Scientific Realism without the Wave-Function: An Example of Naturalized Quantum Metaphysics

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Abstract

Scientific realism is the view that our best scientific theories can be regarded as (approximately) true. This is connected with the view that science, physics in particular, and metaphysics could (and should) inform one another: on the one hand, science tells us what the world is like, and on the other hand, metaphysical principles allow us to select between the various possible theories which are underdetermined by the data. Nonetheless, quantum mechanics has always been regarded as, at best, puzzling, if not contradictory. As such, it has been considered for a long time at odds with scientific realism, and thus a naturalized quantum metaphysics was deemed impossible. Luckily, now we have many quantum theories compatible with a realist interpretation. However, scientific realists assumed that the wave-function, regarded as the principal ingredient of quantum theories, had to represent a physical entity, and because of this they struggled with quantum superpositions. In this paper I discuss a particular approach which makes quantum mechanics compatible with scientific realism without doing that. In this approach, the wave-function does not represent matter which is instead represented by some spatio-temporal entity dubbed the primitive ontology: point-particles, continuous matter fields, space-time events. I argue how within this framework one develops a distinctive theory-construction schema, which allows to perform a more informed theory evaluation by analyzing the various ingredients of the approach and their inter-relations.

1. Introduction

Can we describe what the world is like through a fundamental physical theory? In the answer to this question lies the historic disagreement between scientific realists and antirealists. According to the antirealist, we should be content with physics to be, for example, just empirically adequate. In contrast, the realist believes that physics informs us about metaphysics. Quantum mechanics has always been taken to be devastating for the realist program, being so full of contradictions and mysteries. This situation started changing after the 1950s, when several realist quantum theories have been proposed. However, until recently, scientific realists were convinced that in order to make quantum mechanics amenable to a realist interpretation, one would have to give a material interpretation of the fundamental mathematical object of the theory, namely the wave-function. In this paper, I explore an alternative realist proposal, dubbed the primitive ontology (PO) approach, which instead is not committed to this.[1] In this paper I show how the PO approach provides a distinctive account of theory construction in which the PO is chosen first, and then the rest of the theory is built around it to ensure empirical adequacy. Since many such theories are produced in this way, which cannot be ruled out by empirical means, I argue that coherence and parsimony considerations together with general reflections on the supervenience relation (or lack of thereof) between the PO and the wave-function, as well as on the type of scientific realism that this approach suggests, will allow to make a more informed decision about which theories are the best candidates for the scientific realist.

The following is the outline of the paper. In the next section, I present the PO approach for classical theories and then I extend it to the quantum domain. I contrast it with wave-function realism, the view that the wave-function is a material field, and I argue that the source of the tension between quantum mechanics and scientific realism is the idea of considering the wave-function as representing physical objects. In Section 3, I outline the general theory-construction schema for the PO approach, and in Section 4 I present some possible empirically adequate quantum theories in which the wave-function is not physical. These theories are obtained varying the type of PO (particles, fields, or spatio-temporal events, dubbed flashes), its evolution, and the evolution of the wave-function. In Section 5, I move to the meaning of the wave-function in these theories, which is taken to have a nomological character. These observations lead into Section 6, which discusses more in detail the type of realism this approach suggests, where one is realist about the PO but not about the wave-function. I continue in Section 7 noting how the theories presented earlier could be better classified in terms of the PO being independent or dependent of the wave-function. In Section 8 I discuss how this, among others, can be a consideration in theory selection.

2. Theory Architecture

The PO approach, like any realist framework, emphasizes that any theory should specify its scientific image:[2] what the world is according to the theory. Since theories are formulated mathematically, this implies the specification of the mathematical entities representing the physical ones. However, differently from other views, the emphasis is that scientific realism is better served when this is done at the very beginning of theory construction. That is, when the scientist proposing the theory has already a metaphysical hypothesis in mind, so that the correspondence rule is there from the

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[1] This proposal has been introduced in particular Dürr, Goldstein and Zanghí (1992, 1995, 1997), Goldstein (2008), and developed in Allori, Goldstein, Tumulka and Zanghí (2008, 2011, 2014), Allori (2013a, 2013b).
[2] Sellars (1962).

beginning. For instance, Newton assumed the world is made of particles. Then, he put the theory in mathematical form using the mathematical object that naturally corresponds to his metaphysical hypothesis, namely points in three-dimensional space.[3] The other variables in the equations are interpreted accordingly: some represents matter, and some represent its properties. For instance $G\frac{mM}{r^2}+qE(r)=m\frac{d^2r}{dt^2}$ represents the temporal evolution of a material entity, namely a point-particle with mass m and charge q, whose trajectory in space-time is given by the solution $r(t)$ of this equation. In this way, some mathematical objects in the theory are privileged over the others since they capture the fundamental nature of reality. These variables are the *primitive ontology*, PO, of the theory. Thus, theories are born with a hierarchical structure, determined by the role the various variables play in the theory. On the foundation there is the primitive variable, which captures the metaphysical hypothesis. Then we have many other variables: some are constants, like G; some others may be taken as describing properties of matter, like m or q. These variables are suitably 'dressing up' the fundamental entities so that the theory accurately accounts for the phenomena. None of these variables represents matter: table and chairs are not made of charges, say, they are made of particles *with* charges.[4] What about other variables, like E above? Traditionally, they are taken to represent electromagnetic fields, and accordingly they have been dubbed 'local beables'.[5] However, in this account they do not represent matter: since they are needed to make the theoretical particle trajectories empirically adequate, they are best regarded as non-primitive variables.[6]

As a result of taking particles as its PO, classical mechanics is arguably able to account for observed phenomena. As long as we can neglect quantum effects, macroscopic bodies and their properties can arguably be accounted for in terms of the motion of point-like particles moving in three-dimensional space using the familiar notions of reduction and compositionality. There are two ingredients for this explanatory schema to be satisfactory: (1) the PO is *microscopic*; (2) the PO is in *space-time*. The first requirement ensures that the objects in the PO are the building blocks of

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[3] In contrast, for instance vector or scalar-valued functions from three-dimensional space to three-dimensional space would naturally represent various types of fields.

