Bohmian trajectories and the ether: Where does the analogy fail?

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Abstract

Once considered essential to the explanation of electromagnetic phenomena, the ether was eventually discarded after the advent of special relativity. The lack of empirical signature of realist interpretative schemes of quantum mechanics, like Bohmian trajectories, has led some to conclude that, just like the ether, they can be dispensed with, replaced by the corresponding emergence of the concept of information. Although devices like Bohmian trajectories and the ether do present important analogies, I argue that there is also a crucial difference, related to distinct explanatory functions of quantum mechanics.

KEY WORDS: Bohmian trajectories, ether, information, quantum mechanics, interpretation.

1 Introduction

Quantum information theory has been one of the most active areas of development of quantum mechanics in the past two decades. The realization that transfer protocols based on quantum entanglement may be absolutely secure has opened new windows in the field of cryptography (Bennett & Brassard, 1984). And the development of quantum algorithms thought to be exponentially faster than their best classical counterparts has drawn great interest in the construction of quantum computers (Shor, 1994). These face up extraordinary challenges on the experimental side (Vandersypen et al., 2001). But attempts to build them are likely to throw much light on the fundamental
process of decoherence (Zurek, 1991) and perhaps on the limits of quantum mechanics itself ('t Hooft, 1999; Leggett, 2002).

Along with quantum information theory came also a reemphasis of the view that the wave function (or state vector, or density matrix) properly represents knowledge, or information (Rovelli, 1996; Fuchs & Peres, 2000; Fuchs, 2002). This is often called the epistemic view of quantum states. On what the wave function is knowledge of, proponents of the epistemic view do not necessarily agree. The variant most relevant to the present discussion is that rather than referring to objective properties of microscopic objects (such as electrons, photons, etc.), the wave function encapsulates probabilities of results of eventual macroscopic measurements. The Hilbert space formalism is taken as complete, and its objects in no need of a realistic interpretation. Additional constructs, like value assignments (van Fraassen, 1991; Vermaas, 1999), multiple worlds (Everett, 1957; DeWitt, 1970; Wallace, 2003), or Bohmian trajectories (Bohm, 1952; Bohm & Hiley, 1993; Holland, 1993) are viewed as superfluous at best.

The methodological rule calling to discard additional constructs to the Hilbert space has been likened to the one that led to abandon the concept of the ether in the early part of the twentieth century\(^1\) (Bub, 2004, 2005; Bohr, Mottelson, & Ulfbeck, 2004). H. A. Lorentz and his contemporaries viewed electromagnetic phenomena as taking place in a hypothetical medium called the ether. From this, Lorentz developed a description of electromagnetism in moving reference frames, and he found that the motion is undetectable (Lorentz, 1909). Following Einstein’s formulation of the electrodynamics of moving bodies (Einstein, 1905), the ether was recognized as playing no role, and was henceforth discarded. So should it be, according to most proponents of the epistemic view of quantum states, with interpretations of quantum mechanics which posit observer-independent elements of reality. They predict no empirical differences with the Hilbert space formalism, and therefore should be discarded.

The purpose of this paper is to analyse, in their respective contexts, the explanatory roles of the ether and additional constructs to the Hilbert space formalism. To be specific, and because earlier discussions have largely focussed on them, I shall formulate my argument in terms of Bohmian tra-

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\(^1\)Of course the chronology of added constructs is reversed in the two episodes. Ether theories predated special relativity, whereas Bohmian trajectories came after the Hilbert space formalism. Cushing (1998) has argued that history could plausibly have been reversed in the latter episode.
jectories, without however implying any fundamental commitment to that choice. I will first recall that Bohmian trajectories coexist rather well with the notion of a preferred reference frame, which the ether traditionally defines. I will next point out what was involved in the transition between ether theories and special relativity. The function of Bohmian trajectories will then be investigated, in connection with two distinct explanatory roles of quantum mechanics. This will evince a crucial difference between Bohmian trajectories and the ether, and illustrate why interpretative schemes cannot be dispensed with in quantum mechanics.

