

Primitive Ontology in a Nutshell

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Abstract

The aim of this paper is to summarize a particular approach of doing metaphysics through physics - the primitive ontology approach. The idea is that any fundamental physical theory has a well-defined architecture, to the foundation of which there is the primitive ontology, which represents matter. According to the framework provided by this approach when applied to quantum mechanics, the wave function is not suitable to represent matter. Rather, the wave function has a nomological character, given that its role in the theory is to implement the law of evolution for the primitive ontology.

1. Introduction

The primitive ontology (PO) approach, developed in [Goldstein 1998], [AGTZ 2011, 2008], [Allori 2013a,b], provides a characterization of what it takes for a fundamental theory to be satisfactory when used to ‘read off’ the metaphysics from the physics. In this paper, I will not motivate or defend the view against possible objections because this has been done elsewhere (see [Allori 2013 a,b]). Instead, I will articulate and summarize the main ingredients behind the idea of PO, and I will review what implication this approach has in the case of quantum mechanics.

According to the PO approach, all fundamental physical theories have a common structure, which provides a general explanatory schema that one could use to do metaphysics from physics. If taken from a realist point of view, any satisfactory fundamental physical theory contains a metaphysical hypothesis about what constitutes physical objects, the PO, which lives in three-dimensional space or space-time and constitutes the building blocks of everything else. In the formalism of the theory, the variables representing the PO are called the primitive variables. In addition, there are other variables necessary to implement the dynamics for the primitive variables: these non-primitive variables could be interpreted as law-like in character. Once the primitive and the non-primitive variables are specified, one can construct an explanatory scheme based on the one used in classical theories. This will allow determining, at least in principle, all the macroscopic properties of familiar physical objects in terms of the PO. This structure holds for classical as well as for quantum theories.

Here is the outline of the paper. In sections 1 through 8, I present the various ingredients of the PO approach: first the requirements that the primitive variables are defined in three-dimensional space and on the microscopic level, the distinction between the primitive and the non-primitive variables, how theories with the same

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evolution of the PO are the same theory, how one can generate new theories mixing up different primitive variables and different evolutions, and how symmetries are properties of the PO. Then, in sections 9 through 12, I apply the PO approach to quantum theories, focusing on the meaning of the wave function and on the characterization of the fundamental features of the various theories. I conclude with some remarks on how the PO approach can be helpful in constructing a future relativistic invariant quantum theory.

2. Ontology and Primitive Ontology

The starting point is a realist conception of fundamental physical theories: the picture of reality described by our best theories is accurate, and thus we can use physics as a guide to metaphysics. Then, it should be obvious that any fundamental physical theory should have a clear ontology. If the ontology of a theory is not clear, then it is not clear what entities the theory is assuming to exist, and then it is hard to see how one could even begin to do metaphysics starting from it. To specify what the ontology of a theory is amounts to select, among all the variables in the theory, are to be taken as representing what exists in the world. For instance, consider classical mechanics. Arguably, the ontology of this theory is given by particles, with position and momentum. However, in the PO approach in order to do metaphysics properly starting from physics, one should also specify which, among the elements in the ontology, should count as the PO of the theory. The discussion in the literature has focused mostly on the situation in quantum mechanics but the approach aims to be general (see, e.g. [Allori 2013 b]).

The basic idea is that, when we are using a fundamental physical theory to figure out what the physical world is like, some part of the ontology is 'more important' than other parts. In other words, among the variables that represent the ontology of a theory, there are primitive and non-primitive variables. The primitive variables, in contrast with the non-primitive ones, represent matter; what physical objects like tables and chairs are made of. For instance, in classical mechanics matter is made of point-like particles, whose fundamental characterization is their location in space. Thus, the primitive variables of classical mechanics is the positions of particles.