[4] One may think instead that particles are bundle of properties like for instance position, mass and charge without any hierarchical structure. This would not affect the arguments in this paper aside from defining particles differently. However, it is argued in Allori (manuscript) that the proponent of the PO approach should not endorse this view.

[5] This terminology has been introduced by Bell (1987). They are mathematically specified by functions on three-dimensional space ('local'), as opposed to in an higher-dimensional space ('nonlocal'). The 'beable' part of the name comes in opposition with 'observable': they may represent something which exists rather than merely what is observed in an experiment.

[6] See Allori (2015) for an elaboration on the possible choices of the PO of classical electrodynamics and its consequences.

everything else: particles clump together to form bigger objects, which behave independently on their initial composition.[7] This hierarchy of objects straightforwardly allows the explanation of the macroscopic properties in term of the microscopic constituents.[8] This is where the second requirement comes in: this schema works if the building blocks live in the same space as the macroscopic entities, namely three-dimensional space.[9]

If the PO represent matter, what about the other variables in the theory? In a very important sense, a theory has to give us an image of reality. In this approach, this is done through the spatio-temporal trajectories of the PO. They are like the output generated by a computer program simulating a system[10], while the other variables serve as *means* for generating this output: they are internal variables of the program, needed for the computation. Given this role, they may be dubbed nomological variables: they appear in the laws of nature which govern the behavior of matter. Be that as it may, setting aside for the moment the status of the non-primitive variables (see Section 5), let us see how to extend this framework to the quantum domain.

In contrast with classical theories, it was widely claimed that quantum mechanics is incompatible with scientific realism. The measurement problem, or the problem of the Schrödinger cat, played a crucial role in this, and can be summarized as follows. Alssume the fundamental object of quantum mechanics, the wave-function ψ, is physically real, and assume it evolves in time as described by the solutions of the Schrödinger equation $\psi = \psi(t)$. As a mathematical fact, sums of solutions are also solutions[11], which therefore describe possible states of affairs of the system. If the description of matter provided by the wave-function is complete, then these 'superpositions' may represent a cat which is dead and alive (i.e. non-dead) at the same time, or a particle being here and there (i.e., not-here) at the same time. Thus, in the

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[7] For instance, protons, neutrons and electrons bind together to form atoms, and they behave according to the laws of chemistry (which could not care less of the atomic composition); then atoms bind together to form more complicated molecules that obey the laws of biology (which could not care less of the molecules chemical composition), and so on.

[8] However, notice that theories with macroscopic fundamental entities have been put forward. For instance, Allori, Goldstein, Tumulka and Zanghí (2008) propose that Bohr's quantum theory could be seen as an example such theories, where pointer positions, which reveal the experimental results, are fundamental. Nonetheless, as these authors point out, aside from being intrinsically vague (what counts as a macroscopic object?) the explanatory schema to recover the manifest image from the scientific image would fail to apply because in this theory microscopic entities such as atoms and molecules are 'made of' macroscopic one, namely pointer positions.

[9] If the fundamental building blocks of nature live in a different space then there is an additional step to be made, namely to explain how we think we live in three-dimensional space while we actually do not (see Section 5).

[10] Allori, Goldstein, Tumulka and Zanghí (2008).

[11] This is a direct consequence of the fact that the Schrödinger equation is an equation for a wave, and waves can superimpose (to create interference and diffraction patterns).

1930s this contradiction was taken to show that quantum mechanics could merely have an instrumental value. However, it was realized in the 1950s that this instead only shows that one of the assumptions below is mistaken:[12]

1. The wave-function completely describe every physical system;
2. The wave-function evolves according to Schrödinger's equation;
3. Macroscopic objects have non-contradictory properties.

At least three theories have been proposed to solve this problem: the pilot-wave theory, the spontaneous collapse theory, and the many-worlds theory. The pilot-wave theory[13] is taken to reject the first premise above in that it adds particles to the description of the wave-function. The theory has therefore another equation describing the motion of particles in terms of the wave-function.[14] The spontaneous localization theory [15] is taken to reject the second assumption: here the wave-function evolves according to the Schrödinger equation until a random time, at which it undergoes an instantaneous localization in a random point.[16] The many-worlds theory[17] is taken to reject the third premise, since it accepts that physical objects may possess contradictory properties. That is, the two terms of the superposition that describe an alive cat and a dead cat both exist but they interact so little that they can be interpreted as living distinct 'worlds' occupying the same region of space-time.'

This is the traditional story: the problem of quantum mechanics is the presence of macroscopic superpositions. According to the proponents of the PO approach, instead, *the problem lies in the assumption that the wave-function represents physical objects*. This is an implicit and seemingly undeniable assumption: all the theories just seen, as stated, take the wave-function as representing matter. That is, it was assumed that the natural way of rescuing scientific realism in the quantum domain was to commit to some form of wave-function realism. Notice that one is tempted to seriously consider the wave-function as representing a physical field only in a theory like quantum mechanics, in which there is no starting metaphysical assumption. Quantum mechanics as developed

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[12] Bell (1987), Maudlin (1995).

[13] This theory is also called de Broglie-Bohm theory or Bohmian mechanics, from the names of the early proponents (de Broglie 1927, Bohm 1952). See also Bell (1987), Dürr, Goldstein and Zanghí (1992).

