [2006]; Maudlin [2010]; Belot [2012]).

It is obvious that a dualism consisting in a conjunction of these two options is not an attractive position: if one takes the quantum state as represented by the universal wave-function to be the physical object of quantum physics, then that state as it exists in the very high-dimensional space on which the universal wave-function is defined, is the physical reality. There then is no point in taking that state to also be the state of matter distributed in three-dimensional space. The task, rather, is to show how the dynamics of the quantum state existing in the configuration space of the universe can be such that this state develops in that space—for example, through decoherence—into something that can account for our experience of matter being distributed in a three-dimensional space.

By the same token, if one commits oneself to a primitive ontology of matter distributed in three-dimensional space being the referent of the formalism of quantum physics, then there is no point in adding to that commitment another commitment to the quantum state existing in the high-dimensional configuration space of the universe. The reason is, in brief, that it is not intelligible how the quantum state could fulfil the role that it has in the primitive ontology theories of quantum physics—namely, to guide the temporal development of the primitive ontology—if it were a physical object on a par with the primitive ontology, but existing in another space. It would, for instance, be unclear how a field existing in the very high-dimensional configuration space of the universe, represented by the universal wave-function, could guide the motion of matter in three-dimensional space. Since the quantum state enters the primitive ontology theories through the role that it plays in the temporal development of the primitive ontology, it is reasonable to regard it as nomological, by contrast to a physical entity on a par with the primitive ontology (cf. Dürr *et al.* [2013], Chapters 11.5 and 12). We will consider in Sections 4 and 5 two proposals to spell out what it means to say that the quantum state is nomological, namely, Humeanism and dispositionalism.

This article is concerned with the second option. We aim to push the idea of a primitive ontology of quantum physics to its ultimate consequence and to show that the primitive ontology option applies throughout physics. The ultimate conclusion will be that matter is primitive stuff, *materia prima*, having no physical properties at all. What are usually regarded as physical properties enter into the theory through their role in the dynamics of the primitive stuff, that is, through their nomological role. In other words, the way in which the primitive ontology theories of quantum physics are often presented—namely, in terms of introducing the elements of the primitive ontology as being characterized by classical properties such as mass and charge—is incoherent, as is the dualism of a primitive ontology existing in three-dimensional space and a quantum state existing in configuration space. The reason for this incoherence is that the dynamics of classical physics is fundamentally different: in classical physics, dynamical variables such as mass and charge are attributed to point particles taken individually. Given the laws of classical physics, the distribution of mass and charge in the universe fixes how the particles move.

In quantum physics, by contrast, it is generally not possible to attribute a wave-function to the particles taken individually, but in the last resort only to the whole configuration of matter in the universe at a given time. In the primitive ontology theories of quantum physics, the wave-function then has the job of fixing the temporal development of the configuration of matter (in a deterministic or probabilistic manner). It is incoherent to assume that the determination of the dynamics encoded in the wave-function is superimposed on a determination of the dynamics through the classical properties of the particles taken individually, that is, through their mass and their charge. In brief, either the dynamics is determined from above, so to speak, by variables that apply only to the primitive ontology as a whole, or the dynamics is determined from below by variables belonging to the elements of the primitive ontology taken individually. Since the latter option is excluded for quantum physics, it is reasonable to pursue the former. This means taking the primitive ontology to be primitive stuff, instead of particles that are equipped with intrinsic properties each, and conceiving the dynamics as being determined by variables belonging to the whole configuration of the primitive stuff.

In the next two sections, we first elaborate on the metaphysics and then on the physics of matter as primitive stuff, using the formalism of Bohmian mechanics for identical particles. In Section 4, we show how a recent proposal for a Humean conception of the dynamical variables can shed light on this view of matter. In Section 5, we apply this proposal to a more ambitious metaphysical stance, according to which the dynamical variables literally determine the temporal development of an initial configuration of primitive stuff.

2 Primitive Ontology: Primitive Stuff

The term 'primitive ontology' goes back to Dürr *et al*. They write:

> What we regard as the obvious choice of primitive ontology—the basic kinds of entities that are to be the building blocks of everything else (except, of course, the wave function)—should by now be clear: Particles, described by their positions in space, changing with time—some of which, owing to the dynamical laws governing their evolution, perhaps combine to form the familiar macroscopic objects of daily experience. (Dürr *et al*. [2013], p. 29; a forerunner of this notion can be found in Mundy [1989], p. 46)

This term has been created in the context of quantum mechanics in order to remind us of the fact that the formalism of quantum mechanics is supposed to represent something—namely, matter in space—and is supposed to describe its behaviour, for instance, in measurement situations. The first sense in which the ontology of matter distributed in physical space is primitive is that this ontology cannot be inferred from the formalism of textbook quantum mechanics, but has to be put in as the referent of that formalism. According to the proposal pursued in this article, that ontology is furthermore primitive in the sense that it consists in primitive stuff, that is, stuff that has no physical properties as such. Dürr *et al*. allude to this meaning of 'primitive' in the quotation above when they say that the particles are described only by their position in space. That is to say, a particle being located at a point of space merely signifies that the point in question is occupied instead of being empty. But as far as the primitive ontology is concerned, there are no physical properties—such as a mass or a charge—instantiated by the particle.

The de Broglie-Bohm theory, going back to de Broglie ([2009]) and Bohm ([1952]). It is known today as Bohmian mechanics (see Dürr *et al*. [2013]) and is the oldest primitive ontology theory of quantum mechanics. Bohmian mechanics puts forward a discrete primitive ontology of point particles whereby, as mentioned above, a particle being located at a point of three-dimensional space means that the point in question is occupied by primitive stuff instead of being empty. What accounts for the primitive stuff occupying points being particles is that, according to Bohmian mechanics, there are continuous lines of occupation of points in space-time, so that there are worldlines constituting particle trajectories. The role of the wave-function, developing according to the Schrödinger equation, is to determine the velocity of each particle at any time t given the position of all the particles at t via what is known as the guiding equation. We will go into the physics of Bohmian mechanics in the next section. For present purposes, it is only important to note that velocity is not a property that the particles have over and above being located in space, but simply the first temporal derivative of position.

The view according to which all physical properties, including mass and charge, are best understood at the level of the wave-function rather than at the level of the Bohmian particles has been suggested in the literature, on the basis of experimental considerations involving interference phenomena, for instance, in the context of the Aharonov-Bohm effect and of certain interferometry experiments (see, for example, Brown *et al.* [1995] and references therein; Pylkkänen *et al.* [forthcoming]). Brown *et al.* ([1996]) explicitly discuss this view—which they call the 'parsimonious view'—but only within the framework of a dualistic ontology that recognizes both the Bohminan particles and the wave-function as genuine ontological entities on their own right. However, as we have argued above in Section 1, there is no point in doing so. In particular, it remains entirely mysterious how the wave-function understood as a physical object on configuration space could guide the Bohmian particles. Indeed, Brown *et al.* ([1996], Section 4) acknowledge this fact when they concede that their 'parsimonious view' faces what they call the 'problem of recognition': explaining how the wave-function of a given particle 'knows' which particle to guide when there are several particle species in a region of overlap of the respective wave-functions, assuming a factorizable total wave-function for simplicity.

