Why Scientific Realists Should Reject the Second Dogma of Quantum Mechanics

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Abstract

The information-theoretic approach to quantum mechanics, proposed by Bub and Pitowsky, is a realist approach to quantum theory which rejects the "two dogmas" of quantum mechanics: in this theory measurement results are not analysed in terms of something more fundamental, and the quantum state does not represent physical entities. Bub and Pitowsky's approach has been criticized because their rejection of the first dogma relies on their argument that kinematic explanations are more satisfactory than dynamical ones. However, little attention has been given to the second dogma. If anything, some have discussed the difficulties the informational-theoretical interpretation faces in making sense of the quantum state as epistemic. The aim of this paper is twofold. First, I argue that a realist should reject the second dogma without relying on the alleged explanatory superiority of kinematical explanation over dynamical ones, thereby providing Bub and Pitowsky with a way to avoid the first set of objections to their view. Then I propose a functionalist account of the wavefunction as a non-material entity which does not fall prey of the objections to the epistemic account or the other non-material accounts such as the nomological view, and therefore I supply the proponents of the information-theoretical interpretation with a new tool to overcome the second set of criticisms.

Keywords: two dogmas of quantum mechanics, measurement problem, information-theoretic interpretation of quantum mechanics, primitive ontology, wavefunction realism, epistemic interpretations of the wavefunction, nomological interpretation of the wavefunction, pragmatic interpretation of the wavefunction, kinematic vs dynamical explanation, principle vs constructive theories, functionalism

1. Introduction

Bub and Pitowsky (2010) have proposed the so-called information-theoretic (IT) approach to quantum mechanics. It is a realist approach to quantum theory which rejects what Bub and Pitowsky call the 'two dogmas' of quantum mechanics. These dogmas are as follows: D1) measurement results should not be taken as unanalysable primitives; and D2) the wavefunction represents some physical reality. In contrast, in the IT approach measurements are not analysed in terms of something more fundamental, and the wavefunction does not represent physical entities. Bub and Pitowsky reject the first dogma arguing that their approach is purely kinematic, and that dynamical explanations (used to account for experimental outcomes) add no further insight. Their approach has been criticized by Brown and Timpson (2006) and by Timpson (2010), who argue that kinematic theories should not be a model for realist quantum theories. The second dogma is rejected as a consequence of the rejection of the first. Bub and Pitowsky assume that their rejection of the wavefunction as representing physical entities commits them to an epistemic view in which the wavefunction reflects is a reflection of our ignorance, and as such they have been criticized by some authors, such as Leifer (2014) and Gao (2017).

Little has been done to investigate whether it is possible to reject the second dogma without appealing to the alleged superiority of dynamical explanations, and whether one could think of the wavefunction as not representing matter without falling prey of the objections to the epistemic view (or the so-called nomological view). The aim of this paper is to explore such issues. Therefore, first I argue that Bub and Pitowsky, as well as scientific realists in general, should reject the second dogma to start with, *independently of whether they decide to accept or deny the first dogma.* This argument supports the IT account to motivate their view, but it also stands alone as an argument to reject the wavefunction as a material entity in general. Then, in connection with this, I propose a functional account of the wavefunction which avoids the objections of the alternative views. This can nicely fit in the IT interpretation by dissolving the objections against it which relies on the wavefunction being epistemic, but also can be helpful in answering general questions about the nature of the wavefunction.

Here's the scheme of the paper. In Section 2 I present the IT approach of Bub and Pitowsky. Then in Section 3 I discuss the distinction between dynamical and kinematical explanations, as well as the principle/constructive theory distinction, and how they were used by Bub and Pitwosky to motivate their view. In Section 4 conclude this paper of the paper by presenting the objections to the view connected with the explanatory superiority of kinematic theories. In Section 5 I move to the most prominent realist view which accepts dogma 2, namely wavefunction realism. Then in Section 6 I provide alternative reasons why a realist should reject the second dogma by introducing the primitive ontology approach. I connect the rejection of the first dogma to scientific realism in Section 7, showing how a realist may or may not consistently reject dogma 1.

Then I move to the second set of objections to the IT account based on the epistemic wavefunction. First, in Section 8 I review the objections to the ontic accounts, while in Section 9 I discuss the ones to the epistemic account. Finally in Section 10 I propose an account of how the wavefunction based on functionalism, and I argue that it is better than the alternatives. In the last section I summarize my conclusions.