[14]In this way, the cat is either dead or alive: she is alive when her particles are under the living cat wave, and she is dead when her particles are under the dead cat wave. Notice that there are other possible particle configurations that do not correspond to either a dead cat or a live cat, which are however dynamically unlikely.

[15] This theory also goes under the names spontaneous collapse theory, and GRW theory, from the name of those who proposed it (Girardi, Rimini and Weber 1986).

[16] The rate of localization of the wave-function is proportional to the size of the object, hence macroscopic objects, like cats, very quickly collapse either into the state that describe a dead cat or into the one describing the cat who's still alive.

[17] Sometimes the theory is dubbed Everettian quantum mechanics, from the name of its proponent (Everett 1957). See also de Witt (1970), Wallace (2002).

by Heisenberg, Born and Jordan in the 1920s merely provided a formalism. They did not care of providing an interpretation of it given their antirealist inclinations. In the years that followed, scientific realists, when facing the measurement problem, had to interpret this formalism *post hoc*, and it was natural for them to think of the wave-function as providing (at least part of) the correspondence between physics and metaphysics. In contrast, the proponent of the PO approach thinks that this is an unfortunate consequence of historical contingencies: the wave-function is not the right kind of mathematical object that one would have naturally considered as representing a metaphysical assumption. If so, one should always deny the first premise, namely that the wave-function completely describes physical systems, not because it is incomplete, but because it is not physical. In this sense, something in space-time representing matter is always needed. This goes back to the 1920s, when Lorentz, de Broglie, Heisenberg and Einstein expressed perplexities about considering the wave-function as a physical field.[18] However these worries have been long forgotten, receiving new attention only recently.[19] One problem, dubbed the *configuration space problem*, is that the link between the scientific and the manifest image provided by the wave-function is not sufficiently explanatory. In fact, the wave-function $\psi = \psi(r_1, \dots, r_N)$ is a field that lives in configuration space:[20] the space of possible particles configurations $q = (r_1, \dots, r_N)$. The dimension of such space is $M = 3N$. If the wave-function is a material field, then physical space would be configuration space. If so, one would have to explain why *we think* we live in a three-dimensional world instead, and it is controversial whether this can be successfully done.[21] In any case, the explanatory schema developed in classical theories to derive the macroscopic properties in terms of the microscopic constituents has to be dropped in this framework, and a new one needs to be developed.[22] Moreover, it is difficult to see how within wave-function realism theories can have symmetry properties.[23] For instance, quantum mechanics turns out not Galieli invariant: the wave-function is a scalar field in configuration space and as such will remain the same under

[18] See Bacciagaluppi e Valentini (2009) for a very interesting discussion of the various positions on this issue and others during the 1927 Solvay Conference.

[19] See Albert and Ney (2013), and references therein.

[20] See Albert (1996, 2013, 2015), Lewis (2003, 2004, 2006, 2013), Ney (2012, 2013, 2015, 2017) and North (2013).

[21] One would need to add a correspondence rule between configuration space and three-dimensional space (see Albert 1996). Whether the proposed maps are successful is up for debate (see Monton 2002, 2006, Allori 2013a, 2013b).

[22] See Albert (2015) and Ney (2017) for two different proposals on how this may be accomplished. However, it seems there is no need for re-thinking such schema, given that, as we will mention in Section 3, this is still available to the PO approach.

[23] In contrast with the PO approach (see Section 3).

a Galilean transformation, while invariance would require a more complicated transformation.[24]

3. Quantum Theory Construction Kit

Because of the reasons discussed in the previous section, the proponents of the PO account reject the assumption that the wave-function represents matter. Consequently, the theories proposed as responses to the measurement problem are regarded as satisfactory only if they all postulate something in three-dimensional space to describe material objects. The role of the wave-function is, similarly to the one of electromagnetic fields in classical electrodynamics, to generate the space-time histories of the PO. The pilot-wave theory can be naturally understood as a theory with a particle PO. However, the situation is trickier in the spontaneous localization theory and in many-worlds: one can add different, more or less natural, PO for these theories, as we will see in Section 4. In fact, the PO approach provides us with a set of rules for generating quantum theories:

1. Make a metaphysical assumption and select a corresponding spatio-temporal PO, which therefore has an ontological role;
2. Select an evolution law for the PO, which is implemented in terms of some appropriate mathematical objects among which the wave-function that in virtue of this assume a nomological role;
3. Select a law of evolution for this/these object/s.

A variety of such theories have been proposed and analyzed.[25] However, not all possible theories are good ones. A first constraint is empirical adequacy: the manifest image has to be successfully recovered. Quantum mechanics is empirically adequate, so

[24] There are other ways to think of the wave-function as material but avoiding some of these problems. Noticeably, a new formulation of the pilot-wave theory has been proposed (Norsen 2010) in which to each particle is associated a conditional wave-function (a function ψ defined by the wave-function of the universe Ψ once the positions of all the other particles in the universe $Y(t)$ are fixed: $\psi_t(x) := \Psi(x, Y(t))$). However, to recover the correct trajectories one needs to add infinitely many fields, which makes the theory hardly satisfactory. Alternatively (Forrest 1988, Hubert and Romano 2018), one can think of the wave-function as a 'poly-wave' on three-dimensional space, a generalization of an ordinary classical field (as a classical field specifies a definite field value for each location of three-dimensional space, the multi-field, given an N-particle system, specifies a value for the N-tuple of points in three-dimensional space). However, this approach suffers from the *communication problem* (Belot 2012, Solè 2013 and Suárez 2015): how does the wave-function communicate to three-dimensional space in order to fix each of the fields and the positions of particles? Since the communication is one-way, from the wave-function to the particles and not the other way around, this interaction cannot be understood physically (however, see Hubert and Romano 2018 for a reply). Perhaps more importantly, also within this framework the theory loses important symmetry properties given that the multi-field transforms under Galilean boosts differently from a classical field (Belot 2012).