2 Quantum mechanics and special relativity

The ether has long been viewed as defining a preferred inertial frame of reference. In this sense, it can find room in the conceptual structure of quantum mechanics, at least in some of the ways the formalism is presented.

Take, for instance, the theory’s highly influential articulation proposed by von Neumann (1932). There the wave function of a quantum system evolves in two very different ways. Outside the context of measurements, it obeys the Schrödinger equation or, equivalently, it evolves through the action of a unitary operator (von Neumann’s process 2). At the end of a measurement, however, it stochastically transforms into one of the eigenfunctions of the observable being measured (process 1, or collapse). That evolution is not unitary, and does not obey the Schrödinger equation.

It is not difficult (for one particle at least) to make process 2 consistent with the special theory of relativity. One just has to replace the Schrödinger equation by the Dirac equation. Process 1, however, is much more tricky. The wave function of a quantum system usually covers the whole of three-dimensional space, that is, its support is unbounded. Since the collapse is taken to occur instantaneously (or very nearly so), the wave function, as a consequence of measurement, changes values everywhere at the same time. It is very difficult to make this process relativistically covariant. Indeed wave function collapse seems to single out a preferred inertial reference frame.

Due to the statistical character of the predictions of quantum mechanics,

\footnote{See Tumulka (2004) and Brown and Wallace (2005) for two different recent assessments of Bohmian mechanics.}

\footnote{Von Neumann really writes that the pure state density matrix transforms into a mixture, but for a given quantum system, only one component of the mixture obtains.}
wave function collapse does not, as is well known, allow the transfer of information faster than the speed of light. In this sense, at least, it is consistent with special relativity. It would thus seem that the frame being singled out cannot be determined experimentally.

Similar considerations can be made in the context of Bohmian mechanics. Consider a set of \( N \) particles of masses \( m_a \) and charges \( e_a \), in an electromagnetic field specified by the four-potential \( A^\mu \). The Dirac wave function \( \Psi \) then has \( 4^N \) components, which if needed can be specified by \( N \)-tuples of four-valued indices. Let \( \gamma_{a\mu} \) represent Dirac matrices acting on the \( a \)th index, and let \( \alpha_{ak} = \gamma_{a0}\gamma_{ak} \). The Dirac equation can then be written as

\[
-\frac{i}{c} \frac{\partial \Psi}{\partial t} + \sum_a \left\{ \frac{e_a}{\hbar} A^0(\mathbf{r}_a, t) \Psi - i\alpha_{ak} \frac{\partial \Psi}{\partial x_{ak}} + \frac{e_a}{\hbar} \alpha_{ak} A^k(\mathbf{r}_a, t) \Psi + \frac{m_a c}{\hbar} \gamma_{a0} \Psi \right\} = 0. \tag{1}
\]

Eq. (1) entails that

\[
\frac{\partial j_0}{\partial t} + c \sum_a \frac{\partial j_{ak}}{\partial x_{ak}} = 0, \tag{2}
\]

where

\[
j_0 = \Psi^\dagger \Psi, \quad j_{ak} = \Psi^\dagger \alpha_{ak} \Psi. \tag{3}
\]

Bohmian trajectories can be introduced by specifying that the three-velocity of particle \( a \) at the space-time point \( (\mathbf{r}_a, t) \) is given by

\[
v_a^i = c \frac{j_a^i}{j_0^0}^{-1}. \tag{4}
\]

It can be shown (Bohm & Hiley, 1993; Holland, 1993) that the magnitude of the velocity never exceeds \( c \), and that if particles are distributed according to the probability density \( \Psi^\dagger \Psi \) at a given time, they will be distributed according to \( \Psi^\dagger \Psi \) at any other time.

The \( N \)-particle Dirac equation being relativistically covariant (Bohm & Hiley, 1993), it can be used indifferently in any inertial reference frame. Probabilities obtained in one frame transform correctly into probabilities obtained in any other frame. Since, however, the quantities \((j_0^0, j_a^i)\) do not make up a four-vector (for \( N > 1 \)), the Bohmian trajectories are not covariant. That is, trajectories computed in frame \( \Sigma \) through Eqs. (1), when transformed into \( \Sigma' \) by means of the Lorentz transformations, will not match trajectories
computed in $\Sigma'$ directly through $[4]$. Hence Eqs. $[4]$ can hold in only one inertial reference frame (modulo rotations and space-time translations).