The qualification 'primitive ontology' instead of just 'ontology' comes from the idea that the PO does not exhaust all the ontology, but it rather just accounts for physical (namely material) objects. Other things might exist (numbers, mathematical objects, abstract entities, laws of nature, and so on), and some of them (like natural laws) might be described by other objects in the ontology of a fundamental physical theory. As we will see in Section 9, in quantum mechanics the wave function is a non-primitive variable, and it is arguably more similar, in kind, to laws than to material objects.

Notice that the primitive variables are not chosen *a posteriori*, once the formalism of the theory has been specified. Rather, there is already a natural interpretation for

each mathematical object present in the theory, namely the one the proponent of the theory intended to give them. The scientist's choice of what physically exists in the world will more or less automatically determine the mathematical object to represent it. If one wanted matter to be made, say, of point-like particles, then the natural way to mathematically describe them would be using points in three-dimensional space. Sometimes, though, like in the case of quantum mechanics, the situation is more complicated, since it is not clear what the initial metaphysical hypothesis behind the construction of the theory is. Thus, we find ourselves with the 'bare' formalism, and we are obliged to 'interpret' it *a posteriori*. This is the reason why only in the quantum framework, in contrast with what happens in the classical theories, we have so many possible theories, as we will see in Section 9. The PO approach will allow ruling out at least some of the proposed theories, namely those which will have the wave function as primitive variable.

3. Three-Dimensional Space

Mathematically, the primitive variables are defined in three-dimensional space or four-dimensional space-time. There can be different kinds of primitive variables: each given type of three-dimensional object can represent a different possible PO for a fundamental physical theory. A point x in \mathbb{R}^3 , for instance, represents a possible PO, since it can be taken to be represent point-like material particles. This is the case of classical mechanics. Also, a function $f(x)$ defined on \mathbb{R}^3 can also be a primitive variable, since it can be taken to represent a matter density field. This, arguably, could be the case of electromagnetic fields in classical electrodynamics. In addition, points in \mathbb{R}^4 , when interpreted as space-time, are a possibility, because they can be taken to represent space-time events, or 'flashes.'

Roughly², as we will see in the following sections, the three-dimensionality of the primitive variables allows for a direct contact between the variables in the theory and the objects in the world we want them to describe. In fact, a PO represented by an object in a space of dimension d , different than 3, would imply that matter - including us - lives in a d -dimensional space. Thus, our fundamental physical theory would have to be able to provide an additional explanation of why we think we live in three-dimensional world while we actually do not. It has been argued that this is, at best, undesirable³, in part for reasons connected to another feature that a good PO is supposed to have, namely its fundamentality.

4. Fundamentality

From what we have said so far, the only limitation to the primitive variables is that they are supposed to be defined in three-dimensional space or four-dimensional space-time. In principle, they could be microscopic or macroscopic entities. However, a microscopic

² For more on this, see [Allori 2013b].

³ See, e.g., [Allori, 2013a,b], [Monton 2006].

PO, in which the PO constitutes the building blocks of everything else, is able to ground a scheme of explanation that allows determining the properties of macroscopic physical objects in terms of the behavior of the PO. In fact, consider classical mechanics, a theory that provides an example of a microscopic PO. In this theory, arguably⁴ any physical body (gases, fluids, and solids) is satisfactorily described as a collection of (microscopic, three-dimensional) particles. Once the PO and its temporal evolution are given, everything else follows: in classical mechanics (as well as in classical electrodynamics) we can identify macroscopic properties more or less straightforwardly given how the (microscopic) PO combines and interacts to form (macroscopic) physical bodies.

The variables representing the ontology, O , can be written in terms of the couple (primitive; non-primitive variables). That is, we can use the symbol of the semicolon “;” to divide in the ontology the primitive from the non-primitive variables, the primitive ones being on the left of the semicolon⁵. For example, when we write $O=(a;b)$ we mean that matter is represented by a alone. In classical mechanics, as we described it so far and as we will see in the next section, we would have $O=(x;p)$, where x is the position of particles and p their momentum. Since the PO specifies what matter is in a given fundamental physical theory, the specification of the PO and its temporal evolution, or its spatiotemporal history, completely determines the theory. Thus, we have different theories depending on where we place the semicolon: one would have (among other less interesting possibilities⁶) $T_a = (a;b)$, a theory in which matter is represented by a , and $T_b = (b;a)$, in which matter is represented by b .