[25] See Allori, Goldstein, Tumulka and Zanghí (2008, 2011, and 2014) for details.

all it takes is that the theory under consideration is empirically equivalent to quantum mechanics. One can distinguish between exact and effective empirical equivalence. Two theories are *exactly* empirically equivalent when there is no possible experiment that can in principle distinguish between the two. Theories are instead *effectively* empirically equivalent when they cannot be currently experimentally distinguished in practice.

Before discussing some of these theories, let me briefly explain how symmetries are implemented in this framework. Because the various solutions to the measurement problem are ultimately not about the wave-function but about histories of a PO in space-time, the law of evolution of the wave-function should no longer be regarded as playing a central role in determining the symmetries of the theory. Indeed, they are determined by the PO, not by the wave-function. Roughly put, to say that a theory has a given symmetry is to say that the possible histories of the PO (those that are allowed by the theory), when transformed according to the symmetry, will again be possible histories for the theory.[26] That means that the symmetries transform empirically adequate histories into other empirically adequate histories.[27] Changing PO could (and probably will) change the symmetry properties of the theory. This is particularly relevant in the context of developing relativistic invariant theories: without the PO one focuses on the relativistic invariance of the wave-function, while in this framework one should look at a relativistic invariant evolution for the PO.[28]

4. Primitive Ontology

Here are some examples of how different POs can be combined with different evolutions, and different nomological variables to construct empirically adequate

[26] Allori, Goldstein, Tumulka and Zanghí (2008).

[27] Notice that the entities in the theory which do not represent matter, such as the wave-function in quantum mechanics, can transform as needed to preserve the symmetry. There could be different ways of producing the same trajectories, for example using two wave-functions that differ by a phase factor. Or one can generate the same trajectories by either a Schrödinger-evolving wave-function and static operators (as in the Schrödinger picture) or a static wave-function and evolving operators (as in the Heisenberg picture). If one assumes that the wave-function does not represent matter, and wants to keep the symmetry, then one can allow the wave-function to transform as to allow this. See Allori (2018) for an argument based on Galilean symmetry that the wave-function is best seen as a projective ray in Hilbert space rather than a physical field.

[28] For instance, in reference to the theories that we will discuss later, GRWf has been modified to make it relativistic invariant in this sense (Tumulka 2006), a relativistic extension of Sm has been proposed in Allori, Goldstein, Tumulka and Zanghí (2011), and one for GRWm in Bedingham, Dürr, Ghirardi, Goldstein, Tumulka and Zanghí (2014).

quantum theories according to the theory construction kit this approach provides. I consider here only three types of PO: particles, matter density fields, and flashes.[29]

Particles: If matter is made of point-particles, the following is a list of some empirically adequate theories.

A. The pilot-wave theory: This theory can be naturally read as a theory of particles moving in three dimensions according to a suitable guidance equation that involves a Schrödinger-evolving wave-function.
B. Sip: In this theory the PO is given by instantaneous randomly distributed configurations without any temporal correlation among them, whose probability distribution is governed by a Schrödinger-evolving wave-function.[30]
C. GRWp3: This theory combines a particle PO, evolving according to the same guidance equation as in the pilot-wave theory, and a wave-function that is stochastically evolving as in the original GRW theory. However, here each localization point is the actual position of the particle at the localization time `displaced' at random.[31]
D. GRWp6: Here the particles evolve according to the same guidance equation as in the pilot-wave theory between the localizations of the wave-function, like in GRWp3. However, at the localization center all the particles jump at random.[32]

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[29] Other choices, such as strings, are possible, but they are not considered here. As already noted, the reason why we did not have so many theories in the pre-quantum era is that, in contrast with what happened in quantum mechanics, in classical mechanics it was clear from the very beginning what the metaphysical hypothesis was. Newton started from the hypothesis that the world is made of particles and, accordingly, their law of evolution was selected as the simplest among the (infinite) alternatives. This seems compatible with the fact that Lagrangian and Hamiltonian formulations of classical mechanics have been originally designed (and are usually regarded by physicists) as calculation tools and not as providing insight into the ontology of classical mechanics: if one has already a perfectly sensible ontology given by particles in three-dimensional space, why would one feel the need to reify the generalized coordinates and think of phase space or configuration space as physical?

[30] This theory was proposed by Bell (1987) and later discussed in Allori, Goldstein, Tumulka and Zanghí (2008). The 'S' in the name comes from the Schrödinger evolution of the wave-function, 'i' stands for the fact that the particles are independent, and 'p' denotes the PO of particles. The logic is similar for the names of the other theories.

[31] This theory was proposed by Bedingham (2011) and later analyzed by Allori, Goldstein, Tumulka and Zanghí (2014).