The upshot is that Bohmian trajectories, like von Neumann’s collapse, naturally coexist with the ether construed as defining a preferred, albeit unobservable, reference frame.\textsuperscript{4} There remains to see whether the justification of the former, in quantum mechanics, is of the same nature as that of the latter, in electromagnetic theories.

### 3 Ether and field

The concept of ether has a long history (Whittaker, 1951; Darrigol, 2000), and it was used in a number of different contexts. In one of these, mainly developed in the nineteenth century, the ether was viewed as a substratum wherein electric and magnetic phenomena take place. Much effort was spent on detailed mechanical models of the substratum. It is not the purpose of this paper to recapitulate them, but it may be worthwhile to recall one proposed by Maxwell, as he described it in an 1861 letter to W. Thomson (quoted in Whittaker, 1951, p. 250).

I suppose that the “magnetic medium” is divided into small portions or cells, the divisions or cell walls being composed of a single stratum of spherical particles, these particles being “electricity.” The substance of the cells I suppose to be highly elastic, both with respect to compression and distorsion; and I suppose the connection between the cells and the particles in the cell walls to be such that there is perfect rolling without slipping between them and that they act on each other tangentially.

I then find that if the cells are set in rotation, the medium exerts a stress equivalent to a hydrostatic pressure combined with a longitudinal tension along the lines of axes of rotation.

Maxwell goes on drawing detailed analogies between his cells and cell walls and “a system of magnets, electric currents and bodies capable of magnetic induction.” It should be pointed out, however, that such models played a less important role in Maxwell’s great treatise (1873), which relied more on a Lagrangian formulation. Model building was progressively abandoned in the

\textsuperscript{4}Maudlin (1994) gives a detailed argument why the introduction of a preferred frame may be the more rational choice to make in a quantum-mechanical theory.
most fruitful late nineteenth century contributions to electromagnetic theory, those of Lorentz in particular.

Lorentz’s largely definitive views on electromagnetic theory were expounded in his 1906 Columbia University lectures, published a few years later. His ontology is threefold: there is ponderable matter, there are electric charges ("electrons"), and there is the ether, "the receptacle of electromagnetic energy and the vehicle for many and perhaps for all the forces acting on ponderable matter" (Lorentz, 1909, p. 30). The ether is supposed to be at rest, and this determines an absolute inertial reference frame.

As there was no reason to expect that the earth is at rest with respect to the ether, the question arose as to how to describe electromagnetic phenomena in a moving frame. The calculation would go roughly as follows. Maxwell’s equations, assumed to hold in the frame where the ether is at rest, would be used to compute the electric and magnetic fields of moving electrons and matter. These fields would act back on charges and matter, and (partly at least) determine their configuration. It could be shown, in particular, that if all forces in moving matter shared the characteristics of electric and magnetic forces, the so-called Lorentz-FitzGerald contraction would naturally follow.

In this context, Lorentz and others were able to prove a rather remarkable result. Suppose we introduce spatial coordinates \( r' \) at rest in the moving frame, and define a “local time” \( t' \) as \( t' = t - (r' \cdot w)/c^2 \), where \( w \) is the velocity of the moving frame. Furthermore, introduce new electric and magnetic fields related to the old ones by what is now called a Lorentz transformation. Then the numerical values of the new fields coincide with values of the (old) fields that would be obtained from electrons and matter having a similar configuration in the frame where the ether is at rest. Moreover, the new fields and space-time coordinates satisfy Maxwell’s equations.

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5Lorentz does not commit himself on whether all matter is made of electric charges, nor on whether all mass has an electromagnetic origin.

6Everyone realized that if the earth is at rest in the ether now, it should not be in a few months, due to its orbital velocity around the sun. Unless perhaps the ether is dragged along the motion, but this causes numerous other problems.