5. Non-Primitive Ontology

In contrast with the primitive variables, the non-primitive variables have the role of implementing the law of motion for the PO. For this reason, such variables are sometimes called ‘nomological’ variables. Roughly speaking, the primitive variables tell us what there is, and the non-primitive variables tell the primitive variables how to ‘behave.’ In classical mechanics, for example, the complete description of any physical system at a given time is given by the couple given by the position x and momentum p of the particles. The position is the primitive variable, while the momentum allows the equation for the position to be defined. In fact, the evolution of position is given by $\frac{dx}{dt} = \frac{p}{m}$ where m is the mass of the particles. The evolution of momentum itself is given by $\frac{dp}{dt} = -\nabla V(x) = F(x, p)$, where V is the potential and F the force. These two first-order equations can be written in a second-order equation plugging in the second equation

⁴ Assuming reductionism to be true.

⁵ This idea is original of Sheldon Goldstein [private communication].

⁶ We could also have $(;a,b)$, corresponding to a theory with no ontology at all, so it can never represent physical reality, and $(a,b;)$, in which we would have no non-primitive variables.

into the derivative with respect to time of the first (assuming that the mass remains constant in time). In this way, we get back the usual Newton's equation: $\frac{d^2x}{dt^2} = \frac{F}{m}$.

Thus in this sense the PO is the most fundamental ingredient of the theory. It grounds the 'architecture' of the theory: first, we describe matter through the primitive variables, then we describe its dynamics, implemented by some non-primitive variables. Then we are done, all the macroscopic properties are recoverable. This is also connected with the 'primitiveness' of the PO: even if the primitive variables do not exhaust all the variables in the ontology, because they describe matter in the theory, and because in principle every macroscopic property can be recovered in terms of them, we can directly compare the macroscopic behavior predicted by the theory to the actual behavior of matter. Not so for the other non-primitive variables, which can only be 'observed' indirectly in terms of the ways they affect the behavior of the PO.

6. Physical Equivalence

Since the empirical adequacy of a theory is decided by the histories of the PO, there could be empirically adequate theories with the same PO but whose evolution is generated by different non-primitive variables. This leads to the notion of physical equivalence: two different theories that provide the same evolution for the PO, no matter how it is implemented, describe the same physical world. They are indistinguishable as far as the empirical appearances are concerned. Therefore, on the one hand, if we change the PO and its evolution, we change theory, since we change the way the theory describes matter. On the other hand, however, if we keep the same histories of the PO while we change the way in which this evolution is obtained then we have theory that is physically equivalent to the original theory. For instance if the spatiotemporal histories of the PO in T_a , whose ontology is $O=(a;b)$, are the same as the spatiotemporal histories of PO in $T_{a'}$, whose ontology is $O=(a;c)$, then T_a and $T_{a'}$ are physically equivalent, even if they have a different non-primitive variables.

The notion of physical equivalence between theories was introduced in [AGTZ 2008] in the framework of quantum mechanics. Nonetheless, it is not necessary to go to quantum theories to give an example of physically equivalent theories. Here is a very simple example of physical equivalent theories. If a force is conservative, it can be defined as the opposite of the gradient of the potential. This particular mathematical operation involves derivatives, and because of this, it is always possible to find two different potentials that give rise to the same histories of the PO: any two potentials that differ by a constant will do the trick. In fact, they both give rise to the same force (and therefore the same histories of the PO), given that the derivative of any constant is always zero. Hence, two theories with such potentials will be physically equivalent.

