The Direction of Time in Bohmian Mechanics

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Abstract

In this paper, we investigate the treatment of the direction of time in Bohmian mechanics. We show how Bohmian mechanics can account for the direction of time in different ways. In particular, we argue that Bohmian mechanics can be employed to accommodate reductionism, because there always is an asymmetry in the initial conditions when forward and backward evolutions of the configuration of matter are compared. It can also be employed to accommodate primitivism and relationalism due to the fact that Bohmian mechanics is a first order theory that recognizes only position as a primitive physical magnitude. We show how this fact can be employed to support a primitive direction of time by assuming Leibnizian relationalism, which reduces the direction of time to change in the configuration of matter with that change being directed as a primitive matter of fact.

Keywords: Direction of Time, Bohmian Mechanics, Reductionism, Primitivism, Relationalism

1. Introduction

The problem of the direction of time in physics and philosophy has many facets. Some have taken it as evidence of a clash between a temporally symmetric microphysics and a temporally asymmetric macrophysics (Reichenbach 1956, Price 1996, Callender 1997). Others have rather formulated the problem in terms of whether or not the space-time structure comes equipped with a temporal orientation (Earman 1974, Castagnino and Lombardi 2009). From a metaphysical perspective, the problem could more generally be seen as whether the direction of time is a primitive element in our ontology or not. In this line, there are then two possible views – *primitivism* and *reductionism*. Primitivists believe that the directionality of time is a necessary posit in one's ontology in virtue of its explanatory advantages. It is therefore an irreducible, fundamental feature of the natural world that explains many temporally asymmetric phenomena. Reductionists rather believe that the seeming directionality of time requires an explanation in terms of some non-temporal physical asymmetry to which it can be reduced. In this way, the direction of time is the explanandum, while the non-temporal physical asymmetry is the explanans. Reductionism can be seen as either conservative or eliminativist. According to the former, the direction of time is non-fundamental, but real; according to the latter, the direction of time is unreal. The metaphysical map of the different philosophical attitudes towards the direction of time then looks as follows: primitivism holds that the direction of time is real and fundamental; conservative reductionism maintains that it is real, though reducible to a non-temporal physical basis; eliminativist reductionism claims that it is unreal *tout court*.

In this paper, we investigate the problem of the direction of time in its metaphysical formulation in Bohmian mechanics (Dürr, Goldstein and Zanghì 2013; Dürr and Teufel 2009). We show that the theory can accommodate both conservative reductionism and primitivism on the direction of time. Bohmian mechanics can accommodate *conservative reductionism* because it straightforwardly shows how temporal asymmetries (as the counterfactual asymmetry between forward and backward evolutions of the configurations of matter) ultimately reduce to an epistemic asymmetry in our knowledge of the initial particle positions. Bohmian mechanics can also accommodate *primitivism* about the direction of time if Leibnizian relationalism is adopted.[1] According to it, the direction of time is the direction of change of the particle configuration. Change in a Bohmian relational ontology, we argue, is to be taken as primitively directed in order to distinguish between variation within the particle configuration and change of the particle configuration. In conclusion, Bohmian mechanics does not settle the problem of the direction of time, but as it can accommodates alternative metaphysical views on the direction of time, it can also be employed to give them physical support.

2. Bohmian Mechanics and the Problem of the Direction of Time

In its standard formulation, quantum mechanics is just a recipe for predictions (Maudlin 2019). In order for it to be a full-fledged scientific theory, one that yields substantive knowledge about what the world is like, it needs to be properly interpreted and to overcome the famous measurement problem (Albert 1992, Maudlin 1995). This problem basically states that the following three assumptions are mutually incompatible:

(1) The quantum state (the wave function) is a complete description of the system.
(2) The quantum state always evolves in accord with a linear dynamical equation (such as the Schrödinger equation)
(3) Measurements usually have determinate outcomes.

Any so-called interpretation of quantum mechanics is an attempt to overcome the measurement problem by abandoning (or at least modifying) one or more of these assumptions. So called additional-variable theories (also known under the misleading label "hidden-variable theories") are a family of quantum theories that aim to overcome the measurement problem by abandoning assumption (1): the quantum state does not yield a complete description of the system, because there are additional variables; the information about them is not encoded in the quantum state. As Maudlin (1995) showed, the only viable option for such a theory to solve the measurement problem is to admit position as additional variable.