7Brown (2001) points out that a simple contraction is not the only deformation that can account for the null result of the Michelson-Morley experiment, a fact which Lorentz, and probably FitzGerald, fully realized.

8The argument was first made with terms of first order in \( w/c \), and then more generally.
The above result was interpreted, by Lorentz and most generally by Poincaré, as showing that motion with respect to the ether is undetectable (Poincaré, 1905; Paty, 1993). Yet Lorentz and Poincaré never abandoned the ether, and Lorentz maintained that the local time is just a definition, the true time always referring to the rest frame of the ether.\(^9\) It was Einstein’s fundamental contribution to view the local time as the time genuinely measured in the moving frame, with no more and no less reality than the time measured in any other inertial frame. Suddenly the ether was seen as playing no useful role, and was eventually discarded.

Many now believe that Lorentz’s conception of (unobservable) true time and absolute rest, and Einstein’s notion of complete equivalence between inertial frames, are both logically consistent and in agreement with empirical results (Grübaum, 1973; Bell, 1976). Yet in less than a decade, most people adopted Einstein’s views (Pais, 1982). The great simplicity of Einstein’s purely kinematical approach and the fact that it allowed complete freedom in the choice of the inertial frame where calculations would be made no doubt contributed to that decision.

It is important to realize, however, that the rejection of the ether has not left a void in its stead. From Maxwell’s quotation to Lorentz’s final views, we have seen that the ether was progressively deprived of much of its complicated mechanical attributes. There only remained something to define a preferred frame and transmit the electric and magnetic forces. But as the ether was discarded, the electromagnetic field acquired by itself an independent reality. For Einstein, this way of seeing the field was one of the most important consequences of the conceptual development leading to special relativity (Einstein, 1949; Paty, 1993).

Even before the full development of quantum mechanics and quantum field theory, the electromagnetic field was generally considered as being real, as anything carrying energy and momentum is. The ether was discarded in its role as defining absolute time and absolute motion. The methodological choice, however, was not one between the ether and nothing, but one between the ether as sustaining the field and a self-sustaining field.

\(^9\)Poincaré (1898) saw the conventional character of the simultaneity of distant events. Later he recognized that clocks synchronized by means of light signals mark the local time, which however he contrasted with the true time (Pais, 1982, Chap. 6).
4 Bohmian trajectories and information

Bohmian trajectories and the ether are elements of two different theoretical structures. They present both analogies and differences. The analogy that is relevant here is that neither Bohmian trajectories in quantum mechanics nor the ether in special relativity lead to specific empirical consequences. Does that mean that the trajectories, or other interpretative devices, have in quantum mechanics the same status as the ether in special relativity? And if one can dispense with such devices, is there something which, like the field, plays the role they would otherwise have?

To examine these questions, it is appropriate to start with the following observation. Although all measurements are made by means of macroscopic apparatus, quantum mechanics is used, as an explanatory theory, in two different ways: it is meant to explain (i) nonclassical correlations between macroscopic objects and [ultimately through quantum field theory] (ii) the small-scale structure of macroscopic objects. That these two functions are distinct is shown by considering a hypothetical situation where only one of them is operating.\footnote{More about the world described in the following paragraphs can be found in Marchildon (2004), where it was introduced in terms of slightly different experimental instruments.}

Consider a world which, as far as macroscopic objects are concerned, is very similar to our own. By this I mean that the laws of classical mechanics, classical electrodynamics, and thermodynamics apply to these objects with at least as much generality as in our world. They may even apply better, in the sense that their scope may reach scales smaller than the $10^{-9}$ to $10^{-10}$ m characteristic of molecules and atoms in our world. I shall not, however, specify the microscopic structure of the hypothetical world, except for one restriction soon to be made.

In the hypothetical world, the macroscopic objects sometimes behave in ways that cannot be explained by the classical theories. In one class of situations, for instance, there are devices (much like our Geiger counters) that click when specific objects (like our radioactive materials) are brought nearby. We label the former $D$ and the latter $E$. Although the clicks are random, their probability distributions follow well-defined and reproducible laws. We assume that these laws coincide with the quantum-mechanical rules for the propagation of wave packets. If, for instance, there is some material between $E$ and $D$, the number and distribution of clicks are influenced just
like the quantum-mechanical theory of scattering predicts.