Furthermore, there are two primitive ontology theories of quantum mechanics using the dynamics proposed by Ghirardi, Weber, and Weber (GRW) ([1986]), which seek to include the textbooks' postulate concerning the collapse of the wave-function upon measurement into a modified Schrödinger equation. Bell ([1987], Chapter 22) suggests that whenever there is a spontaneous localization of the wave-function in configuration space, this development of the wave-function in configuration space represents an event occurring at a point in physical space. These point-events are today known as 'flashes'; that term was introduced by Tumulka ([2006], p. 826). According to the GRW flash theory (GRWf), the flashes are all there is in space-time. As far as the primitive ontology is concerned, the GRWf theory is the Bohmian particle ontology without the trajectories: instead of particle trajectories—that is, continuous lines of occupation of points in space-time—there are only isolated points being occupied by primitive stuff.

Bohmian mechanics and the GRWf theory both propose a primitive ontology of primitive stuff that is 'discrete': particles or flash-events at space-time points. By contrast, Ghirardi *et al.* ([1995]) develop an ontology of a 'continuous' matter density distribution in physical space (GRWm). The wave-function in configuration space and its temporal development as described by the GRW equation represent at any time the density of matter in physical space, and the spontaneous localization of the wave-function in configuration space (its 'collapse') represents a spontaneous contraction of the matter density in physical space, thus accounting for measurement outcomes and well localized macrophysical objects in general (see also Monton [2004]). Again, matter is primitive stuff, as pointed out by Allori *et al.* ([2014]):

> Moreover, the matter that we postulate in GRWm and whose density is given by the *m* function does not *ipso facto* have any such properties as mass or charge; it can only assume various levels of density. (Allori *et al.* [2014], pp. 331–2)

Thus matter is gunk, filling all of space. This, however, implies that the primitive stuff admits of degrees, as expressed by the *m* function in the GRWm formalism: there is more stuff at some points of space than at others, with the density of matter at the points of space changing in time; otherwise, the theory would not be able to accommodate variation. But it remains unclear what could constitute the difference in degrees of stuff at 'points' of space, if matter is just primitive stuff. Hence, the GRWm theory is committed to the view of matter being a bare substratum and it being a primitive fact that this substratum has various degrees of density at points of space or space-time. In other words, there is a primitive-stuff essence of matter that admits different degrees of density. On Bohmian mechanics and the GRW flash ontology, by contrast, the only variation consists in some points of space being occupied while others are empty, with there being a change in time in which points of space are occupied. This ontology can then easily account for the concentration of matter in certain regions of space by maintaining that in some regions of space, more points are occupied than in other regions of space.

Nonetheless, Bohmian mechanics and the GRWf face the following question: What is it that occupies points of space? In other words, what accounts for the difference between a point of space being occupied and its being empty? There are no intrinsic properties such as mass or charge available that could make up for that difference. Bohmian particles or GRW flashes do not have an intrinsic essence constituted by intrinsic properties. Even if there are no intrinsic properties, one could still maintain that Bohmian particles or GRW flashes have a primitive 'thisness' (haecceity). However, haecceitism is a very controversial metaphysical stance. In any case, it is a purely metaphysical view that is always available if one is willing to pay the price, physics be as it may. That is to say, there is no motivation for haecceitism from physics (especially given the explicit and generalized permutation invariance that we will explain below in Section 3). It seems then that in the case of a primitive ontology of discrete objects (particles, flashes), we also have to fall back into admitting a primitive-stuff essence of matter that accounts for the difference between a point of space being empty and its being occupied. The only difference between a primitive ontology of discrete objects and a primitive ontology of gunk would then be that in the latter case that primitive-stuff essence also has to include different degrees of density at points of space. In a nutshell, it seems that the primitive ontology theories of quantum physics are committed to conceiving matter as a Lockean bare substratum.[1]

This consequence puts these theories in an uncomfortable position: the commitment to a bare substratum is a controversial metaphysical stance. One may motivate this stance by claiming that there has to be a primitive-stuff essence at the bedrock of matter. But one can also, and with reason, object that a primitive-stuff essence in the guise of a bare substratum is mysterious. In any case, again, the view that there is a primitive ontology of physics is well-motivated, since physics, including quantum physics, can with good reason be taken to be about matter in space-time; but there is no motivation from physics to conceive the primitive ontology in terms of a primitive-stuff essence of matter (cf. the objection that Ladyman and Ross ([2007], p. 136, footnote 15) raise against Bohmian particles). The upshot of these considerations is that if one admits an essence of matter, that essence can be constituted by properties—or relations, as we shall argue—but will never be primitive.

The impasse we face with the question of what accounts for the difference between a point of space being occupied and its being empty is a consequence of conceiving primitive ontology theories in terms of a commitment to absolute space into which matter is inserted. Only in the case of a dualism, whereby points of space and matter occupy these points, does that question arise. However, whereas working with an absolute background space is certainly an elegant manner in which to present these theories (at least as long as the issue of including gravity is left out), there is no reason why the primitive ontology theories should be committed to a dualism of matter and space. In other words, speaking in terms of points of space being occupied or empty is just a convenient manner of setting out the view of matter as primitive stuff, but should not be taken literally. If we conceive the primitive ontology in terms of discrete objects (particles, flashes), we can formulate its core claim in the following manner: Matter is primitive stuff. It is discrete, consisting in matter points. These are matter points because there is a non-vanishing three-dimensional distance between any two such points. In other words, they are matter points in virtue of being connected by metrical relations. Switching from absolutism to relationalism about space removes the commitment to a bare substratum or a primitive-stuff essence because it opens up the possibility of conceiving of the primitive stuff in terms of standing in metrical relations that are its essence.

[1] We are grateful to one of the referees for raising this objection.

A primitive ontology theory that treats matter as primitive stuff, while seeking to avoid a commitment to a primitive-stuff essence or bare substratum cannot but adopt the Cartesian characterization of matter in terms of spatial extension. In a nutshell, what distinguishes points of a primitive matter stuff from points of a hypothetical primitive mental stuff is only that the former are connected by metrical relations. Nonetheless, there are no space-time points. There are substances that are not extended in themselves (points). These are material, because they are connected by spatial relations, and move, so that there is change in their spatial relations and thus a temporal development of the spatial configuration of these point-substances. If they were not connected by spatial relations but rather by hypothetical fundamental mental relations, they would not be primitive matter stuff (matter points) and not be physical entities, but primitive mental stuff.