[32] Simpler theories with a particle PO and a GRW-like evolution for the wave-function turn out not empirically adequate. The simplest attempt, GRWp1, would be a theory in which the motion of particles is the same as in the pilot-wave theory and wave-function the same as the original GRW theory. The second simplest attempts, GRWp2, would allow the center the localization of the wave-function to be the actual particle position. Then GRWp4 would make the particles move according to how the average position in orthodox quantum mechanics would prescribe, instead than according to the guidance equation of the pilot-wave theory. Finally, in GRWp5 the particles would move as in the pilot-wave theory between

E. MBM: In this theory the wave-function is completely absent. The particles evolve according to something similar to the pilot-wave's guidance equation, but instead of the wave-function we have a density matrix which evolves according to the Limblad equation.[33]

Matter Field: Alternatively, the world could be continuous. Thus, matter is represented by a scalar field m in three-dimensional space defined in terms of the wave-function.[34] Given this PO, here are some empirically adequate theories:

A. Sm: In this theory the matter density field evolves governed by a law which involves a Schrödinger evolving wave-function.[35]
B. GRWm: The matter density here evolves according to a law mediated by a stochastically evolving wave-function.[36]
C. Mm: In analogy with MBM, the matter density field evolution is implemented by a Limblad-evolving density matrix rather than a wave-function.[37]

Flashes: A particle theory usually provides space-time histories where configurations at different times are continuously connected. However, as shown in Sip, configurations may jump from one moment to the next without any connection. This suggests that matter could be thought as constituted by a set of spatiotemporal events, the 'flashes': $F = \{(X_1, T_1), \dots, (X_k, T_k), \dots\}$, k being a progressive natural number indicating the time

localizations; however at that time also the configuration of the particle in the localization point would jump. See Allori, Goldstein, Tumulka and Zanghí (2014) for more details about such theories.

[33] This theory is called 'master equation Bohmian mechanics,' hence 'MBM,' and has been proposed in Allori, Goldstein, Tumulka and Zanghí (2014). It is effectively empirically equivalent to the pilot-wave theory, and thus it is empirically adequate. More precisely, it is empirically equivalent to GRWm and GRWf, which we will describe later in this section.

[34] For completeness, it looks like this:
$m(x,t) = \sum_{i=1}^{N} m_i \int dq_1 \dots dq_N \delta^3(q_i - x) |\psi_t(q_1 \dots q_N, t)|^2$, where N is the number of 'particles,' and m_i their masses.

[35] Schrödinger tried to see whether an ontology based on the wave-function was possible. He assumed matter was represented by a three-dimensional matter field defined in terms of the wave-function (evolving according to the Schrödinger equation). This theory has thus been dubbed Sm in Allori, Goldstein, Tumulka and Zanghí (2008). However, this field inherited the same superpositions of the wave-function, and thus he dismissed this possibility.

[36] This theory has been proposed originally in Benatti, Ghirardi and Grassi (1995) and called "GRWm" in Allori, Goldstein, Tumulka and Zanghí (2008). This theory's predictions differ from the ones of orthodox quantum theory, but they are currently undetectable. Thus, the theory is empirically adequate, and can be proven to be empirically equivalent to MBM (Allori, Goldstein, Tumulka and Zanghí 2014).

[37] It can be proven that this theory is empirically equivalent to GRWm (and thus to MBM), see Allori, Goldstein, Tumulka and Zanghí (2014).

progression of the flashes.[38] Below is a list of possible empirically adequate 'flashy' theories:

A. Sf: The flash distribution is determined by the wave-function, like the localization point is determined by the stochastic evolution in the spontaneous localization theory. However, in Sf wave-function evolves according to Schrödinger's equation.[39]
B. GRWf: In this theory the wave-function evolves according to the GRW stochastic evolution and every flash corresponds to one of the spontaneous localizations of the wave-function.[40]
C. Mf: In analogy with MBM and Mm, Mf is a theory of flashes in which the rate of the flashes is not generated by the wave-function but by a Limblad density matrix. [41]

5. The Wave-function

As scientific realists we are interested in the metaphysics the above theories are giving us. However, if the PO of the theory constitutes the building blocks of matter, what is the wave-function? How is this approach compatible with scientific realism? Let us focus on the first question in this section, and move to the second one in the next. As briefly anticipated, the role of the wave-function, just like electromagnetic fields in classical electrodynamics or more generally the potential or the Hamiltonian in classical mechanics, is to help implementing the law governing the spatio-temporal trajectories of the PO. Hence, it is better understood as having a nomological character rather than representing matter: it is best regarded as (part of the) laws of nature.[42] This view fits particularly well with a Humean account of laws, according to which laws are axioms and theorems of our 'best system' of the world. Since the wave-function is part of the axioms, it can be naturally regarded as a Humean law.[43]

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[38] A note about all these theories: if the number N of 'particles' is large, as in the case of a macroscopic object, the number of flashes is large, too (if $\lambda = 10^{-15}\, s^{-1}$ and $N = 10^{23}$, we obtain a rate of 10^8 flashes/second). Therefore, for a reasonable choice of the parameters of the theory, a cubic centimeter of solid matter contains more than 10^8 flashes per second. That is to say, large numbers of flashes can form macroscopic shapes, such as tables and chairs. At almost every time, however, space is in fact empty, containing no flashes and thus no matter.

[39] See Allori, Goldstein, Tumulka and Zanghí (2008).

[40] This theory was first proposed by Bell (1987) and then adopted in Tumulka (2006). The predictions of this theory are in accordance with the one of GRWm (and thus with MBM and Mm). Therefore, the theory is effectively empirically adequate.

[41] This theory turns out to be empirically equivalent to MBM, Mm and GRWm, making the theory effectively empirically adequate, see Allori, Goldstein, Tumulka and Zanghí (2008).

[42] Dürr, Goldstein, Zanghí (1997), Goldstein and Teufel (2000), Goldstein and Zanghí (2013), Allori (2018).