To account for these correlations, one can envisage at least two very different explanatory schemes. In the first one, we postulate that $E$ emits “particles” that are detected by $D$ after possibly interacting with intervening objects. In the second one, we postulate that $D$ clicks in a way that is genuinely fortuitous (Ulfbeck & Bohr, 2001; Bohr, Mottelson, & Ulfbeck, 2004), the spatiotemporal probability distribution of the clicks, however, being dependent on the distribution of various types of nearby macroscopic objects.

Now I make the assumption (and this is the crucial way in which the hypothetical world differs from our own) that the “particles” used in one explanatory scheme to account for the macroscopic correlations have no function whatsoever in any attempt to explain the microscopic structure of macroscopic objects. That is, whether matter is discrete or continuous at microscopic scales, its small-scale constituents have nothing to do with whatever is responsible for the clicks described above.

How similar would the ether and the particles be, as explanatory devices, in this hypothetical world? Very much indeed. Neither would have predictive power not already contained in the alternative explanations provided by the principle of relativity, in one case, and probabilistic correlations, in the other. And both could be dispensed with in a rational and completely articulated account of nature. Those who would keep the ether might do so because of some prejudice in favour of absolute simultaneity or motion. Those who would keep the particles might be influenced by the greater or smaller number and types of them necessary to explain the phenomena, or might find such contact interactions more palatable.

Let us now leave the hypothetical world and turn to the actual world, the one we live in. Here quantum mechanics is also used to explain the ultimate structure of macroscopic objects. Moreover, it does so with the same mathematical tools as the ones it uses to account for the correlations described above. That is, the state spaces and parameters associated with the “particles” are also the ones (or at least part of the ones) associated with the building blocks of macroscopic objects.

In this context, what is the function of Bohmian trajectories (or, for that matter, of other interpretative schemes of quantum mechanics)? They provide us with one clear way that the particles can behave so as to reproduce the quantum-mechanical rules and, therefore, the observable behaviour of
macroscopic objects.\textsuperscript{11} Although they could be dispensed with in the hypothetical world, they cannot in the real world unless, just like the ether was replaced by the field, they are replaced by something that can account for the structure of macroscopic objects.

It has been argued that the emergence of the notion of an autonomous field, connected with the development of special relativity, has a parallel in the emergence of the concept of information in the context of quantum mechanics. The motivation for this is an important result recently obtained by Clifton, Bub, and Halvorson (2003; Halvorson, 2004). Working in the setting of $C^*$-algebras, these investigators characterized the quantum theory by three properties: (i) kinematic independence, i.e. the commutativity of the algebras of observables pertaining to distinct physical systems; (ii) the noncommutativity of an individual system's algebra of observables; and (iii) nonlocality, i.e. the existence of entangled states for spacelike-separated systems. They then showed that these properties are equivalent to three information-theoretic constraints, namely, the impossibility of superluminal information transfer, of perfect broadcasting, and of unconditionally secure bit commitment.

Drawing on this result, Bub (2005) has proposed that quantum theory should be treated as “a theory about the representation and manipulation of information” (p. 557), where quantum information is “a new physical primitive not reducible to the behaviour of mechanical systems (the motion of particles and/or fields)” (p. 546). This, he argues, renders Bohmian trajectories no more useful in quantum mechanics than the ether is in special relativity (Bub, 2004, p. 262):

\textit{[J]ust as Einstein’s analysis (based on the assumption that we live in a world in which natural processes are subject to certain constraints specified by the principles of special relativity) shows that we do not need the mechanical structures in Lorentz’s theory (the aether, and the behaviour of electrons in the aether) to explain electromagnetic phenomena, so the [Clifton, Bub, and Halvorson] analysis (based on the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information) shows that we do not need the mechanical structures in Bohm’s theory (the guiding field, the behaviour of particles in the guiding field) to explain quantum phenomena.}\footnote{Indeed from a Bohmian perspective, the trajectories are just the kind of variables that show up in a measurement, in sharp contrast with the ether in electromagnetic theories.}