Hence, what makes a point a matter point is nothing intrinsic to that point—no intrinsic properties, no primitive thisness, no bare substratum or primitive-stuff essence—but the fact that it stands in spatial relations. The view of matter as primitive stuff thereby joins the stance known as (moderate) ontic structural realism in claiming that the identity of the fundamental physical objects—matter points in this case—is provided by certain relations, namely, metrical relations (see Esfeld and Lam [2008]). Nonetheless, these relations are strong enough to allow the matter points to fulfil Leibniz's principle of the identity of indiscernibles in that they can be absolutely discernible[2]: it is possible that each matter point is distinct from all the other ones by some of the distance relations that it bears to other matter points. If they are absolutely discernible, the matter points are individuals by the standards commonly used in the philosophy of physics. As the development of ontic structural realism has made clear, neither individuality nor absolute distinguishability need be grounded in intrinsic features (Ladyman [2007] nicely illustrates this point). In a nutshell, the famous slogan 'no entity without identity', coined by Quine ([1969], p. 23), applies to the matter points, although they are primitive stuff: they do not have an intrinsic identity, but a relational one provided by spatial distances that can be so strong that they make them absolutely discernible entities. Furthermore, if they are particles, their trajectories endow them with a diachronic relational identity: each particle is absolutely discernible from the other ones not only by its position at any given time, but also by its history.

To sum up, the matter points are primitive stuff in the following two senses: (i) they are fundamental—that is, they are not composed of anything else, but their configurations compose everything else; (ii) they are primitive

[2] Recall that two entities are absolutely discernible if and only if there is a physically meaningful monadic predicate or, more generally, a physically meaningful formula with one free variable that applies to one but not to the other.

objects—that is, they do not have an intrinsic essence constituted by intrinsic properties. However, they are not primitive in the sense of possessing a primitive-stuff essence: they are not bare substrata. If they have an essence, the relations in which they stand and that individuate them—namely, the metrical relations—are their essence.

As regards the metaphysical literature on objects, the primitive ontology of primitive stuff motivated by quantum physics falls into neither of the two main stances: it obviously does not conceive objects as bundles of properties since there are no such properties available in quantum physics, neither does it conceive objects as bare substrata. By contrast, it joins the stance of moderate ontic structural realism in the philosophy of science by being committed to objects, but maintaining that these objects are individuated by certain relations in which they stand, namely, metrical relations. Coming back to the metaphysical literature, the view that comes closest to this one is the proposal by Heil ([2003], [2012]) according to which there are substances but these substances are not bare particulars: they always exist in certain ways (modes) of being that individuate them. However, whereas Heil conceives these ways of being as intrinsic features of these substances and refuses to admit any relations on the ontological ground floor (see Heil [2012], Chapter 7), in the primitive ontology of quantum physics, there are no such intrinsic features available, as mentioned above. Thus, we have to go structural, conceiving the relations in which these substances stand as their basic way of being (the metrical relations). Nonetheless, we thereby join the old Cartesian tradition of conceiving matter as *res extensa* only.

3 The Physics of Matter as Primitive Stuff

Let us turn to Bohmian mechanics in order to illustrate the physics of matter as primitive stuff, since Bohmian mechanics is the best-known example of a primitive ontology formulation of non-relativistic quantum mechanics and the only primitive ontology theory for which there is a version worked out in terms of permutation invariance available. Although if spelled out in a consequent manner, the primitive ontology of matter as primitive stuff should go with relationalism about space, for the sake of this illustration we will use the formulation in terms of an absolute background space with some occupied points, whereby these points make up the configuration of matter in the universe. Our primary aim in this section is to show what the physics of primitive stuff, in contrast to the physics of material objects with intrinsic essences, looks like. Casting such a physics in spatio-temporal relationist terms at the same time would by far go beyond a single paper. The main challenge here is to investigate whether Bohmian mechanics admits a universal wave-function that has all the right symmetries to depend only on the metrical relations between the particles.

Bohmian mechanics, as commonly presented (see the papers in (Dürr *et al.* [2013]) and the textbook (Dürr and Teufel [2009])), is a theory about point particles moving in three-dimensional space, whereby the quantum wave-function figures in a non-local law of motion for the configuration of particles. Usually, the theory is introduced by formulating the laws of motion on the configuration space $\mathbb{R}^{3N}$, where N is the number of particles and $Q(t) = (Q_1(t), \ldots, Q_N(t)) \in \mathbb{R}^{3N}$ represents their positions at time t.

The configuration then evolves according to the guiding equation

$$\frac{\mathrm{d}Q_k}{\mathrm{d}t} = \frac{\hbar}{m_k}\frac{\psi^*\nabla\psi}{\psi^*\psi}(Q_1, \ldots, Q_N), \tag{1}$$

where $\psi(q_1, \ldots, q_n)$ is the wave-function representing the quantum state of the system. The time-evolution of this wave-function, in turn, is given by the Schrödinger equation,

$$\imath\hbar\frac{\partial\psi}{\partial t} = \left(-\sum_{j=1}^{N}\frac{\hbar^2}{2m_j}\Delta_j + V(q_1, \ldots, q_n)\right)\psi, \tag{2}$$

familiar from standard quantum mechanics. The non-local character of the law is manifested in the fact that the velocity of any particle at time t depends on the position of every other particle at time t; the law of motion, in other words, describes the evolution of the particle configuration as a whole. This is necessary in order to take quantum non-locality—as illustrated for instance by Bell's theorem (Bell [1987], Chapter 2)—into account.

The parameters m_k appearing in Equations (1) and (2) correspond to the mass of the k-th particle. Furthermore, we observe that for (static) electromagnetic interactions, the charges, e_k, of the particles enter the Schrödinger equation via the Coulomb potential:

$$V(q_1, \ldots, q_n) = \sum_{i<j}\frac{e_i e_j}{\|q_i - q_j\|}, \tag{3}$$

We will address the status of these parameters later in this section.[3]

It is important to note that, at a fundamental level, there is only one wave-function in Bohmian mechanics: the universal wave-function, Ψ, guiding the motion of all the particles in the universe together. Nonetheless, in many relevant cases, it is possible to provide a description of a (suitably isolated) sub-system as an autonomous Bohmian system in terms of an effective wave-function ψ, which is derived from Ψ and the actual spatial configuration of the

[3] If the full electromagnetic interactions are taken into account, the gradient in Equation (1) is replaced by a covariant derivative, into which the vector potential and the particle charges enter.

environment—that is, the rest of the universe that is 'ignored' in the description of the sub-system. These effective wave-functions can be seen as the Bohmian analogue of the usual quantum wave-functions familiar from textbook quantum mechanics.

An easy mistake to make in connection with Bohmian mechanics is to confuse the theory's commitment to particle positions with a realism regarding any of the physical quantities commonly associated with quantum mechanical observables. In fact, the opposite is correct. Bohmian mechanics is a theory about the motion of particles, conceived as the basic constituents of matter, and hence a theory about the distribution of matter in space and time. A statistical analysis of this theory, for situations corresponding to quantum measurements, then reproduces the outcome statistics of textbook quantum mechanics in terms of the effective wave-function (the quantum state) ψ of the measured microscopic sub-system. The respective measurement outcomes, however, do not reflect any properties that the particles possess over and above their spatial configuration—rather, they are shown to arise from their disposition for motion, which is encoded in ψ, upon interaction with a macroscopic measurement apparatus.