The de Broglie-Bohm-Bell theory shows how to do this. Originally formulated by Louis de Broglie (1928), it was then modified by David Bohm in 1952 as a second-order theory that explains the motion of the particles in terms of the action of a quantum potential generated by the wave-function, interpreted as a real field (Bohm 1952). The theory was then simplified and cast as a first-order theory without the commitment to a specifically quantum force or potential by John Bell in the 1960s (see the papers in Bell 1987, in particular chs. 4, 7, 17) and set out in a clear and concise way by Detlef Dürr, Sheldon Goldstein and Nino Zanghì in the 1990s (see the papers collected in Dürr, Goldstein and Zanghì 2013). In this theory, called Bohmian mechanics in its contemporary formulation, the

[1] It is worth clarifying that we only hold that Bohmian mechanics can accommodate relationalism *with respect to time*, what does not mean that Bohmian mechanics can fully be formulated as a relational theory. To the best of our knowledge, it is not clear if Bohmian mechanics can be given a full-fledged relational reformulation.

motion of the particles is given by a first order equation that yields the velocity of the particles by means of the wave function as output given the particle positions as in input. Hence, the complete state of a quantum system is specified by both the wave function (i.e., the quantum state) and the particle positions:

$$(\psi(t), Q(t)) \tag{1}$$

where $\psi(t)$ is the wave-function of the system, $\psi(t) = \psi(x_1, \ldots, x_N, t)$, and $Q(t)$ represents the actual positions of the composing particles, $Q(t) = (Q_1(t), \ldots, Q_N(t))$. Since particles always have determined positions and they vary in time, particles naturally have trajectories, too. This is how Bohmian mechanics modifies assumption (1).

As for assumption (2), Bohmian mechanics introduces an additional dynamical equation—the guidance equation. While the Schrödinger equation describes the behavior of the wave-function (ψ) and the wave-function always evolves according to the Schrödinger equation, the guidance equation describes the behavior of the particles (basically, the change of their relative positions in time). It does so by providing the velocity of the particles at any time as a function of the wave-function at that time, its spatial derivative, and the position of all particles at that time. According to Bohmian mechanics, the dynamics of quantum systems is then twofold:

$$(-\frac{h^2}{2m}\nabla^2 + V(q,t))\psi(q) = i\hbar\frac{\partial\psi(q)}{\partial t} \tag{2}$$

$$\frac{dQ_k(t)}{dt} = \frac{\hbar}{m_k}\, Im \frac{\psi^*\partial k\psi}{\psi^*\psi}\,(Q_1, \ldots, Q_N) \tag{3}$$

To put it simply, Bohmian mechanics is a non-relativistic quantum theory about the motion of particles, whose behavior is described by a twofold dynamics in terms of the Schrödinger equation and the guidance equation. Since both equations are deterministic, any randomness is epistemic, namely due to our ignorance of the exact particle positions. Finally, Bohmian mechanics is a non-collapse quantum theory, in the sense that quantum systems do not collapse either by measurements or spontaneously. Bohmian mechanics usually introduces a distinction between the "universal wave-function" and "effective wave-functions" (or "conditional wave-functions"). While the former never collapses, the second may be said to collapse as "a pragmatic affair" (Goldstein 2021). In essence, effective wave-functions are special wave-functions that are decoupled from the universal wave-function, which is more fundamental, involving features of the actual configuration of the environment.

It is clear that the primitive ontology of Bohmian mechanics is one of particles moving on trajectories. Less clear is the ontological status of the wave-function, $\psi(q, t)$. Some have argued that it is a field in configuration space (Bohm 1952, Valentini 1997) or a multi-field in physical space (Hubert and Romano 2018, Romano 2021). Others have claimed that the wave-function is nomological (or quasi-nomological) in the sense that it mainly plays the role of accounting for the motion of the particles (Dürr, Goldstein and Zanghì 2013, ch. 12). While realists about laws of nature would hence regard the wave-function as a law-like entity ('governing' the motion of particles), deflationists would regard it as part of the representational tools to describe quantum phenomena (Bell 1987, ch. 7, Esfeld 2014). Be that as it may, the ontological status of the wave-function in Bohmian mechanics is not crucial for the purpose of this paper, namely the discussion of the direction of time.

In asking whether the direction of time is primitive or derivative in Bohmian mechanics, we wonder whether the direction of time is an irreducible element in its ontology, or whether it is a derivative element in the theory that can be obtained from a directionless basis. The same question arises in standard quantum mechanics as well. If the focus is on the unitary evolution of quantum systems or on interpretations that do not introduce a non-unitary dynamics, the direction of time must be shown to be a derivative element of the theory that is reducible to more basic, physical processes. For instance, in some formulations of the many-world interpretation, the quantum dynamics is exclusively given by the Schrödinger equation, which is time-reversal invariant. The manifest temporal asymmetry then "emerges" from other non-fundamental processes, as the branching structure or decoherence (Bacciagaluppi 2007). In this sense, the direction of time is real, but reduces to a non-fundamental physical process. The fundamental basis therefore lacks a direction of time.

In collapse quantum theories, in turn, the non-unitary, stochastic, and non-linear nature of collapses could well serve as a basis for the direction of time—any temporal asymmetry can be explained in terms of a non-time-reversal invariant dynamics. In spontaneous collapse models, quantum systems undergo spontaneous collapses that are intrinsically irreversible, yielding a direction of time (see Arntzenius 1997, Callender 2000, North 2011 among others; see Lopez 2022b for some caveats). The same goes for measurement-induced collapses (see Penrose 1989, Arntzenius 1997, Healey 2002, Ellis 2013 among others; see Lopez 2022a for some caveats). Therefore, it could be argued, such theories require to posit a primitive direction of time that provides the right background structure to support non-time-reversal invariant laws (see Horwich 1987).