7. Theory Construction

In the process of theory construction, the scientist has a considerable amount of freedom. In fact, first she has freedom of choosing the kind of PO (particles, fields,

flashes,...). Then she is free to choose the PO's temporal law of evolution, in particular whether it is stochastic or deterministic. In addition, she has the freedom of implementing such a law with the aid of some non-primitive variables evolving (or not) according to their own equation, which can be either stochastic or deterministic. Thus, the histories of the PO have to be such that, macroscopically, will recover the empirical predictions, but all the other choices will be guided by super-empirical virtues like simplicity or explanatory power.

In the literature, no one has discussed the plethora of theory that one could generate selecting a PO, the non-primitive variables and their respective evolutions except that in the case of quantum mechanics, as we will see in Section 9. In [ATGZ 2008], where some of the various possible empirically adequate quantum theories are discussed, the notation is not very illuminating and indeed can be misleading. In fact, it focuses on the evolution of the wave function that, as we will see, is not a good candidate to be a PO. Rather, a better notation would be one that would focus on the evolution of the PO. If X denotes a generic PO (x for particles, m for matter density fields, ϕ for more generic fields, and f for flashes), one could then specify in a subscript the type of law u for the evolution of the PO (deterministic or random), and with a superscript the law F for the evolution of the non-primitive variable (again, deterministic or random). That is: X_u^F . In the case of classical mechanics, we would then have: $x_{deterministic}^{deterministic}$. The fundamental object (the PO) in fact is x , the particles; the superscript indicates that the particles evolve deterministically (according to $\frac{dx}{dt} = \frac{p}{m}$), while the subscript indicates that the momentum evolve deterministically as well (according to $\frac{dp}{dt} = F$). Obviously, since there are infinitely different deterministic and indeterministic possible equations, this notation is not precise. However, it would be unreasonable to require this from a notation: an effective notation should be able to provide at glance the fundamental features of a given theory, rather than the precise details, and the new notation certainly does that. In contrast, the old notation, in addition of being equally imprecise, was drawing attention to the wrong object, namely the non-primitive variables, rather than to the PO, as we will see, and thus was potentially misleading.

8. Symmetry Properties

There is an important connection between the PO and the symmetry properties of a theory. Roughly put⁷, since the histories of the PO provide the metaphysical picture of the world, if the theory is invariant under a given symmetry this picture should not change under the symmetry transformation connected to the symmetry. Given their role, the non-primitive variables will instead transform under the symmetry in such a way as to ensure that the histories of the PO will remain invariant. Invariance is

⁷ For more on this, see [ATGZ 2008].

therefore a property of the dynamics of the PO: changing the PO of a theory might change its symmetry properties. Therefore, before asking whether a given theory has a given symmetry, it is necessary to identify its PO and see whether the transformed histories of the primitive ontology are still possible histories for the theory. In addition, choosing one PO rather than another might make the theory acquire or lose symmetries. In this way, if one considers having a given symmetry a *desideratum* for a theory, symmetries could then be used to select, among other super-empirical virtues such as simplicity or explanatory power, the most desirable PO.

9. Quantum Mechanics

Now that we have outlined the main ingredients of the PO approach, let us see how we can apply it to the quantum framework. The so-called orthodox quantum mechanics that one can find in physics textbooks has not a clear ontology at all: is it about the motion of microscopic entities, or is it about the measurement results? Luckily, other quantum theories have a clear ontology, and thus can be used as a guide to metaphysics. They are Bohmian mechanics (BM), the GRW theory (GRW), and the Many-Worlds theory (MW). In the following, I will present these theories from the perspective of the primitive ontology approach.

Particles are the PO of BM, and they are specified by their position x in three-dimensional space. The trajectories of a system of particles are determined by Bohm's guidance equation (see [Bohm 1952], [Bell 1987], [DGZ 1992]). This equation involves the wave function ψ . Because of its role in generating the histories of the PO of BM, the wave function is a non-primitive variable. The wave function in turn evolves in time according to Schrödinger's equation. Schematically, then, we have $O=(x; \psi)$, and in the notation proposed in this paper, BM would be denoted $x_{deterministic}^{Schrodinger}$.