[43] See Miller (2014), Esfeld (2014), Callender (2015) and Bhogal and Perry (2017). There are other ways in which someone could think of the wave-function, broadly speaking, as nomological. One can think of the wave-function as a property which expresses some non-material aspect of the particles (Monton 2013). Similarly, one can endorse a dispositional account where laws are understood in terms of dispositions,

Several objections have been raised against this view, the most compelling of which focuses on the disanalogies between the wave-function and the general conception of laws.[44] First, one may argue that since the wave-function interacts with the particles then it has to be material. However, classic potentials interact with particles as well but no one considers them as real. More challenging is the observation that the wave-function evolves in time, while laws are do not. In reply, one could notice that evidence suggests that in a future quantum cosmology the wave-function would be static, eliminating the problem.[45] However, if so, one would have to wait until such a theory will be developed to rightfully do metaphysics. Perhaps more convincingly, one could reply by noting that the Schrödinger evolution could be regarded as a constraint on a time-independent wave-function of the universe rather than an evolution equation.[46] Another objection is that the wave-function is contingent, since it varies with the subsystem, while laws are not.[47] However, the wave-function which is contingent is the wave-function of the system, and that can be therefore considered as a property of the system. Instead, the wave-function with nomological status is the wave-function of the universe, since it is the one for which the Schrödinger equation holds.[48] One may counter-reply insisting that the universal wave-function is also contingent in the sense that there could have been a physically distinct one. However, one could reply that there could have been other laws as well. Anyway, I think that the best reply to this, as well as the previous objection, is to maintain that we should not force at any cost classical intuitions onto quantum mechanics,[49] especially about laws of nature, and we should be open to modify our nomic concepts accordingly, if needed. This may be a surprising reaction, given that the PO supporters have always emphasized their preference to traditional frameworks. However, it is by allowing a looser notion of laws of nature as entities `guiding' the motion of the PO that one can still use the classical

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which in turn are described by the wave-function (Esfeld, Lazarovici, Hubert and Dürr 2014; Sàurez 2015). Arguably, since dispositions can be time dependent, here the temporality objection seems less compelling. Having said that, I think these proposals are not very promising in that they rely on the notion of properties which are notoriously a rough nut to crack. As Esfeld (2014) has pointed out, there are several severe problems in trying to spell out what fundamental properties are, both in the classical and the quantum domain.

[44] See most notably Brown and Wallace (2005), Belot (2012).

[45] Goldstein and Teufel (2000).

[46] Esfeld, Lazarovici, Hubert and Dürr (2014).

[47] A similar complaint is that the wave-function is controllable (we can prepare physical systems in the state that we want), while we have no control about what laws are.

[48] Goldstein and Zanghí (2013).

[49] Callender (2015).

explanatory framework to recover macroscopic properties in terms of the microscopic PO.[50]

6. Explanationist Realism

The existence of the theories presented in Section 4 shows that scientific realism is alive and well even in a quantum world, and even without considering the wave-function as physically real. However, one may worry that this cannot be correct: isn't scientific realism telling us that whatever the theory postulates, one should consider real? Luckily, there is already a variety of scientific realism, dubbed selective or restricted realism, which gives up on such a complete correspondence. In particular, as we will see in this section, there is one kind of selective realism which is well suited to accommodate the PO approach.

The main argument for realism, the no-miracle argument, states that the empirical success of a theory is evidence of its truth; otherwise this success would be a miracle. Nonetheless, the so-called pessimistic meta-induction argument aims to show that the empirical success of a theory is not a reliable indicator of its truth, given that past successful theories turned out to be false. One way to respond to this challenge is to restrict realism, and argue that one should not be realist about the whole theory, but about a restricted set of entities. If one can show that the entities that are retained in moving from one theory to the next are the ones that are responsible for the empirical success of the theory, the previous argument is blocked. One particular way of doing this is the so-called explanationist realism according to which one should be realist with respect to the *working posits* of the theory, the ones involved in explanations and predictions. If the working posits are preserved during theory change, one could argue that past theories were successful because they got the working posits right. At the same time, these theories are also false since they got something wrong too, namely the *presuppositional posits*. Thus, the realist is justified in believing in the physical reality of the working posits, without being committed to the existence of the presuppositional posits, which are somewhat 'idle' components of the theory.[51] The proponents of this

[50] There are other ways in which someone could think of the wave-function, broadly speaking, as nomological. One can think of the wave-function as a property which expresses some non-material aspect of the particles (Monton 2013). Similarly, one can endorse a dispositional account where laws are understood in terms of dispositions, which in turn are described by the wave-function (Esfeld, Lazarovici, Hubert and Dürr 2014; Sàurez 2015). Arguably, since dispositions can be time dependent, in this context the temporality objection seems less compelling. Having said that, I think these proposals are not very promising in that they rely on the notion of properties which are notoriously a rough nut to crack. As Esfeld (2014) has pointed out, there are several severe problems in trying to spell out what fundamental properties are, both in the classical and the quantum domain.

[51] See Kitcher (1993) and Psillos (1999). For a rediscovery of this approach and an application to effective quantum field theories see Williams (forthcoming).

view have argued for it in the framework of classical theories (e.g. Fresnel's theory of light). The case for explanationism is however fundamentally incomplete if one does not consider the theory change from classical to quantum mechanics. Interestingly, it bears striking similarities with the PO approach in that the theory predictions, being encoded in pointer positions, are determined by the PO, not by the wave-function. Similarly, the explanations of the phenomena are in terms of the PO, and only indirectly about the wave-function. That is, the PO reminds of the working posits and the wave-function reminds of a presuppositional posit. If so,[52] this type of realism finds a natural home to the wave-function as conceived by the primitivists, and moreover the PO approach provides a very nice framework for the explanationist to extent her view in the quantum domain.[53]

7. Dependent and Independent Primitive Ontologies

The theories presented in Section 4 are mutually exclusive and, being all empirically adequate, cannot be distinguished on the basis of empirical constraints. Thus, they need to be assessed using some *super-empirical* virtues, as discussed in Section 8. Interestingly, one of such considerations is distinctive of the PO approach, as I discuss in this section. Notice that the matter field m and the flashes F are functionals of the wave-function, in contrast with theories such as the pilot-wave theory in which PO and wave-function are independent. So, the construction kit presented in Section 3 could be spelled out more explicitly by underlying that the specification of the metaphysical assumption of the theory (the PO) may be in terms of some other mathematical object (the wave-function). In philosophical jargon, dependence is sometimes translated in terms of supervenience: Y supervenes on X if no two possible situations are indiscernible with respect to X while differing in Y.[54] The matter density and the distribution of the flashes supervene on the wave-function: there cannot be a difference in the matter density or in the distribution of the flashes without a difference in the

[52] See Allori (forthcoming).