To come back to the original question, can Bohmian mechanics be interpreted in such a way to accommodate a primitive direction of time? Can it also be alternatively interpreted to accommodate a derivative direction of time? In what follows, we argue that Bohmian mechanics can actually accommodate both philosophical positions. In the next section, we show how Bohmian mechanics can accommodate conservative reductionism on the direction of time in terms of an epistemic asymmetry between initial and final conditions. In the Section 4, we show how Bohmian mechanics may require a primitive direction of time to account for change in the configuration of matter in a Leibnizian relational framework.

3. Bohmian Conservative Reductionism on the Direction of Time

Both the Schrödinger equation and the guidance equation are assumed to be time-reversal invariant. Strictly speaking, the guidance equation is time-reversal invariant *if* the Schrödinger equation is time-reversal invariant. According to conventional wisdom, the Schrödinger equation is time-reversal invariant in its basic expressions (e.g., a free particle model) if the time-reversal transformation is implemented by an anti-unitary operator that transforms the time coordinate, $T: t \rightarrow -t$, and takes the complex conjugate over the wave-function, $T: \psi \rightarrow \psi^*$ (see Earman 2002, Roberts 2017, Lopez 2021; see Callender 2000, Lopez 2019 for an alternative view). By modus ponens, it follows that the guidance equation must also be time-reversal invariant. If the Bohmian dynamics is time-reversal invariant, then there are good reasons to suppose that the fundamental evolution of Bohmian particles is temporally directionless. Therefore, any Bohmian explanation of the direction of time should come from non-dynamical elements of the theory.

In standard quantum mechanics plus the collapse postulate, measurement-induced collapses can straightforwardly justify any manifest asymmetry between counterfactual backward and forward evolutions in simple experiments. For instance, suppose a Mach-Zehnder experiment where two sources of electrons (S1 and S2) and two electron detectors after each source (D1 and D2) are at work. When an electron is fired out by S1, the electron detector D1 will emit a flash of light. The same goes for S2 and D2. In the middle of the experimental arrangement, there is a half-silvered mirror. Since D1 and D2 let each electron to pass through, when an electron reaches the half-silvered mirror, it has 0.5 probability of bouncing off and 0.5 probability of passing through it. At the other extreme of the experimental arrangement, there are two electron detectors (F1 and F2), which emit a flash of light when an electron has either been reflected by the half-silvered mirror or when passed through it (see Fig. 1).

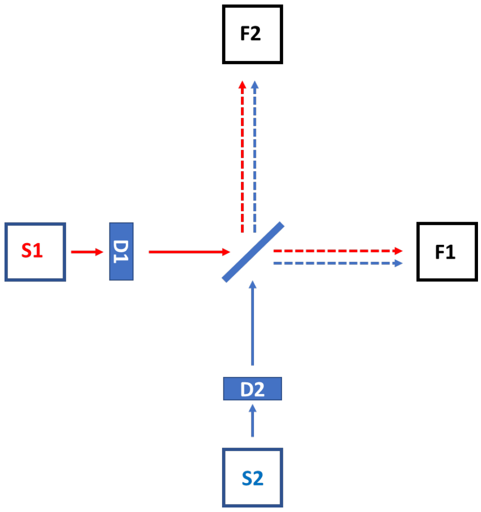

Fig 1. A Mach-Zehnder experiment (adapted from Arntzenius 1997)

This simple experiment allows us to draw some empirically based conclusions about temporal asymmetries. For instance, it is possible to formulate some FORWARD questions and claims such as "what is the probability that F1 detects given that D2 detected?". Questions like this regard certain conditional probabilities of some *later* state given an *earlier* state. Analogously, it is also possible to formulate BACKWARD questions and claims such as "what is the probability that D2 detects given that F1 detected?". Quantum mechanical empirical evidence tells us that the reply to both questions is asymmetric, in the sense that it will assign different probabilities depending on whether FORWARD or BACKWARD questions are formulated: in the first case the probability is 0.5, while it is 1 in the latter (see Penrose 1989, Arntzenius 1997). This is the FORWARD-BACKWARD asymmetry.

In collapse quantum theories, the temporal asymmetry between FORWARD and BACKWARD can be explained because a quantum system collapses but not de-collapses. That is, in a Mach-Zehnder experiment of this kind, a quantum system undergoes a collapse when measured by F1 (or F2), but it then does not de-collapse when travelling backward (see Penrose 1989; for criticisms see Lopez 2022a). Since Bohmian mechanics is an empirically equivalent theory to standard quantum mechanics plus the collapse postulate (insofar as the Born rule applies), it is to be expected that it makes true the same counterfactuals, recovering the predictions and retrodictions of standard quantum mechanics. That is, it must recover the FORWARD-BACKWARD asymmetry. As it was mentioned before, as Bohmian mechanics dispenses with collapses, such an explanation is out of the table. Bohmian mechanics should then be able not only to give the same answers to FORWARD and BACKWARD, but also to explain its asymmetry without relying on collapses.