A paradigmatic example is the Bohmian treatment of spin. In the token measurement of spin, let's say in the z-direction, a particle is sent through an inhomogeneous magnetic field (a Stern-Gerlach magnet) and then detected on a screen to see if it was deflected upwards or downwards, corresponding to the measurement outcome 'spin up' or 'spin down', respectively. How does Bohmian mechanics account for this experiment?

Consider a particle whose (effective) quantum state is described by a spinor-valued wave-function of the form

$$\psi(q) = \begin{pmatrix} \varphi_1(q) \\ \varphi_2(q) \end{pmatrix} = \left(\varphi_1(q) \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \varphi_2(q) \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right). \tag{4}$$

The Schrödinger time-evolution for ψ in an inhomogeneous magnetic field is such that the part of the wave-function corresponding to the upper spin-component is propagating in the positive z-direction, whereas the part of the wave-function corresponding to the lower spin-component is propagating in the negative z-direction.[4] Consequently, the two spin-components of the initial wave-function (4) become spatially separated. The trajectory of the particle, determined by Equation (1) will then follow one of the two wave-packets, depending on its initial position, and thus hit the screen above or below the zero-line, corresponding to a measurement of 'z-spin up' or 'z-spin down', respectively (for a detailed account of spin in Bohmian mechanics see

[4] More precisely, ψ is governed by the Pauli equation, which is the non-relativistic wave-equation describing particles with spin.

(Dürr and Teufel [2009], Chapter 8.4; Norsen [2014])). Hence, we see in particular that the measured spin-value does not correspond to any property that the particle possesses over and above its position. For a Bohmian particle to have 'spin up' or 'spin down' means nothing more and nothing less than to be guided by the part of the wave-function that corresponds to the upper or lower spinor-component—that is, to 'move', in the pertinent measurement-context, in the respective way.

A different issue is the status of the dynamical parameters 'mass' and 'charge', which occur in Schrödinger's Equation (2) and—in the case of mass—in the Bohmian guiding Equation (1). The crucial observation here is that the way in which the parameters m_k and e_k figure in Equation (2), and thus the evolution of the wave-function on configuration space, is insensitive to the actual configuration of the particles in physical space. For this reason, it is inappropriate, in general, to think of mass and charge as intrinsic properties of the Bohmian particles 'carried along' as they move in space.

This point is illustrated very clearly in the following experiment: Consider a charged particle whose (effective) wave-function is of the form $\psi = \phi_A + \phi_B$, where ϕ_A and ϕ_B are of equal size and shape, but concentrated on two distant regions of space that we denote by A and B, respectively. (Those regions could be surrounded by infinite high potential walls—or, more simply put, a box—to keep the wave-function from spreading.) The particle will be located in one of those regions, let's say in A. Not surprisingly, the trajectory of a second charged particle passing near A will be affected by the electromagnetic interactions and deflected towards A if it has opposite charge, or away from A if it has equal charge as the first particle. However, if that second particle were passing near region B, it would be affected in the very same way, no matter how far away it was from the actual position of the other particle. This scenario demonstrates, first, the explicitly non-local character of Bohmian mechanics. It also shows that it would be wrong to think of charge in the familiar way, as something localized at the position of the particles. A similar reasoning applies to the particle mass, in so far as gravitational interactions play a role in quantum mechanics.

A common reply to this issue is that mass and charge should be regarded not as properties of the particle, but as properties of the wave-function. The intuition (presumably) is that the absolute value of ψ—or rather $|\psi|^2$—can represent (something akin to) a charge distribution. But this view is untenable for a variety of reasons. To begin with, we have already seen that the view of (effective) wave-functions as physical entities over and above the particles is unwarranted. If the wave-function associated with a particle is not a physical entity, it cannot carry physical properties. Moreover, as soon as we consider an entangled wave-function of two or more particles, it will correspond to a (non-factorizing) function on a high-dimensional configuration space and cannot be taken to represent a distribution of physical quantities in three-dimensional space.

So what attitude shall we adopt vis-à-vis mass and charge in Bohmian mechanics? First and foremost, one should take the theory seriously in its own right and acknowledge that all the (classical) intuitions that we associate with mass and charge are *a priori* questionable. In the first instance, $m_1, \dots, m_N$ and $e_1, \dots, e_N$ are merely numerical parameters that appear in the formulation of the Bohmian laws of motion. To illustrate this point, let us assume for the moment that there exists but a single species of particles, that is, that $m_k = m_l = m$ and $e_k = e_l = e$ for all $k, l \in \{1, \dots, N\}$. Hence, we see from Equations (1) and (2) that we are left with the same three constants—$\hbar$, m, and e—appearing in the equation of motion for any of the N particles. There plainly no reason to treat m and e differently from Planck's constant $\hbar$. In particular, there is no justification for attaching m or e to the particles or for interpreting them as localized physical quantities, any more than we would do for $\hbar$. Rather, we would regard m and e as nothing more than two additional constants of nature, numerical parameters entering the equations of motion without referring to anything in the physical ontology.

However, the commitment to a single type of particle—that is, a single elementary mass and charge—is clearly unsustainable from a physical point of view. Modern particle physics introduces an entire zoo of elementary particles varying in mass or charge, or both: electrons, positrons, muons, anti-muons, the nucleons their constituent quarks, and so on. Hence, there must be something in the world that makes it the case that certain terms (certain coordinates, respectively) in the equations of motion refer to, say, an electron rather than a muon.

Goldstein *et al.* ([2005a], [2005b]) demonstrated the possibility of accounting for the different species of elementary particles in modern particle physics by reformulating Bohmian mechanics in a way that reflects the ontological commitment to property-less particles as primitive stuff, treating all particles as identical. To appreciate what this means and how the reformulation is carried out, let us begin with the following observation: If we insist that particles are distinguished only by their position (that is, spatial relations instead of intrinsic properties) we note that the configuration space $\mathbb{R}^{3N}$ has too much mathematical structure in that it 'cares' about permutations of the particle labels. That is to say, the nature of the Bohmian law of motion (being a first-order differential equation on configuration space) is such that it determines at every time t the change of the system's spatial configuration depending on the current configuration, $Q(t)$. However, unless one presupposes a primitive identity or haecceity of the particles, the instantaneous configuration of an N-particle system is completely characterized by a set of N points in physical space that are designated as being occupied by matter. There are no intrinsic properties, nor internal or external relations, distinguishing the configuration represented by the tuple $(Q_1, Q_2, \ldots, Q_N)$ from, let's say, the configuration represented by the tuple $(Q_2, Q_1, \ldots, Q_N)$ with the first and second particles interchanged. It is thus understood that—for so-called 'identical' or 'indistinguishable' particles—the natural configuration space of an N-particle system is not $\mathbb{R}^{3N}$, but

$$^{N}\mathbb{R}^3 := \left\{S \subseteq \mathbb{R}^3 \middle| \sharp S = N\right\}, \tag{5}$$

which is the set of all subsets of $\mathbb{R}^3$ containing exactly N elements. Note that this space lacks the mathematical structure to represent permutations of the particle labels in contrast to $\mathbb{R}^{3N}$: a point $Q(t) = \{Q_1, Q_2, \ldots, Q_N\} \in {}^{N}\mathbb{R}^3$—in contrast to the ordered N-tupel $(Q_1, Q_2, \ldots, Q_N)$—describes the fact that at time t there is a particle occupying space-point Q_1, a particle occupying space-point Q_2, and so on; it does not state that the first particle occupies Q_1, the second particle occupies Q_2, and so on.