\textsuperscript{11}
To assess the validity of this claim, one should point out that there is a fundamental ontological difference between field and information. The electromagnetic field, in the framework of special relativity, is an autonomous entity that carries energy and momentum. Since Maxwell’s equations have solutions corresponding to vanishing charge and current densities, the field can exist, in principle, even in the complete absence of matter. This is not the case with information, not in the sense of Shannon at least. To exist, it needs some kind of material (or other) support. Whether in classical or quantum mechanics, information is a functional on states of objects. It does not live autonomously.

This means that information-theoretic considerations are relevant to the first explanatory function of quantum mechanics, the one that pertains to nonclassical correlations of macroscopic objects. But is information, as “a new physical primitive,” of any help in the second explanatory function, i.e. in accounting for the structure of macroscopic objects? It seems that no proponent of the epistemic view would go so far as suggesting that information is a fundamental building block of nature, something objects are made of. This is very much unlike the electromagnetic field, which at the turn of the twentieth century was thought to account for part or even for all the mass of charged particles (McCormmach, 1970). Hence the question about the relevance of information to the second explanatory function should be answered in the negative.\textsuperscript{12}

5 Discussion

Several objections can be made to the claims that Bohmian trajectories and the ether fulfill distinct explanatory functions, and that information is not a fundamental entity. They must now be addressed.

I have argued that quantum mechanics is used to explain both (i) the

\textsuperscript{12}Timpson (2004) has provided an in-depth analysis of the Clifton, Bub, and Halvorson result. He first investigated the extent to which the no bit-commitment constraint is needed in characterizing quantum mechanics in the framework of $C^*$-algebras. He then examined the relevance and generality of that formalism. Closer to the aim of the present paper, he next enquired whether viewing quantum mechanics as a theory about the manipulation of information can constitute an interpretation in an interesting sense. Based on a distinction between the technical and everyday senses of information, and on the observation that “in both settings ‘information’ functions as an abstract noun, hence does not refer to a particular or substance,” his answer is largely negative.
nonclassical correlations between macroscopic objects and (ii) the small-scale structure of macroscopic objects. But are these two functions really different? Suppose, for instance, that we use the quantum theory to explain properties of a macroscopic crystal, such as its elasticity or heat capacity. We should then make hypotheses on, among other things, the atomic structure of the lattice and the quantum-mechanical Hamiltonian. But none of these hypotheses can be tested directly. They are tested indirectly through their consequences on macroscopic parameters such as elasticity constants or heat capacity. And the values of these parameters are measured through correlations established between experimental preparations and results displayed by macroscopic pointers.

This is also the case with molecular properties. Suppose that chemical analysis has revealed that a given substance is chemically pure, so that we ascribe its constitution to one type of molecule only. Properties of the substance, such as its visible or infrared absorption, can then be explained by applying the quantum theory to the electrons and nuclei making up the molecule. But again, none of this can be tested directly. Absorption frequencies, in the end, show up as readings on some macroscopic device, and the whole experimental protocol reduces to correlations between macroscopic preparations and macroscopic measurements.

I should readily admit that the empirical consequences of both types of explanation provided by quantum mechanics are of the same nature. But the explanations themselves are very different epistemologically, as was illustrated in the last section by the example of the hypothetical world. The explanation given of the structure of macroscopic objects, in terms of atomic or subatomic constituents obeying the laws of quantum mechanics, essentially answers the question, What happens when objects are repeatedly split? That question seems unavoidable in a complete understanding of macroscopic objects.