We submit that the most adequate Bohmian explanation for the FORWARD-BACKWARD asymmetry relies on an asymmetry of our knowledge between initial and final states, in particular our *lack* of knowledge of the precise positions of the particles in their initial states. Therefore, the Bohmian explanation of the FORWARD-BACKWARD asymmetry, which could count as an indication of the temporal asymmetry, ultimately reduces to our epistemic constraint to know of the exact positions of Bohmian particles. Let us consider each case in tandem. As for FORWARD, the physical state of an electron fired by S1 is given by its wave-function, $\psi(q_{S1}, t_0)$, *and* the position of the electron in S1. The wave-function is non-zero in the region covering the vicinity of the source S1 and can be written down as a superposition of "detected by F1" ("$F1$") and "detected by F2" ("$F2$")

$$\psi(q_{S1}, t_0) = \sqrt{\frac{1}{2}}(F1 + F2) \tag{4}$$

The exact position of the electron at the source (q_i) completes its initial state. According to Bohmian mechanics, the final state of the system (whether it is detected by F1 or F2) deterministically depends on the exact initial positions. It follows that if the exact position of the system were known, then its final state would be also known. Yet, as a matter of fact, the exact positions are unknown, given the quantum equilibrium distribution. For simplicity, it is possible to imagine that the exact position of the electron could be either on the right side (q_R) or on the left side (q_L) of the region within the which the wave function is non-zero. Since initial positions determine future trajectories, it is possible to claim that if the electron starts off on the left side (q_L), it will be reflected by the half-silvered mirror. If it rather starts off on the right side (q_R), it will get through the half-silvered mirror. This only emphasizes that there is a matter of fact based on the initial position of the electron as to whether it gets reflected or goes through when it reaches the half-silvered mirror. Of course, since this information is inaccessible, the only information is that given by the initial wave function of the electron and the frequency with which the electron begins in either region, which is equal to $\int_q |\psi(q_R, t_0)|^2$ and $\int_q |\psi(q_L, t_0)|^2$, where q_R and q_L are the regions within q_{S1} where the initial state of the particle is at t_0. For $\int_q |\psi(q_{S1}, t_0)|^2$, the probability must be 1.

In a single run of the experiment, this is what would happen according to Bohmian mechanics. The electron is fired by S1 at t_0. Next, it is detected by the first electron detector, D1. When it reaches the half-silvered mirror, it can either be reflected or pass through it. Bohmian mechanics rightly predicts that the probability of being reflected or passing through is 0.5 each. When the electron reaches the half-silvered mirror, its wave function splits into two packets corresponding to regions in which it is non-zero: one branch is reflected and the other one passes through. However, only one of these branches (either $F1$ or $F2$) will "contain" the actual particle, giving the trajectory that the electron follows. When the final state of the system is known, it is straightforward to infer the initial position of the electron: if F2 detects, then the electron was reflected by the half-silvered mirror, and then it was localized in the region q_L at the source. If the electron had been located in the region q_R, then it would have been detected by F1.

From this simple example, the following temporal sequences can be extracted:

Future-Headed Sequence $S1\ e(q_R) \rightarrow D1 \rightarrow M \rightarrow F2$ or $S1\ e(q_L) \rightarrow D1 \rightarrow M \rightarrow F1$

And the usual FORWARD transitions probabilities. For instance,

FORWARD "the probability that F2 detects given that D1 detected is 0.5"

Therefore, it is easy to see that Bohmian mechanics can recover standard quantum mechanics predications for FORWARD. But instead of relying on measurement-induced collapses, the story depends on the agent's ignorance about the initial position of the electron. If one knew the initial conditions, say the electron's initial position is $e(q_L)$, then the right sequence would be $S1\ e(q_L) \rightarrow D1 \rightarrow M \rightarrow F2$.

This explanation allows us to see in which way the FORWARD-BACKWARD asymmetry emerges. If the trajectory of the electron through the Mach-Zehnder is exclusively determined by its initial state and the dynamics remains deterministic all along, then the only possible explanation for such an asymmetry is to depend on our knowledge of the initial conditions for FORWARD and BACKWARD. Setting aside any caveats concerning whether time is being reversed adequately, in the FORWARD case the probability that F2 detects given that D1 detects is 0.5, and the probability that D1detects given that S1 fired out an electron is 1. But in the BACKWARD case, the probability that D1 detects is no longer 1, but 0.5. Furthermore, in FORWARD the wave function was located in the region of the source S1, $\psi(q_{S1}, t_0)$ and in a superposition of $\sqrt{\frac{1}{2}}(F1 + F2)$. In BACKWARD, the wave function is now localized in $\psi(q_{F2})$ and in a superposition of $\sqrt{\frac{1}{2}}(D1 + D2)$. More importantly, the electron's position is now within the region of F2, either on the right side (q_R) or on the left side (q_L) of F2. This yields the following temporal sequences for BACKWARD:

Past-Headed Sequences $F2\ e(q_R) \rightarrow M \rightarrow D1$ or $F2\ e(q_L) \rightarrow M \rightarrow D2$