Consequently, the wave-function of the system should now be defined on the configuration space ${}^{N}\mathbb{R}^3$ as well, which in fact can be done (Goldstein *et al.* [2005a], Section 4). Nevertheless, it is still more convenient, in general, to represent the quantum state as a function on $\mathbb{R}^{3N}$ (which can be regarded, mathematically, as the universal covering space of ${}^{N}\mathbb{R}^3$). As long as we consider a system in which all particles are associated with the same mass and charge, the demand of consistency then leads immediately to a wave-function that is symmetric or anti-symmetric under permutations of the particle coordinates and hence to the famous 'boson/fermion alternative'. In (Dürr *et al.* [2013]), ${}^{N}\mathbb{R}^3$ was thus already introduced as the configuration space of identical or indistinguishable particles, referring to a single species of particles, and it is shown how the quantum statistics of identical particles thus arise in the Bohmian theory (see also Dürr and Teufel [2009], Chapter 8.5).

However, we now note that as soon as we have to admit more than one value for the parameters m_k, the standard formulation of Bohmian mechanics breaks down. That is because Equation (1) no longer defines a law of motion on ${}^{N}\mathbb{R}^3$, since it discriminates different particles by their associated mass, while configurations represented on ${}^{N}\mathbb{R}^3$ do not do so. The basic idea of Goldstein *et al.* ([2005a], [2005b]) is thus to symmetrize Equation (1) in order to get a permutation invariant equation, because any permutation invariant equation on $\mathbb{R}^{3N}$ defines, in a canonical way, a law of motion on ${}^{N}\mathbb{R}^3$, the configuration space of identical particles. In this way, they show that we can treat all particles as identical, while still accounting for the empirical data that, as usual, are explained in terms of a particle 'zoo'.

To preserve equivariance of the law—the conservation of total probability by the Bohmian flow—the symmetrization has to be done in the following way. The standard guiding Equation (1) can be written in the form

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{j(Q(t))}{\rho(Q(t))}, \tag{6}$$

where

$$\rho = \psi^* \psi$$

is the probability density, and $j = (j_1, \ldots, j_N)$ with

$$\boldsymbol{j}_i = \frac{\hbar}{m_i} \mathrm{Im}\psi^* \nabla_i \psi$$

the probability current corresponding to the system's wave-function ψ. In Equation (6), numerator and denominator have to be symmetrized independently by summing over all possible permutations of the particle labels $1, \ldots, N$. Hence, we get a new, permutation-invariant guiding equation, which reads

$$\frac{\mathrm{d}Q_k}{\mathrm{d}t} = \frac{\sum_{\sigma \in S_N} \boldsymbol{j}_{\sigma(k)} \circ \sigma}{\sum_{\sigma \in S_N} \rho \circ \sigma}(Q(t)). \tag{7}$$

Here, the sum goes over all elements of the permutation group S_N, and

$$\sigma Q := \left(Q_{\sigma^{-1}(1)}, \ldots, Q_{\sigma^{-1}(N)}\right)$$

means that every coordinate Q_i is assigned a new index $Q_{\sigma^{-1}(i)}$, changing the order in the N-tupel.

In this theory, which Goldstein *et al.* ([2005a], [2005b]) dubbed 'identity-based' Bohmian mechanics, we do not attribute *a priori* any mass to any specific particle. The law of motion merely determines N trajectories for N particles, and it is a characteristic of this law that one of those trajectories happens to behave—at least in the relevant circumstances—like the trajectory of a particle with mass m_1, another like the trajectory of a particle with mass m_2, and so on, depending only on the (contingent) initial conditions of the system (respectively, the universe).

To illustrate how this works, let us discuss an example given in (Goldstein *et al.* [2005a], Section 3) that compares the standard formulation of Bohmian mechanics with the identity-based version. Consider a two-particle universe consisting of an electron with mass m_e and a muon with mass m_μ. Suppose, for simplicity, that they are in a non-entangled state $\Psi(q_1, q_2) = \phi(q_1)\chi(q_2)$ (note that we could symmetrize this wave-function, though this would be redundant when plugged into the symmetrized guiding-equation). Then, the standard guiding law in Equation (1) leads to the following equations of motion:

$$\frac{dQ_1}{dt} = \frac{\hbar}{m_e} \mathrm{Im} \frac{\nabla\phi(Q_1)}{\phi(Q_1)}, \qquad \frac{dQ_2}{dt} = \frac{\hbar}{m_\mu} \mathrm{Im} \frac{\nabla\chi(Q_2)}{\chi(Q_2)} \tag{8}$$

In contrast, the symmetrized guiding Equation (7) reads

$$\frac{dQ_1}{dt} = \frac{\frac{\hbar}{m_e}|\chi(Q_2)|^2 \mathrm{Im}(\phi^*(Q_1)\nabla\phi(Q_1)) + \frac{\hbar}{m_\mu}|\phi(Q_2)|^2 \mathrm{Im}(\chi^*(Q_1)\nabla\chi(Q_1))}{|\phi(Q_1)|^2|\chi(Q_2)|^2 + |\phi(Q_2)|^2|\chi(Q_1)|^2}$$
$$\frac{dQ_2}{dt} = \frac{\frac{\hbar}{m_\mu}|\phi(Q_1)|^2 \mathrm{Im}(\chi^*(Q_2)\nabla\chi(Q_2)) + \frac{\hbar}{m_e}|\chi(Q_1)|^2 \mathrm{Im}(\phi^*(Q_2)\nabla\phi(Q_2))}{|\phi(Q_1)|^2|\chi(Q_2)|^2 + |\phi(Q_2)|^2|\chi(Q_1)|^2} \tag{9}$$

We see that Equation (8) ascribes—or presupposes—an intrinsic mass and thus a distinct type to every particle: particle 1, described by the coordinates Q_1, is the electron with mass m_e; while particle 2, described by the coordinates Q_2, is the muon with mass m_μ. In Equation (9), by contrast, neither Q_1 nor Q_2 is designated as the position of the electron (the muon, respectively). *A priori*, the two particles are distinguished only by the position that they occupy at time t. However, if we consider a situation in which ϕ and χ have disjoint support—say, when one wave-packet is propagating to the left and the other one to the right—one of the two sums in the nominators and denominators will be zero, so that the equation of motion effectively reduces to Equation (8) (possibly with the indices 1 and 2 interchanged). That is to say, in particular, in situations where the two-particle wave-function is suitably decohered, one of the particles will play the role of the electron—being effectively described by Equations (1) and (2) with the parameter m_e—while the other one will play the role of the muon—being effectively described by Equations (1) and (2) with parameter m_μ.