The situation in GRW is more complicated. GRW is a theory in which the wave function evolves in time according to a stochastically modified version of the Schrödinger equation, also called GRW dynamics. Roughly, the wave function evolves according to the Schrödinger equation until a random time, randomly distributed with rate $N\lambda$ ($\lambda=10^{-15} \text{ s}^{-1}$ is a new constant of nature). Then the wave function undergoes an instantaneous collapse with random center, which is mathematically represented by the multiplication of a Gaussian operator ($\sigma =10^{-7} \text{ m}$, the width of the Gaussian, is also a new constant of nature). Historically, GRW has been taken to be a theory in which matter is described by the wave function. This is not the case in the PO approach. In fact, the wave function is a mathematical object that lives in a very abstract space: the space of all the positions of all the particles in the universe, configuration space. If there are N 'particles' ⁸ in the universe, configuration space has dimension $M=3N$. Thus, by

⁸ Strictly speaking, whether there are particles or not (intended as point-like building blocks of every material object in the world) depends on the primitive ontology of the theory: in a theory like this with a

definition, the wave function is not a suitable primitive variable. One proposal for a reading of GRW as a theory in which the wave function does not represent the PO has been put forward by Benatti, Ghirardi and Grassi in their [BGG 1995] and later dubbed GRWm in [AGTZ 2008]. In this theory the PO is a three-dimensional matter field $m(x,t)$ defined in terms of the wave function, which evolves according to GRW dynamics. In the new notation proposed in this paper, this theory would be dubbed m_{random}^{GRW} . Another proposal along similar lines was first suggested by Bell in his [Bell 1987], then adopted in [Tumulka 2006a,b] and called GRWf in [AGTZ 2008]. In this theory, the PO is represented by points (events) in space-time, the ‘flashes.’ These flashes are randomly distributed in space-time in a way determined by the GRW evolving wave function: every flash corresponds to one of the spontaneous collapses of the wave function. Thus, using the notation introduced here, we would call this theory f_{random}^{GRW} .

Lastly, in the MW theory the wave function evolves linearly according to Schrödinger’s equation. Almost all the proponents of MW agree in considering the wave function as the object in the theory that describes physical objects, but this is again incompatible with the PO approach. There is a MW theory, originally developed by Bell in his [Bell 1987], in which the wave function evolves according to the Schrodinger equation and matter is made of particles, like in BM, but they do not have a continuous trajectory in space-time. Rather, their configuration at different times is distributed according to a $|\psi|^2$ distribution, and there is no temporal correlation among them. The theory has later dubbed BMW (Bell Many Worlds) in [AGTZ 2008] and later called Sip (S from the Schrödinger evolution of the wave function, i for independent, p for particle ontology) in [AGTZ 2011]. Here we would call $x_{random}^{Schrodinger}$. Because there is no connection whatsoever between two configurations at different times, records of the past are most likely to be false. [AGTZ 2011] also describe a MW theory in which the PO is represented by a three-dimensional matter field $m(x,t)$, while the wave function evolves according to Schrödinger’s equation. This theory has been dubbed Sm (S for the Schrödinger equation and m for the matter density function), while here we would call it $m_{deterministic}^{GRW}$. In this theory, we have different worlds superimposed one onto another and reciprocally transparent.

In addition to the theory already described, we can imagine a variety of other theories, like table 1 below is able to show, mixing up the various types of PO and the various evolution equations. Stochastic mechanics (SM) is a theory of particles that move stochastically, while the evolution of the wave function is deterministic, given by the usual Schrödinger equation [Nelson 1985], [Goldstein 1987]. SM, dubbed Sp’ in [AGTZ 2008], in our notation will be $x_{random}^{Schrodinger}$. Another example involving stochastically evolving PO of particles with a deterministically evolving wave function

primitive ontology of wave functions (namely fields, i.e. extended objects) there will not be any particles in this sense, hence the quotes.