BACKWARD "the probability that D1 detects given that F2 detected is one half"

What is then the source of the asymmetry between FORWARD and BACKWARD conforming with Bohmian mechanics? It is our epistemic constraint to know the exact positions of the particles either in FORWARD or in BACKWARD. To emphasize, if Bohmian mechanics is a quantum theory about particles and their trajectories, and the history of each particle is invariably and completely determined by the twofold Bohmian dynamics and the particles' initial state, then the FORWARD-BACKWARD asymmetry can only come from either of them. As it was mentioned, the dynamics is deterministic and fully time-reversal invariant. So, the only option available is an asymmetry in our knowledge of the initial state. To put it differently, the FORWARD-BACKWARD asymmetry emerges from non-dynamical elements of the theory, and it just reflects our lack of knowledge of the exact positions of the particles in the initial state. This is how Bohmian mechanics can explain many temporal asymmetries as well as recovers the standard quantum mechanical phenomenology. In other words, the FORWARD-BACKWARD asymmetry is part of the quantum-mechanical phenomenology. The bone of contention is *how to account for it*. While standard quantum mechanics relies on the collapse postulate (an in-built time-asymmetric process) to explain and to predict the asymmetry, Bohmian mechanics relies on our epistemic constraint in knowing exactly the initial state of the system. In this way, it can both explain and predict the FORWARD-BACKWARD asymmetry.

The explanation of the FORWARD-BACKWARD asymmetry in terms of an asymmetry in our knowledge of the initial conditions has also been put forward by Frank Arntzenius (1997) for alternative additional-variable theories. He argues that in the de Broglie-Bohm pilot-wave theory the *constraint* on the initial conditions is what implies the FORWARD-BACKWARD asymmetry. The constraint consists in assuming that the initial wave function is located roughly near to the region S1 and D1, and in a superposition of being detected by F1 and F2. In BACKWARD, it is assumed that the initial (final) condition is to be *different*, starting with a wave-function roughly near to F2 and in a superposition of D1 and D2. According to him, it is this assumption what explains the usual frequencies that are obtained experimentally. Arntzenius puts it this way:

> This is an assumption that we always make in Bohmian theories, and rarely even notice. Of course, it is a good thing that we do this, for if we did the opposite, we would have an empirically inadequate theory, for it would predict non-invariant forward transitions frequencies and invariant backward one, and that is just wrong (Arntzenius 1997: 219)

In the same vein, Callender writes:

> According to some interpretations, such as Bohm's, [FORWARD] is merely derived from the laws and the initial conditions. (…) The guidance equation is TRI [time-reversal invariant] if the Schrödinger equation is. Assuming for the moment the conventional wisdom that the Schrödinger evolution is time symmetric, this implies that the fundamental laws in a Bohmian universe are TRI. The observed asymmetry [i.e., FORWARD-BACKWARD asymmetry] is due to asymmetric initial conditions (Callender 2000: 260).

All this implies that in so called hidden-variable theories whose dynamics is deterministic (Bohmian mechanics among them), there is no reason to suppose that the direction of time is primitive; it is rather derivative. An asymmetry in our knowledge of the initial conditions explains why the quantum mechanical phenomenology looks temporally asymmetric; but it is insufficient to ground a primitive, fundamental direction of time. This does not imply, however, that in Bohmian mechanics the direction of time is unreal, or that it is a timeless theory. The direction of time might still be real, but it is clearly not primitive: it can be explained in terms of non-dynamical aspects of the theory. The fundamental dynamics is indeed undirected.

It is in this sense that we argue that Bohmian mechanics can accommodate conservative reductionism about the direction of time. When the focus is exclusively on the dynamics of the theory, it always produces a space of solutions that can be partitioned in two disjoint sets: forward-in-time and backward-in-time solutions, $W = W^f + W^b$ (where W is the whole space of solutions, W^f contains the forward-in-time solutions, and W^b the backward-in-time ones). Since a time-reversal transformation preserves the space of solutions, it is a structure-preserving mapping that goes from one to the other. At this level, no directedness of time is exhibited in the theory. However, when the initial conditions and our lack of knowledge of them are taken into account (which are essential for the theory to work as intended), the asymmetry immediately appears. Each specific solution relies on initial conditions with precise particle positions. Since our knowledge of these positions is limited, it seems that FORWARD and BACKWARD are asymmetric. To put it differently, in each Bohmian possible world, any agent will account for the same FORWARD-BACKARD asymmetry because she will have limited knowledge of the exact position of the particles in her world.

4. Bohmian Primitivism on the Direction of Time

Primitivism about the direction of time, as it was mentioned before, is the thesis that the direction of time does not call for an explanation because it is a primitive in the ontology. It is a posit required to explain phenomena and features of the theory. For instance, the existence of non-time-reversal invariant laws requires an underlying direction of time as the structural background that can give support for such laws. One might think that Bohmian mechanics is unable to accommodate a primitive direction of time because its dynamics is fully time-reversal invariant. Nonetheless, we submit that primitivism can be accommodated in the theory under some metaphysical assumptions.