Which trajectory turns out to be guided by which part of the wave-function thereby depends only on the law of motion and the (contingent) initial conditions of the system, rather than on intrinsic properties of the particles. In fact, if both parts of the wave-function were brought back together and then separated again, one and the same particle could switch its role from being the electron to being the muon, and vice versa. Hence, like a particle's spin, we must conclude that to be an electron, a muon, or a positron, and so on is nothing more and nothing less than to move—in the relevant circumstances—electronwise, muonwise, or positronwise, and so forth. There are no properties in this theory defining different species of particles, but only primitive stuff, following a law of motion that accounts for the phenomena conventionally attributed to a multiplicity of particle-types.

Apart from such circumstances in which the different parts of the wave-function are well separated, one could say that the particles in the previous example are guided by a superposition of (what one would usually call) an electron wave-function and a muon wave-function. However, it would be misleading to claim that this amounts to a superposition of being an electron and being a muon. Ontologically, there are no superpositions of anything, only property-less particles moving on definite trajectories. Rather, the labels 'electron', 'muon', and so on are meaningless in the general case.

One obvious objection to the move proposed by Goldstein *et al.* is that the guiding law in Equation (7) is much more contrived than the one in standard Bohmian mechanics. To some extent, this is a correct observation and we are indeed trading a sparse ontology for a more complicated mathematical formalism by endorsing the symmetrized theory. That notwithstanding, a few things can be said to address this worry. First, one should note that the apparent complexity of Equation (7) is really just the price for expressing a law of motion for configurations in ${}^{N}\mathbb{R}^3$ on the coordinate space $\mathbb{R}^{3N}$, and doesn't necessarily amount to more complicated physics. Second, it should be noted that (modulo some subtleties discussed by Goldstein *et al.* ([2005a], [2005b])) the symmetrized theory will give rise to the familiar statistical description of sub-systems in terms of effective wave-functions, which is really all that matters for most practical purposes.

In this context, it should also be noted that, given the universal wave-function, the right statistical description of sub-systems—that is, the one agreeing with the predictions of standard quantum mechanics, arises for typical initial conditions in terms of the particle configuration, that is, in quantum equilibrium (see Dürr *et al.* [2013], Chapter 2). Hence, the emergence of different particle types as empirically observed in nature is not attributed to special initial conditions (quite the opposite), though it is ascribed to the particular form of the universal wave-function—that is, to the physical law—if the latter is understood as nomological (we will expand on the nomological view of the wave-function in the upcoming sections).

Finally, concerning the (empirical) content of the proposed theory, it should be emphasized that the trajectories described by identity-based Bohmian mechanics will, in general, differ from those obtained from standard Bohmian mechanics, but that the statistical predictions for experimental outcomes are the same. In this sense, the symmetrized theory is empirically equivalent to Bohmian mechanics, and hence empirically equivalent to standard quantum mechanics. This shows once more that the physical ontology can neither be empirically determined, nor read off from the measurement-formalism of standard quantum mechanics. On the other hand, the choice of a primitive ontology can supplement or enlighten the structure and formulation of the theory.

In particular, if the physical ontology is one of property-less particles, this strongly suggests permutation invariant laws of motion in which all particles are treated as 'identical'—to borrow once more the terminology commonly employed in physics. Of course, this terminology is misleading in the sense that there is obviously a plurality of particles instead of just one particle. The meaning of identity-based Bohmian mechanics—and more particularly the meaning of permutation invariance within this framework—is rather that we are committed to an ontology of primitive stuff in the sense of particles that do not possess any intrinsic properties nor any intrinsic identity. Permutation invariance thus means precisely that there is nothing to the particles beyond their position in the total configuration, in particular nothing that the laws of motion could refer to in order to establish a different dynamical role for different particles depending on some intrinsic characteristics.

To sum up, identity-based Bohmian mechanics provides for a clear ontological meaning of permutation invariance: it encodes a primitive-stuff ontology of individuals without any intrinsic identity and properties, though (absolutely) discernible in virtue of their position in the total configuration. Furthermore, permutation invariance applies here to all the particles, since there is only primitive stuff and no different species of particles, by contrast to concerning only the particles of the same species as in standard Bohmian mechanics or the wave-function supposedly corresponding to particles of the same species as in textbook quantum mechanics.

4 The Humean Best System Analysis of the Dynamical Variables

Staying within the framework of a primitive ontology of particles as in Bohmian mechanics, how are we to conceive dynamical variables such as mass or charge that are attributed to the particles taken individually without making up for intrinsic essences that constitute different species of particles? Moreover, as mentioned in Section 1, in the primitive ontology approach, it is reasonable to conceive of the quantum state as a nomological entity, in contrast with a physical entity on a par with the primitive ontology. But what does this mean? In this section and the next, we will show that the main philosophical views about laws of nature can be employed in order to answer these questions. We will focus on Humeanism on the one hand and dispositionalism on the other.

Let us start with Humeanism. According to this view, the world is a vast mosaic of local matters of particular fact, such as point particles being connected only by relations of spatio-temporal distance. Given an initial configuration of such point particles, there is nothing about that configuration that puts a constraint on its temporal development. A certain temporal development just happens to occur; there is nothing that guides, governs, or determines it. Nevertheless, considering that temporal development as a whole—that is, the distribution of the point particles throughout the whole of space-time—this distribution exhibits certain patterns or regularities. Consequently, if one sets out to put forward a description of the distribution of the point particles in space-time, one can do better than composing a very long list that registers each particle position. According to what is known as the Humean best system account, the laws of nature are the axioms of the system that achieves the best balance between being simple and being informative in describing the distribution of matter throughout the whole of space and time. In brief, laws of nature both simplify and are informative, striking the best balance between these two virtues (in particular, see Lewis [1973], Chapter 3.3, pp. 72–5, and [1994], Section 3; Cohen and Callender [2009]; there is no space here and it is not the aim of this article to consider the internal problems of Humeanism).

Hall ([unpublished], Section 5.2), in particular, has put forward a version of Humeanism that regards the vast mosaic of local matters of particular fact as consisting only in point particles standing in relations of spatio-temporal distance. These particles are just primitive stuff. Their distribution throughout space-time—that is, the development of the metrical relations among the particles—exhibits certain regularities. Suppose that the laws of classical mechanics and electrodynamics figure in the Humean best system that captures these regularities. Then dynamical variables such as mass and charge appear in these laws. On the basis of these laws being part of the Humean best system, one can then attribute properties like mass and charge to the particles. That is to say, predicates such as 'mass' and 'charge' apply to the particles. However, these predicates do not represent properties that the particles have *per se*, as something essential or intrinsic to them. They apply to the particles in virtue of the contingent fact that their motion throughout the whole of space-time happens to manifest certain regularities. Hence, what makes the application of these predicates true is nothing over and above the distribution of primitive stuff throughout space and time. Nonetheless, this is not instrumentalism. Humeanism, applied to the primitive ontology approach in physics, is the view that the primitive ontology is the entire ontology. However, the primitive ontology is an ontology that stands on its own feet: it consists in theoretical entities such as point particles that exist in the world independently of observers and their beliefs.