[53] Perhaps more speculatively (see Esfeld 2014, Allori manuscript, and reference there in), one can observe some similarities between the PO approach and some form of structuralism, which is another way of restricting realism according to which what carries over in theory change is the mathematical structure of the theory. In this sense, the wave-function is part of such structure. One variety of structuralism, namely eliminativism, claims that the very notion of objects is worth dismissing (see French 2014 and references therein): there are no fundamental objects (as individuals), but only relations and purely relational structures. The PO approach is different in this respect, given that objects exists and are fundamentally made by the entities the PO represents. However, the wave-function in both approaches is not representing matter. Rather, it is better understood as "constituted by the laws" (French 2013).

[54] For instance, chemical properties supervene on physical properties insofar as any two possible situations that are physically indistinguishable are chemically indistinguishable.

wave-function. It has been argued[55] that, because of this dependence, there is no need of adding the matter density or the flashes to the description provided by the wave-function. However, by definition in the PO approach the wave-function does not represent matter and thus some other-spatiotemporal object in the theory should, and in these cases it is either the matter density or the flashes. The question remains however about what kind of dependence (or supervenience) is there between the PO and the wave-function, and whether that can be used in theory selection.

An important distinction is between logical (or conceptual) and natural (or nomic) supervenience. We have *logical* supervenience between X and Y when X entails or implicates Y, i.e. $Y = f(X)$. For instance, the description 'table' supervenes logically on the configuration of the particles composing the table. Instead there is *natural* supervenience between X and Y when Y is a function of X, i.e. $Y = f(X)$, and this function defines a law of nature. An example of natural supervenience is the relation between the pressure exerted by one mole of a gas and its volume and temperature: $p = f(T, V) = KT/V$, where K is a constant. The function f defines Boyle's law and expresses an empirical truth, in contrast with logical supervenience.[56] The distinction between logical and natural supervenience can be summarized as follows: Y logically supervenes on X when Y comes along for free once there is a certain X; Y naturally supervenes on X when one needs to specify a law-like relation to define Yin terms of X. Once the law is defined, X will automatically bring along the Y.

Is the dependence of the PO from the wave-function logical or natural? There is a sense in which one would want it to be natural: there are other logical possible definitions of the matter density in terms of the wave-function, but this one is the one that actually holds. The matter field is defined in that way as a matter of natural law, regardless of how many other possible definitions one could come up with. However, the fact that the PO is defined by a law of nature that involves the wave function specified by some function f as $PO = f(\psi)$, is puzzling: in these theories, there is a law of nature that defines the PO and a law of nature that defines its evolution, both of which involve the wave-function. Doesn't that mean that the wave-function is more primitive than the PO? Indeed, consider the natural dependence of the electric field from the charge density. This relation defines the field in terms of the charge density, but wouldn't we say that the charge density generates the field, which because of this turns out to be less primitive? This seems the exact opposite of what the primitivist needs. However, one could reverse the dialectic. That is, the dependence of PO and

[55] Lewis (2006).

[56] "It is empirically impossible that two distinct moles of gas could have the same temperature and volume, but different pressure [...] This supervenience is weaker than logical supervenience. It is logically possible that a mole of gas with a given temperature and volume might have a different pressure; imagine a world in which the gas constant K is larger or smaller, for example. Rather, it is just a fact about nature that there is this correlation" (Chalmers 1996).

wave-function expressed in terms of the function f may be taken to define what the wave-function is, rather than what the PO happens to be: $\psi = f^{-1}(PO)$. Notice that the matter field could have had many mathematical definitions, including some which do *not* involve the wave-function. Theories like that are not among the ones we have seen in Section 4, but they seem possible, and they would be theories in which the PO and the wave-function are independent.

Be that as it may, this dependence (or lack or thereof) suggests a novel distinction among the solutions of the measurement problem. Since in the PO approach this problem is taken to show the inadequacy of the wave-function as representing matter, its solutions will be different in how they specify some entity in three-dimensional space to play the role of matter. That is, different solutions are characterized by whether the PO is independent of the wave-function or it is not:

<u>Theories of type-1)</u> PO and ψ are independent: once the PO is specified, the wave-function is introduced independently to it to make the theory empirically adequate as specified. This is the case of particle theories.

<u>Theories of type-2)</u> PO and ψ are dependent: once the PO is specified, the wave-function is introduced so that there is a particular dependence between it and the PO: the PO appears to be defined in terms of the wave-function. This is the case of theories with flashes and matter density.

8. Theory Evaluation

As already mentioned, the dispute about which of the theories discussed in Section 4 is best will have to be settled based on something other than empirical adequacy. Here's a list of features that one could use during theory selection.