In advocating the rejection of hidden variable theories, Bub (2005, p. 557) argues that

our measuring instruments ultimately remain black boxes at some level. That is, a quantum description will have to introduce a “cut” between what we take to be the ultimate measuring instrument in a given measurement process and the quantum phenomenon revealed by the instrument, which means that the measuring instrument is treated simply as a probabilistic source of a range of labelled events or “outcomes”[1]
As the phrase “at some level” indicates, our measuring instruments are not total black boxes. Indeed we can go a long way explaining the properties of their parts on the basis of atomic structure. Should one argue that the atomic structure is not to be taken literally, he should be prepared to specify at what scale ought the analysis of matter stop, or the reality of objects dissolve.\footnote{This, by the way, is related to the reason why the epistemic view, \textit{even on its own terms}, won’t solve the measurement problem. The epistemic view is concerned with probabilities of results of eventual macroscopic measurements. But it is not prepared to precisely specify what a macroscopic apparatus is. It won’t tell us, for instance, just how small an apparatus can be. To the credit of its proponents, none (as far as I know) has proposed a purely arbitrary criterion like “an apparatus must have a mass greater than 1 g.” But are there really any others?}

This brings us to a somewhat different objection to the claims being made here. What if the structure of matter did not require explanation, or at least could be accounted for by a very different type of explanation than the one we are used to? It is well known that in the history of science, criteria for what requires explanation, or what counts as a valid explanation, have often changed (Klein, 1972; Gardner, 1979; Cushing, 1990). Gravitation through action at a distance, considered impossible within the seventeenth-century mechanistic worldview, became less and less problematic in the eighteenth century (McMullin, 1989). Indeed the Laplacian school tried to account for all terrestrial phenomena on the basis of central forces which, though either attractive or repulsive, were modeled on gravitation. By then such forces were considered mechanical (Fox, 1974). In the late nineteenth century, mechanical explanations were challenged both by energetics (Ostwald, 1895) and by the electromagnetic view of matter (McCormmach, 1970).

Yet it seems that in all these instances, answers were given to the question, What are objects made of? They could be made of point particles acting on each other (partly at least) without intermediaries. Or else they could be made of energy, or of electromagnetic fields. But again, information is not on a par with such potential constituents. Objects are not made of information.

Few people would go as far as advocating that the small-scale structure of macroscopic objects simply does not require explanation. Yet something close to this might be entailed by the idea of \textit{genuine fortuitousness}. The idea “implies that the basic event, a click in a counter, comes without any cause and thus as a discontinuity in spacetime” (Bohr, Mottelson, & Ulfbeck, 2004, p. 405). Indeed
it is a hallmark of the theory based on genuine fortuitousness that it does not admit physical variables. It is, therefore, of a novel kind that does not deal with things (objects in space), or measurements, and may be referred to as the theory of no things. (p. 410)

Genuine fortuitousness, it turns out, could pretty well fulfill the first explanatory function of quantum mechanics, the one concerned with non-classical correlations of macroscopic objects. Indeed it would be quite unobjectionable, as an explanation of these correlations, in the hypothetical world I have described in Sec. 4. But it fails to fulfill the second explanatory function of quantum mechanics. When its proponents claim to eliminate atoms or elementary particles, they seem always to have in mind their alleged role in producing a click or an ionisation track, rather than their role in accounting for the structure of matter. In fact they cannot help contemplating the structure of macroscopic counters, when for instance they point out that “the click involves such an immense number of degrees of freedom that two clicks are never identical” (Ulfbeck and Bohr, 2001, p. 761). One can immediately ask, How many degrees of freedom are there? What objects do they characterize? Are these objects irreducible? And so on.

To sum up, neither the ether nor Bohmian trajectories have specific empirical consequences. Yet in addition to defining a reference frame where simultaneity would be absolute, the ether functioned as a kind of support for electromagnetic phenomena. That role was transferred to the field when the ether was discarded with the advent of special relativity. Bohmian trajectories, or other interpretative schemes of quantum mechanics, try to make the basic variables of the theory, in terms of which the structure of macroscopic objects is ultimately explained, intelligible. This role, I have argued, cannot be dispensed with.

Acknowledgments

It is a pleasure to thank Pierre Gravel, Karl Hess, and Pierre Mathieu for comments and suggestions. I am also grateful to several anonymous referees whose comments contributed in sharpening the ideas presented in this paper.
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