This idea can also be applied to the wave-function in any of the primitive ontology theories of quantum physics, notably Bohmian mechanics (see Miller [2014]; Esfeld [2014]; Callender [forthcoming]; Dickson [2000]). It can thus be employed to spell out what it means that the wave-function is nomological, in contrast to being a physical entity on a par with the primitive ontology. Again, the Humean mosaic consists in the distribution of primitive stuff throughout the whole of space-time—such as particle trajectories, flash-events, or a matter density field. This distribution exhibits certain regularities. Suppose that the laws of quantum mechanics figure in the Humean best system that captures these regularities, and let these laws be the Bohmian guiding equation and the Schrödinger equation, or a GRW-type equation and a law establishing a link with the primitive ontology. Then a universal wave-function describing the quantum state of the primitive stuff appears in these laws, and the quantum state includes parameters such as mass and charge. However, as these latter parameters do not require an ontological commitment to anything more than the distribution of primitive stuff throughout the whole of space-time in classical mechanics, so the quantum state is no addition to being: given the whole distribution of the primitive stuff throughout space-time, a law describing the temporal development of a universal wave-function enters into the Humean best system as a means to achieve a description of the distribution of the primitive stuff that strikes the best balance between being simple and being informative about how the stuff is distributed. This law simplifies and is informative in any case, since in a deterministic theory such as Bohmian mechanics, specifying the particle configuration and the wave-function at any given time is sufficient to capture the particle configuration at any other time. Given the law in which the wave-function figures, one can then attribute a quantum state as represented by the universal wave-function to the particle configuration, in the sense that the propositions doing so are true; but their truth-maker is the distribution of the primitive stuff throughout the whole of space-time, and not a quantum state that exists over and above the particle configuration.

Finally, coming back to the link between the primitive ontology approach to physics and relationalism about space-time, one can apply the Humean view of the primitive ontology as the entire ontology to space-time itself. Suppose that there is an initial configuration of matter points that are primitive stuff and that are connected by metrical relations. The matter points move so that there is change in their spatial relations and thus a temporal development of the initial configuration of matter points. On Humeanism, there is nothing that puts a constraint on how that change has to occur. Some such change just happens. If one combines Humeanism with relationalism about space and time, there is furthermore nothing about that initial configuration that singles out a particular motion as inertial motion and a particular system of matter points as an inertial system. However, as Huggett ([2006]) has shown, given the whole motion of the matter points, there are some patterns or regularities in this motion that make it possible to conceive a Humean best system achieving a good balance between being simple and being informative in describing that motion. Based on this best system, one can then single out a certain motion as inertial and certain systems of matter points as inertial systems. One can thus account for absolute quantities such as acceleration in an ontology of a Humean space-time relationalism applied to the laws of Newtonian mechanics.

It is evident that this strategy can be put to work for any space-time, not only a Newtonian one, as Humeanism is applicable to any primitive ontology theory of matter. One has to assume an initial configuration of extended stuff—such as matter points being connected by metrical relations—and that this configuration develops in a certain matter. Considering that development as a whole, it exhibits certain patterns or regularities. Based on these patterns or regularities, there is a Humean best system including the laws of both matter and space-time. Given that system, dynamical variables can be attributed to the matter points, some systems of which can be singled out as inertial systems, and so on. On Humeanism, whatever properties are attributed to matter or space-time come in one package, figuring in the Humean best system and being defined by their role in that system, instead of being properties that belong to matter or space-time.

5 Modal Realism about the Dynamical Variables

Although Humeanism is a coherent philosophical way to conceive matter as primitive stuff, showing how all the dynamical variables that are commonly attributed to material objects can be derived from the Humean best system, the physics of matter as primitive stuff is not committed to the metaphysics of Humeanism. In other words, if the universal wave-function is nomological rather than a physical object on a par with the primitive ontology, its nomological character does not have to be spelled out in the framework of Humeanism about laws of nature. Indeed, there are many well-known philosophical worries about Humeanism in general. In particular, Humeanism cannot but regard it as a brute fact that the regularities on which we rely in science, as well as in everyday life, always turn out to be well-confirmed. There is no constraint at all on which local matters of particular fact can and which cannot occur in the future of any given local matter of particular fact, since what the laws of nature are depends on what there will be in the future of any given local matter of particular fact, instead of that future depending on the laws of nature. Hence, the laws of nature cannot be invoked to answer the question of why certain regularities—such as, for example, those experienced as gravitation, or those exhibited in the EPR-experiment—always turn out to be well-confirmed. There simply is no answer to this question in Humeanism. Again, there is nothing incoherent about this position, but the desire to obtain an answer to this question motivates the search for a more ambitious metaphysical framework, namely, one that admits modal connections in nature that put a constraint on can and what cannot happen in the universe, given an arbitrary initial configuration of matter.

The central anti-Humean answer to this question consists in anchoring the laws of nature in properties that are attributed to the physical systems (see, in particular, Bird [2007]). These properties are such that it is essential for them to exercise a certain dynamical role for the temporal development of the physical systems. The laws, in turn, express that dynamical role. These properties hence are 'dispositions' or 'powers'. Thus, on this view, mass and charge in classical mechanics are local properties of the particles whose function is to accelerate the particles as described by the laws of Newtonian mechanics and classical electromagnetism. By way of consequence, of a dispositionalism combined with a primitive ontology view of classical mechanics, the primitive-stuff particles do indeed obtain properties each over and above standing in metrical relations. But these properties are not essential to the particles, and their role is not to provide an intrinsic identity of the particles; their job is exclusively a dynamical one, namely, to put a constraint on how the particles move, given an initial configuration of particles whose identity is provided by the metrical relations in which they stand.

When it comes to quantum physics, it is no longer possible to conceive mass and charge as local dispositional properties or powers that belong to the particles taken individually, as various thought experiments such as the ones mentioned in Section 3 make clear (and see (Brown *et al.* [1995]) for more such experiments). Against this background, we have argued in Section 3 that what stands for mass and charge in the equation of motion are mere parameters without any direct ontological correlate. In brief, there are no mass and charge distributions influencing the motion of the particles. There only is the universal wave-function representing the quantum state. However, the quantum state is defined on configuration space. Hence, if one intends to attribute to the quantum state an ontological weight as a dynamical variable—by contrast to regarding it simply as a convenient means to capture the salient regularities in the motion that the particles happen to take—one faces the difficulty of having to avoid the incoherent dualism mentioned at the beginning of this article, namely, the dualism of being committed to particles existing in physical space and a quantum state existing in configuration space.