Bohmian mechanics, as it was said before, is a theory of particles and their trajectories. At any temporal instant, the basic ontology of Bohmian mechanics is that of a configuration of Bohmian particles spatially separated from one another. Thus, the ontology is one of matter that is spatially arranged (see Fig. 2). Differences in the relative spatial relations between particles give *variation* to the configuration. In Fig. 2, for instance, the distances between particles are different, which renders an asymmetry in the configuration of matter: some particles concentrate in some regions, while in others they are farther apart. Spatial relations are world-making relations in the sense that they are what make particles hold together in a configuration that constitutes a possible physical world. Yet, each configuration is changeless, as a snapshot of photography—if two different configurations (that is, two configurations in which the relative distances among particles vary) are shown, it is impossible to say if they are two possible configurations or the same configuration that changed.

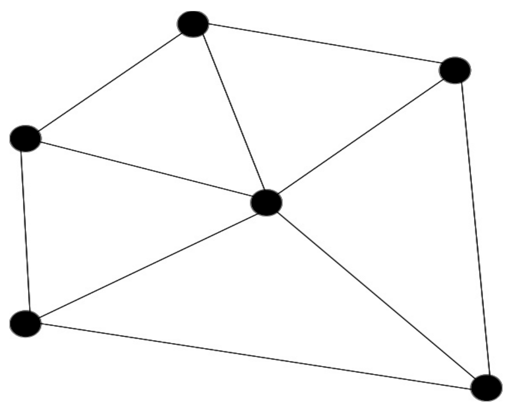

Fig. 2. Variation in the configuration of matter

This picture is nonetheless unsatisfactory for physics. In so far as empirically adequate physical theories are considered, physics is about matter *in motion*. This means that the configuration of matter (i.e., Bohmian particles and their relative spatial distances) not only varies spatially, but also *changes* in time. Metaphysically, this entails to impose another set of world-making relations—temporal relations. They allow us to distinguish cases in which a configuration of matter changes in time from cases in which two possible configurations of matter are considered. When it is said that a configuration of matter changes, it is said that the relative distances among Bohmian particles change—they become longer or shorter. So, what is obtained is a series of stacked configurations of matters at different temporal instants with their relative spatial relations becoming longer or shorter (Fig. 3)

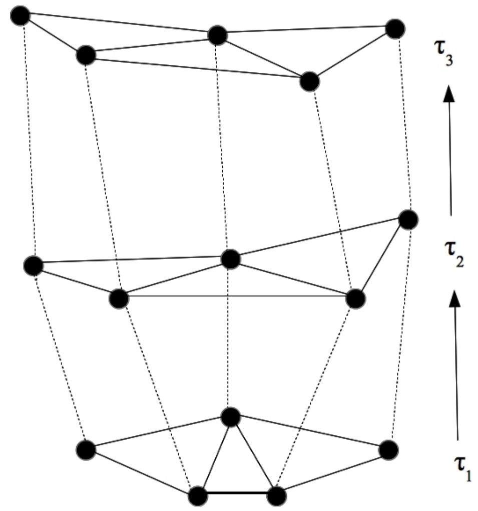

Fig. 3. Change in the configuration of matter

In Fig. 3, the solid lines represent spatial distance relations, while the dotted lines stand for temporal relations. What is metaphysically important is the necessity to distinguish between both relations. One way to do this is by making them to be parasitic on space and time as substances, with time and space existing independently from matter. Spatial and temporal relations between matter supervene on spatial and temporal relations between points and instants, respectively. For instance, in substantivalism, the relative spatial relation between two Bohmian particles supervenes on the absolute spatial relations between the points that the Bohmian particles occupy in substantival space. The same goes for temporal relations and substantival time. In this metaphysical framework, therefore, it is straightforward to distinguish between variation and change since they remit to different substances.

Nevertheless, it can be argued that substantivalism overloads the ontology. Hence, if a comparable distinction between variation and change can be drawn in a more parsimonious framework, then this is to be preferred. In what follows we argue that Leibnizian relationalism provides the appropriate conceptual tools to accomplish this job. The upshot is that Bohmian mechanics can accommodate a primitive direction of time and implement a distinction between variation of a configuration (space) and change of the configuration (time). Leibnizian relationalism provides the rationale for this.

To begin, the central tenet of Leibnizian relationalism is to reduce space to distance relations among objects that constitute a configuration such as the configuration of matter of the universe (order of coexistence in Leibniz's terms) and to reduce time to the change of these relations (order of succession in Leibniz's terms). Let us consider the main ontological tenets of Leibnizian relationalism. It first endorses a monist ontology, in which there exists only one kind of substances in the physical sphere that stand in spatial and temporal relations. This means mainly two things: first, that space and time (or space-time) are not a different kind of substances in addition to matter, but they are just an abstraction (or representation) of the spatial and temporal relations that obtain among the material substances (time and space are *entia rationis* in Leibniz's vocabulary, that is, they are ideal entities that express indeterminate, continuous possibilities); second, that these are *different* relations that must also be primitive. It is commonly said that in Leibnizian relationalism spatial and temporal relations among matter are *direct*, in contrast with substantivalism.