is provided by a Bell-type quantum field theory (BTQFT or Sp'' in [AGTZ 2011]) in which, despite the name, the PO is given by particles evolving indeterministically to allow for creation and annihilation [Bell 1987],[DGTZ 2004, 2005]. This can be dubbed $x_{random}^{Schrodinger}$. Another possibility is a stochastic particle theory called GRWp in the old nomenclature and x_{random}^{GRW} in the new one. In this theory, the motion of the particles is governed by the guiding equation but here the wave function obeys a GRW-like evolution in which the collapses occur exactly as in usual GRW theories except that, once the time and label for the collapse has been chosen, the collapse is centered at the actual position of the particle with the chosen label [BH 1993].

Theory (new nomenclature)	Primitive Ontology	Theory (old nomenclature)
$x_{deterministic}^{Schrodinger}$	Particles	BM (Sp)
$x_{random}^{Schrodinger}$	Particles	BMW (Sip)
$x_{random}'^{Schrodinger}$	Particles	SM (Sp')
$x_{random}''^{Schrodinger}$	Particles	BTQFT (Sp'')
x_{random}^{GRW}	Particles	GRWp
$\phi_{deterministic}^{Schrodinger}$	Fields	BQFT (S ϕ)
$f_{random}^{Schrodinger}$	Flashes	Sf
f_{random}^{GRW}	Flashes	GTWf
m_{random}^{GRW}	Matter field	GRWm

Table 1: The various quantum theories in the new notation that puts emphasis on the PO rather than on the wave function evolution.

Another theory, dubbed Bohmian quantum field theory (in [AGTZ 2011] called thus BQFT of S ϕ , where ϕ stands for a generic field ontology), involves a PO of fields, evolving deterministically [Bohm 1952], [SW 2006], with a Schrödinger evolving wave function. Thus, in the new nomenclature we would call it $\phi_{deterministic}^{Schrodinger}$. Concerning theories with flashes, these are inevitably stochastic, and GRWf or better $f_{random}'^{GRW}$, in which the flashes track the collapses of the wave function, is the prototype. There are also theories with flashes in which the wave function never collapses. For instance $f_{random}^{Schrodinger}$ (Sf, in the old nomenclature [AGTZ 2011]) which has a Schrödinger evolving wave function.

10. The Meaning of the Wave Function

What is the wave function if it does not represent a material object? There are different approaches in the literature. First, the wave function has been taken to be a property of

the particles⁹. Another proposal is that the wave function is just a useful mathematical tool [Monton 2006]. In contrast, the proponents of the PO approach argue that the wave function is best seen as a nomological entity. In other words, the wave function is more suitable to represent a law of nature than a physical object [DGZ 1997], [GT 2000], [GZ 2013]¹⁰. The idea is that the wave function is like the Hamiltonian in classical mechanics is the generator of motion.

Several objections have been raised against this view ([BW 2005], [Belot 2012]). First, since the PO represents what physical objects are made of while the wave function does not, either one denies the existence of the wave function or has to admit that something is more real than something else is. However, saying that the wave function is real but not physical does not imply there are different degrees of reality: in fact, they might be two kinds of substances, or entities. After all, the very same objections could be raised (but they are not) to a Platonist in the philosophy of mathematics, a dualist in the philosophy of mind, and a realist with respect to laws in ethics or in philosophy of science. Other objections focus on the disanalogies between the wave function and the general conception of laws. For instance, it is argued that the wave function cannot be regarded as a law because it interacts with the particles and thus seems to be more alike matter than laws. One could respond saying that the wave function is similar to the potential in classical mechanics in this respect: the potential interacts with the particles but no one considers it real. Also, it has been argued that the wave function evolves in time, while laws are static. In this case, one could just not be bothered by it [Smolin 2013]. In any case, since the idea that laws of nature are static is a classical intuition, one could maintain that instead of trying to force our classical intuitions onto quantum mechanics, we should realize that quantum mechanics is telling us something new about laws of nature [Callender forthcoming]. Be that as it may, one could notice that there is evidence suggesting that in a future quantum cosmology the wave function would be static [GT 2000], eliminating the problem. Another objection is that the wave function is contingent, in the sense that varies with the subsystem, and in contrast laws are universal. A last complaint could be that the wave function is controllable: we can prepare physical systems in the state that we want. If so, it is difficult to regard the wave function as a law, since we do not seem to have control over them. These last two objections can be taken care of remembering that the wave function we can have control and that changes from system to system is the wave function of the system (the conditional or effective wave function [GZ 2013]), while the one that should be intended as nomological is the wave function of the universe (which is universal and we cannot control).