<u>Lack of Many-worlds Character:</u> Because of its linearity, in any theory with a Schrödinger-evolving wave-function there are superpositions. In the pilot-wave theory, this is not a problem: since configurations are continuously connected in time, it is not possible for the configuration to jump, in an instant, from the support of one term of the superposition to a macroscopically distinct one (that is, a dead cat will not become instantly alive). However, because of this, many other theories will show a many-worlds character.[57] For instance in Sip, since there is no connection between different configurations at different times, the configuration will likely visit distant regions at

[57] Note that the concept of a 'world' is just a practical matter, relevant to comparing the matter density function provided by the theory to our observations. However, this is not a problem: there is no need for a precise definition of 'world', just as we can get along without a precise definition of 'table'.

subsequent instances. That means, for instance, that if at time t there are dinosaurs, at time $t + dt$ they have disappeared. Therefore, many worlds exist, not at the same time but one after another. A similar many-world character is shared by Sm and Sf, as well as Mf and Mm, in which the superpositions of the wave-function are inherited by the flashes and the matter density field. By the linearity of the Schrödinger evolution, the flashes and the matter density form independent families of correlated flashes, or matter density, associated with the terms of the superposition, with no interaction between the families: the living cat and the dead cat do not interact with each other, as they correspond to alternative states of the cat. Thus, they can indeed be regarded as comprising many worlds, superimposed on a single space-time. Since the different worlds do not interact among themselves, they are, so to speak, reciprocally transparent. Notice that, since these worlds are undetectable, all other things being equal, none of these theories seems to be among the best alternatives.
Moreover, note that in the theories in which the wave-function localizes (like all GRW-type theories) these many-worlds exist, even if for a short moment.

Empirical Coherence: A theory is empirically incoherent when its truth undermines our empirical justification for believing it to be true.[58] Notice that Sip is empirically incoherent, given that it implies that our records of the past, including evidence to support the theory, may well be completely erroneous. In fact, its many-worlds character is so radical that it implies that our memories and records of the past are most likely to be false. Similar considerations lead to rule out also GRWp6: since all configurations jump at the same time when the wave-function gets localized, one could instantaneously move from one world in which there are dinosaurs to one in which there aren't any.

Simplicity: When considering ontology, particles are the simplest: they require just one parameter to be specified, their location in space. If so, then the pilot-wave theory stands out. It is not the only theory with a particle PO, but what is the point of complicating the theory with a non-linear evolving wave-function, as in GRWp3? Density matrices also seem unnecessarily complicated. Sip and GRWp6, as we just saw, are ruled out because they are empirically incoherent.

Symmetries: Arguably, the PO of continuous fields is less developed and thus requires more work. However, one can argue that theories like GRWm and Sm have relativistic extensions which do not require a foliation, contrarily to the pilot-wave theory, and thus they may be thought to be more compatible with relativity.[59] Among the two, Sm is

[58] Barrett (1999), Huggett and Wüthrich (2013).
[59] Dürr, Münch-Berndl, Goldstein and Zanghí (1998).

arguably better than GRWm, given that its wave-function evolution is simpler. However, they both have a many-worlds character. While one may suggest that the relativistic invariance of Sm might be taken to be an independent justification for many-worlds, there are theories, like GRWf, which have relativistic extensions without a foliation and without a many-worlds character as severe as the one of Sm. Flashes are a more exotic choice of PO, but they seem to be particularly well-suited for relativistic theories.[60] Among flashes theories, therefore, GRWf seems to give the best balance of mathematical simplicity and metaphysical sensibleness, since it does not possess a severe many-world character like the one of Sf, and it is not as mathematically complicated as Mf.

<u>Scientific Realism:</u> General considerations about realism may lead us back to particles. Indeed, they are more familiar: previous, well-developed, and well-known theories like classical mechanics had a PO of particles. In this respect, one could argue that a particle ontology would help the scientific realist responding to the pessimistic meta-induction argument.[61] In fact, if the particle PO is preserved in the classical-to-quantum theory change, and the particle PO is responsible for the empirical success of both theories, then one could defeat the pessimistic meta-induction and therefore be justified to be realist about the PO.

<u>Independent PO:</u> Finally, and perhaps more interestingly, notice that in theories denoted as type-1 in Section 7 in which the PO is independent of the wave-function, such as the pilot-wave theory or other particle theories, the theory architecture is straightforward: the PO evolves in time and as such represents the evolution of matter; the wave-function appears as a suitable ingredient in this evolution. It may be odd that the wave-function evolves in time, as we discussed in Section 5, but insisting that this is just a convenient representation of how the wave-function may generate the spatio-temporal motion of the PO may make it less so. In contrast, in type-2 theories in which the wave-function and the PO are dependent, the structure is more convoluted: the PO still represents matter but the role of the wave-function seems more difficult to accommodate since not only it appears in the definition of the PO but also defines its motion. One could argue that, because of this, independent POs should be preferred. This would lead directly to particle theories, but would leave the door open to yet-unexplored matter density theories which are defined independently of the wave-function.

[60] See Bell (1987) and Tumulka (2006).

[61] Allori (forthcoming).

Summing up the results of these proposed criteria, which by any means are not the only possible, matter density theories (at least the ones presented so far) do not seem to win in any categories. The battle arguably remains between the pilot-wave theory and GRWf. The former seems to be leading, given that it wins in the categories of simplicity, realism and independence but loses in symmetries, while the latter wins in symmetries but loses in simplicity, independence and realism. If anything, this explains why most proponents of the PO account prefer the pilot-wave theory over the alternatives.

Be that as it may, independently on theory evaluation criteria and considerations, if we follow the PO approach and we get the wave-function out of the ontological picture as a possible entity to represent matter, quantum mechanics becomes a theory which, with the discussed qualifications, is compatible with scientific realism given that none of these theories is contradictory or riddled with paradoxes.

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