While spatial relations deliver variation in the configuration of matter, temporal relations deliver change. It is important to stress that spatial relations (i.e., the configuration of matter) are more fundamental than temporal relations (i.e., change). The requirement of temporal relations comes from the necessity to impose change on the configuration of matter. The question of whether the purely spatial ontology changes or not cannot be settled on the basis of the spatial relations alone, but it is to be replied to on the basis of why additional structure is required in the ontology. And the reason to impose change in the ontology is the same reason for why it is necessary to impose any additional structure at all: to explain the phenomena. Change, then, enters the ontology as a primitive together with objects standing in distance relations because it is a necessary assumption to explain the behavior of matter (see also the two axioms proposed and argued for in Esfeld and Deckert 2017: 21). Therefore, the Leibnizian basic ontology comprehends matter engaging in spatial relations and in temporal relations.

The claim that change is intrinsically directed is part of Leibnizian relationalism. In analyzing phenomenal change, Leibniz distinguishes between points and instants. In a letter to Louis Bourguet, dated 5th of August 1715, he writes:

> I admit however that there is this difference between instants and points – one point of the universe has no advantage of priority over another, while a preceding instant always has the advantage of priority, not merely in time but in nature over the following instants. (Leibniz 1989: 664; translated from Leibniz 1887: 581-582)

This passage is crucial to understand the primitiveness of the direction of change in Leibnizian relationalism. For Leibniz, an *instant* is a momentary state of the world of successive phenomena (see Anapolitanos 1999: 136). The distinctive feature of instants is hence an in-built priority (or directedness), a metaphysical difference that distinguishes them from points –instants stand always in a later / earlier relation; if they did not, they would not be instants, but points in mere variation. They acquire this essence because they are generated by the change of the basic ontology. Instants may then be seen as momentary states of the basic ontology that result from the primitive change of the basic ontology as it unfolds. The Leibnizian understanding of change and temporality has indeed a Lewisian resemblance in this respect: change is nothing but just one single instant following another; this constitutes the unfolding or evolution of the basic ontology. This unfolding is *intrinsically* ordered and directed because it is not made of points, but results in instants (see Arthur 1985: 277). For Leibniz, therefore, the notion of undirected change would be meaningless, because being directed is a distinctive feature of what change *is*.

In this metaphysical framework, it is then pertinent to say that since time reduces to change, the direction of time *is nothing* but the direction of change. This suggests a reduction in terms of *identity*. It is not the case that time is unreal or vanishes; nor does it mean that the direction of time is unreal or vanishes. In Leibnizian relationalism, the direction of time is as real as the direction of change because the reduction can be viewed as conservative rather than eliminative: it establishes that time is *identical* to change, so there is no independent matter of fact that distinguishes between the direction of time and the direction of change—they are just the same. It is worth recalling that in Leibniz's metaphysics time (and space) are *entia rationis*, that is, they are ideal entities, which does not mean that they can be eliminated: they are just relations considered in abstraction from determinate relata (see Arthur 1985: 285). All this implies that the direction of time is obtained from the explanatory necessity to include change in the basic ontology, to adopt Leibnizian relationalism to reduce time to change, and to the metaphysical distinction between variation and change in terms of the latter being primitively directed. Therefore, the direction of time is primitive, too.

When Bohmian mechanics is complemented with Leibnizian relationalism, a Bohmian primitive direction of time is a reasonable posit. In the primitive Bohmian ontology, all there is are Bohmian particles in a configuration of spatial relations that change in a directed way as a matter of fact. A configuration of particles constitutes an order of coexistence. For Bohmian mechanics to be a physical theory, motion needs to be imposed. It basically means that change in the relative distances between particles is imposed. When change is imposed upon the configuration of Bohmian particles, it changes in one direction. The direction of change is then primitive to Bohmian mechanics when complemented with Leibnizian relationalism. Since the direction of time is nothing but the direction of change, it follows that the direction of time is also primitive. But there is no need for an ontological commitment to substantival time as an independent substance.

To put it differently, spatial relations lack of a direction in the sense that there is no difference between travelling from one Bohmian particle to the other, or the other way around. But, when the configuration of matter changes, it changes from one configuration to a different configuration, that is, from the configuration at τ_1 to the configuration at τ_2, in Fig. 3. That is, for it to be change, it must be directed change in the sense of going from one configuration to another, but *not* the other way around. It can be argued that the backward evolution (from τ_2 to τ_1) is possible, too. This may well be so, but both evolutions are different from one another in function of their directionality—the fact that it is possible to even distinguish between them is due to the fact that their directionality is different; we have *two* possible evolutions *because* they are different in their directionality.

In this way, Bohmian mechanics can accommodate a primitive direction of time in terms of a primitive direction of change if Leibnizian relationalism is adopted as metaphysical framework. As Leibnizian relationalism shows, when change is imposed as a primitive, temporal relations drive one configuration of Bohmian particles to the next one. Change is then reflected as change in relative spatial relations between Bohmian particles in different configurations. The necessity of distinguishing between variation and change (that is, between spatial and temporal relations) leads to the idea of directed change—while variation is directionless, change must be primitively directed. Otherwise, they would collapse into each other.