11. Bell's Alternatives

⁹ See e.g. [Monton 2006] for a proposal, [Belot 2012] for a criticism, and [ELHD 2014] for a defense.

¹⁰ [Callender forthcoming] has recently motivated the view in the Humean framework of laws of nature.

In some of the quantum theories seen in Section 9, namely the ones with a PO of particles, the PO is independent from the wave function. In contrast, in the theories with a matter density or PO of flashes, the wave function appears in the definition of the PO. This is the reason why, in theories like Bohmian mechanics, the state of the system is given by the couple (x, ψ) . Instead, in theories like GRW the state seems to be given by the wave function alone (even if upon a closer look one would need to specify also a rule to define the matter density or the distribution of the flashes). Thus, while we were used to distinguish between the different solutions of the measurement problem in terms of Bell's alternatives, namely either the wave function is not complete or it does not evolve according to the Schrödinger equation, we now see another possible characterization. On the one hand, we have the theories in which the PO is independent on the wave function; on the other hand, we have theories in which the PO is defined in terms of it. Accordingly, one could label a theory a 'Bohmian' solution of the measurement problem if the wave function and the PO are independent. Instead, we can say that a 'GRW' strategy to solve the measurement problem is the one in which the PO depends on the wave function.

12. The Wave Function and Symmetry Properties

As we have seen, there is an important connection between the PO of a theory and its symmetry properties. In fact, it turns out that if one takes the wave function as representing the PO of a quantum theory, then it does not possess any symmetry property. For instance, in order for the evolution to be Galilei invariant, one would need the wave function to transform in a particular way through the multiplication of a suitable exponential. However, if one regards the wave function as a primitive variable, it seems natural to consider it as a scalar field. As such, it would transform in a very different way, hence making the theory non-Galilei invariant. In contrast, if one assumes that the wave function is not primitive variable, then it will be possible to consider the wave function as a ray or direction in Hilbert space. In this way, the theory will then gain back its symmetries, provided that the PO is chosen adequately¹¹. A proponent of the wave function ontology could bite the bullet and insist that quantum theory is, contrarily to what is commonly believed, not Galilei invariant, but this is implausible since it can be shown it will provide some wrong results in the classical limit (see [Allori 2007]).

In addition, it is important to stress that the notion of PO is helpful in building new theories. For example, because of the connection between the PO and symmetry properties of the theory, choosing one PO instead of another might make it more or less difficult to build a relativistic invariant quantum theory. Recently [Tumulka 2006] has shown that the GRW theory with a flashes PO can be modified so that it becomes a relativistic quantum theory. Similar results have been obtained also by [Dowker and

¹¹ For more on this, see [Allori ms].

Henson 2002] for a relativistic collapse theory on the lattice with a PO of lattice locations (see also [Dowker and Herbauts 2004], [Dowker and Herbauts 2006]). Other proposals for a relativistic quantum theory have been put forward. In a relativistic version of BM [DMGZ 1998], there is an additional physical object that is fundamental, that is the foliation. Such a foliation divides space-time into space-like hypersurfaces, defines absolute simultaneity and temporal ordering of space-like separated points. If we consider this foliation being part of the PO of this theory then we are exactly in the same scheme as above and one can also analyze the hypothesis of the foliation evolving itself in time.

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