Dispositionalism avoids this pitfall in the following manner: As in classical physics, the particles taken individually instantiate dynamical, dispositional properties that determine their motion and that are represented by the mass and the charge variables in the laws of motion. So in quantum physics, the particle configuration as a whole instantiates a dynamical, dispositional property that determines its temporal development and that is represented by the universal wave-function figuring in the laws of (identity-based)

Bohmian mechanics or the GRW theory. In brief, according to dispositionalism, the universal wave-function represents the common disposition of motion of the particle configuration (Belot [2012], pp. 77–80; Esfeld *et al.* [2014], Sections 4 and 5). The motion of the particles is then such that, in certain specific circumstances, it is possible to consider them as if they were carrying some local properties such as mass and charge that influence their motion, even though, from an ontological point of view, there is no such thing. Behaving like a massive particle or a charged particle is only the result of the particular particle motion (rather than its determinant) and contingent on the universal wave-function and the initial conditions.

In the framework of dispositionalism, the shift from classical to quantum mechanics thus amounts to a shift from local dynamical properties determining the motion of the particles to determination by one holistic property of the particle configuration (the quantum state, represented by the universal wave-function). It is then more appropriate to characterize this property as a power rather than as a disposition: if there is one holistic property of the particle configuration determining its temporal development, there is no question of an external stimulus or triggering condition for its manifestation—a mass or a charge qua local property of a particle requires another massy or charged particle to manifest itself in the acceleration of the particles. In brief, on Bohmian dispositionalism, the primitive-stuff particles collectively instantiate one power (represented by the universal wave-function) that determines their motion by determining their velocity. Consequently, this collective power relates, strictly speaking, all the particles to one another, determining their motion in tandem, and thereby explaining quantum entanglement and the EPR correlations.

In general, if dispositions or powers instantiated by the particles taken individually can influence their motion, so can a collective power instantiated by the particle configuration. In both cases the particle positions, consisting in the metrical relations that individuate them, by no means fix the disposition or power that determines the motion and thus the temporal development of the particle positions (that is, their metrical relations). Such a disposition or power is in any case a modal property that has to be admitted in addition to the primitive ontology, but instantiated by the elements of the primitive ontology, as that what fixes what is possible and what is not possible about their motion. The metaphysical conception of dispositionalism applied to the primitive ontology of physics—that is, the commitment to properties as that which puts a constraint on the temporal development of the primitive stuff—is the same in both cases. A holistic property or collective power doing so is no less intelligible and no more mysterious than local properties or powers doing so; the latter just are more familiar to us given our familiarity with classical physics and our unfamiliarity with quantum physics. In other words, the shift from local properties to holistic or collective properties is imposed upon us by the transition from classical to quantum physics. Any philosophical theory of properties has to adapt itself to this shift. Dispositionalism does so by countenancing dynamical properties (dispositions, powers) that are instantiated by the particle configuration as a whole instead of by the particles taken individually.

One can further illustrate this conception by linking it to ontic structural realism. Since this collective power relates all the particles with one another, one can also conceive of it as a structure defined on the configuration of the particles. This again is an ontic structure since, according to dispositionalism, it exists in the world over and above the primitive stuff (the particle configuration), albeit instantiated by it. However, one has to be careful not to confuse this ontic structure with the relational or structural individuation of the primitive stuff explained at the end of Section 2: quantum entanglement conceived as an ontic structure in the framework of the physics of primitive stuff has nothing to do with the individuation or the discernibility of the physical entities; individuation and discernibility, both at a time and in time, is obtained through the metrical relations in which the matter points stand at any time. It is not touched by the issue of Humeanism versus modal realism (dispositionalism) as regards the laws of nature. The entanglement structure, by contrast, concerns only the dynamics of the matter points. If this structure exists over and above the matter points, then it is a modal structure, which puts a constraint on the temporal development of the matter points (that is, their motion). However, there is nothing modal about the metrical relations or structure insofar as they individuate the matter points, which accounts for them being matter points and absolutely discernible. By way of consequence, the modal realist, but not the Humean, is committed to the entanglement structure.

6 Conclusion

This article began with recalling the two principled options for an ontology of quantum physics: (i) quantum state realism, according to which the quantum state as defined by the universal wave-function on configuration space is the physical reality; and (ii) a primitive ontology theory, according to which the physical reality consists in matter existing in three-dimensional space or four-dimensional space-time. The aim of this article was to push the primitive ontology option to its *ultimate consequence*, which is to regard matter as primitive stuff, namely, as points that are matter points only in virtue of the metrical relations in which they stand; in particular, these matter points do not carry any intrinsic properties and do not possess any intrinsic identity. The metrical relations individuate them, making them (absolutely) discernible. These matter points are particles if they persist and if their motion traces out continuous lines in space (worldlines that can be conceived as particle trajectories). Consequently, there are no different particle species in the fundamental ontology and permuting the particles obviously does not lead to any new physical situation. There just are property-less particles qua matter points. We have shown how this view is naturally encoded in identity-based Bohmian mechanics.

We then elaborated on two principled options for introducing physical properties through the role that they play for the dynamics of the primitive stuff. According to Humeanism, there is nothing over and above the primitive stuff throughout space and time. Given an initial configuration of primitive stuff, a certain temporal development of that configuration happens to occur. But there is nothing in nature that puts a constraint on which temporal development can happen and which cannot. Given the distribution of primitive stuff throughout the whole of space–time, this distribution happens to exhibit certain patterns or regularities that make it possible to formulate a Humean best system. The variables figuring in the Humean best system can then be attributed to the primitive stuff, but they do not represent an ontological commitment to anything over and above spatio-temporally extended primitive stuff.

According to modal realism, by contrast, there is something in nature over and above the primitive stuff that puts a constraint on its temporal development, fixing what can and what cannot happen, given an initial configuration of primitive stuff. Dispositionalism spells this idea out in terms of dispositions or powers that the primitive stuff instantiates over and above being individuated by the metrical relations in which the matter points stand. These dispositions or powers enter the ontology only through the role that they play in determining a certain temporal development of the primitive stuff. They thereby ground the laws of nature. In classical physics, these are dispositions or powers that are instantiated by the matter points (the particles) taken individually; in quantum physics, there is in the fundamental ontology only one collective power instantiated by the configuration of the matter points (the particles) as a whole, tying their temporal development together.

To sum up, the primitive ontology option applies to both classical and quantum physics. If one endorses a primitive ontology of particles, the primitive ontology is the same in classical and quantum physics: particles as primitive stuff, individuated by the metrical relations in which they stand. The difference between classical and quantum physics concerns only the dynamics—the dynamical properties (dispositionalism) or predicates (Humeanism) attributed to the particles in order to account for the change in their metrical relations (that is, their motion): local properties in classical physics and a collective property in quantum physics.

Against the background of what has been achieved in this article, we regard it as the foremost task for metaphysics to put the arguments for and against Humeanism and modal realism (dispositionalism) in the framework of a primitive ontology of primitive stuff shared by both these metaphysical stances. With regards to the physics, we take it to be the foremost task to elaborate on the link between the primitive ontology of primitive stuff and relationalism about space-time, thereby also extending this ontology beyond classical and quantum mechanics.

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