As a complementary comment, Leibnizian relationalism applied to Bohmian mechanics is also compatible with presentism and some versions of eternalism in the metaphysics of time. According to Leibnizian relationalism, change is not only primitive, but also eternal. What exists is both the configuration of Bohmian point particles of the universe characterized by the relative distances among them and the change in this configuration, that is the change of the distance relations. The whole change can therefore be taken to simply exist, which goes along with a dynamic view of time. Indeed, as Maudlin highlights, Bohmian mechanics is particularly accommodative to presentism, because its primitive ontology admits only instantaneous positions as primitive, in contrast to Newtonian mechanics that admits both positions and velocities as primitive:

> It is perhaps interesting to note that Bohm's theory is deeply congenial to an ontology which maintains that all which exists is that which exists *now*, i.e., at a point in time classically conceived. Instantaneous velocities can of course be defined, but only as the limit of average velocities over finite periods of time. Those puzzled about the status of velocities in an ontology in which only an instant of time *exists* can happily adopt a Bohmian ontology of particles (with position) and the wave-function. (Maudlin 2011: 113 note 22)

Therefore, Bohmian mechanics and Leibnizian relationalism fit well into both presentist frameworks and dynamic theories of time. Yet, eternalism is not discarded either. Bohmian mechanics and Leibnizian relationalism can adopt the additional thesis that past, present and future are real, but that there is nonetheless a dynamical present (see, for instance, Broad's moving spotlight theory, Broad 1923). In any case, it can be also claimed that the distinction between eternalism and presentism comes down to an only semantic one; it does not cut any ontological ice (see Dorato 2006). Be that as it may, the combination of persisting configuration of matter given by the relative positions of the particles (order of coexistence) *and* the permanent change of their relative positions leave enough room for alternative metaphysics of time.

It might be argued that our argument for primitivism ultimately fails because Bohmian mechanics is time-reversal invariant. As mentioned before, a time-reversal invariant dynamics could be received as an argument against primitivism. Nonetheless, it is possible to deflate the meaning of time-reversal invariance in order to accommodate primitivism (for details, see Lopez and Esfeld 2023). To begin, Bohmian mechanics is built upon the assumption that the dynamics must be time-reversal invariant (see Dürr, Goldstein and Zanghì 2013, ch. 2). For instance, in deducing the guidance equation, Bohmian mechanics assumes that it must be time-reversal invariant like the Schrödinger equation. This fact could be symptomatic of a theoretical stipulation to constrain the form of the Bohmian dynamics, but it does not really represent an aspect of reality. It can, for instance, work as a heuristic principle that guides theory construction—it can be seen as a property of the representational tools that physical theories deploy to explain the phenomena.

Mutatis mutandis, this view of time-reversal invariance can be related to similar Bohmian arguments against a realist interpretation of the wave-function. For instance, John Bell says:

> One of the apparent non-localities of quantum mechanics is the instantaneous, over all space, 'collapse of the wave function' on 'measurement'. But this does not bother us if we do not grant beable status to the wave function. We can regard it simply as a convenient but inessential mathematical device for formulating correlations between experimental procedures and experimental results, i.e., between one set of beables and another. (Bell 1987, ch. 7: 53)

In the same vein, time-reversal invariance can be also seen as a "convenient but inessential mathematical" feature of physical theories. If this is so, then time-reversal invariance cannot be straightforwardly employed in an argument against or in favour of a direction of time. While the latter is an ontological issue, whether a theory is time-reversal invariant (as Bohmian mechanics) is rather a representational issue about how the dynamics should be written down. Both should not be conflated.

5. Conclusions

It is frequently assumed that a physical theory can settle the problem of the direction of time. In general, this assumption has relied either on dynamical considerations (e.g., whether the dynamics is time-reversal invariance) or non-dynamical ones (e.g., an asymmetry in initial conditions). Our aim in this paper was to analyse the problem of the direction of time in Bohmian mechanics and to show that it can actually accommodate two divergent philosophical positions with respect to the direction of time: conservative reductionism and primitivism. By relying on an epistemic asymmetry between initial conditions in FORWARD and BACKWARD, it was shown that Bohmian mechanics can account for the time asymmetric quantum phenomenology in terms of our lack of knowledge of the exact positions of Bohmian particles in the initial conditions. Bohmian conservative reductionism on the direction of time can thus be an attractive explanation of the direction of time for those that are reticent to primitivist approaches. Bohmian primitivism on the direction of time is not discarded, though. We have shown that Bohmian mechanics metaphysically necessitates a distinction between variation (the order of coexistence of Bohmian particles) and change (the order of succession). Leibnizian relationalism, we have argued, is a suitable framework that can do the job—it imposes that change is intrinsically directed, while variation is not. Since time is identical to change, the direction of time is as primitive as the direction of change is. Hence, also those that are prone to adopt primitivism about the direction of time can employ Bohmian mechanics as physical basis.

6. References

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