2. The IT Account, The Two Dogmas, and the Measurement Problem

The IT approach to quantum theory is a realist interpretation of the quantum formalism according to which quantum mechanics is fundamentally about measurement outcomes, whose statistics are recovered by the constraints that Hilbert space structure imposes on the quantum dynamics, and in which the wavefunction has the role of describing an agent's preferences (or expectations or degrees of belief) about measurement outcomes. The approach comes at the end of two lines of research first developed independently and then together.[1]

There are different components to the view, the first of which is given by the CBH theorem (Clifton, Bub and Halvorson 2003), which offers an understanding of the quantum formalism in terms of simple physical principles,[2] which can be suitably translated into information-theoretic constraints on the probability of experimental outcomes. In light of this, Bub (2004, 2005) argued that quantum mechanics is about 'information', taken as primitive. In this way, there is a sense in which the CBH constraints make quantum mechanics a kinematic theory (see Section 3): experimental outcomes are fundamental, and the theory poses constraints on what these outcomes are supposed to be. Bub also argues that further dynamical explanations are not necessary and therefore quantum mechanics does not need any additional fundamental ontology, even if is possible to provide one.[3]

The second ingredient of the IT account is given by Pitowsky's idea that quantum mechanics provides us with a new probability theory (Pitowsky 2005). Like classical probability theory consists of a space of possible events and a measure over it, here the space of possible events is the lattice of the closed subspaces of Hilbert space. Thus, the event space defines the possible experiment outcomes (which are the fundamental elements of the theory) and the wavefunction encodes the experimenter's beliefs.

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[1] See, respectively Clifton, Bub and Halvorson (2003); Bub (2004, 2005, 2007); Pitowsky (2006); Bub and Pitowsky (2010).

[2] Here they are: the impossibility of superluminal information transfer between two physical systems by performing measurements on one of them, the impossibility of broadcasting the information contained in an unknown physical state, and the impossibility of unconditionally secure bit commitment.

[3] He writes: "you can, if you like, tell a story along Bohmian, or similar, lines […] but, given the information-theoretic constraints, such a story can, in principle, have no excess empirical content over quantum mechanics" (Bub 2005, p. 542).

According to Pitowsky, the advantage of this approach is that it can 'dissolve' the measurement problem. First he argues that there are two measurement problems:

- *The "big" measurement problem:* the problem of providing a dynamical explanation of why particular experiments have the outcomes they do; and
- *The "small" measurement problem*: the problem of explaining how an effectively classical probability space of macroscopic measurement outcomes arises from a quantum measurement process.

And then he argues that the 'big' one, which is what is usually called the measurement problem, is actually a pseudo-problem, given that in his approach one cannot talk about one single experimental results, just only the statistics.

One immediate reaction to this interpretation is that it is not truly realist, and therefore it is not in direct competition with the 'traditional' realist quantum theory such as the pilot-wave theory (Bohm 1952), the spontaneous collapse theory (Ghirardi, Rimini, Weber 1986) and Everettian mechanics (Everett 1957). However, Bub and Pitowsky argue that there is a robust sense in which their intent is realist, and that people who deny this implicitly accepts on two 'dogmas', which they think have little justification:

D1: measurement should never be included as an unanalyzable primitive in a fundamental physical theory, and

D2: the wavefunction represents physical reality.

Bub and Pitowsky claim that it is usually thought that realist have to accept them to solve the measurement problem. However, they say, this is true only if they have in mind the 'big' problem, but in order to be realist one merely needs to solve the 'small' problem. In fact, they point out, take the Everett interpretation: it is considered realist even if it only solves the 'small' problem. In Everett's theory, in fact, measurements have no definite outcomes and the experimental statistics are obtained in terms of a many-worlds structure. This structure acts classically due to decoherence plus the idea of considering probabilities as an agent's preferences (Wallace 2002). For Bub and Pitowsky, the difference between their approach and Everett is that while Everettians accept the two dogmas, they do not. However, they have in common that they still solve the 'small' measurement problem, given that in the IT account measurements are taken to be primitive, which is readily solved by the constraints imposed by the Hilbert space structure. This, they argue, shows that one could be realist even if rejecting the two dogmas of quantum mechanics. (In Section 5 I will provide another example of a realist quantum theory which rejects dogma 2).

Moreover, building on what Bub previously did, Bub and Pitowsky also argue that one should reject both dogmas. They do this by appealing to the distinction between dynamical and kinematic explanation, connected with the notions of principle and constructive theories which was originally introduced by Einstein (1919). They argue that kinematic theories are more satisfactory that dynamical ones, and that, given that the IT approach is the only realist interpretation that could be thought as a kinematic theory, it is to be preferred to the alternatives. Since this theory rejects the two dogmas, so should the realist. Let's discuss this argument this in the next section.

3. The IT Approach as a Kinematic Theory

Bub and Pitowsky argue that the IT interpretation is a kinematic theory, that this kind of theories are to be preferred, as dynamical theories add no further insight. Originally, the argument has been presented by Bub in terms of the principle/constructive theories distinction, so let's start with that. Principle theories are formulated in terms principles, which are used as constraints on physically possible processes, as in thermodynamics ('no perpetual motion machines'). Instead, constructive theories involve the dynamical reduction of macroscopic objects in terms of their microscopic constituents, as in the kinetic theory (which reduces the behavior of gases to the motion of atoms).[4] Einstein introduced this distinction when discussing his 1905 theory of relativity, which he regarded as a principle theory, as it was formulated in terms of the two principles of equivalence of inertial frames for all physical laws, and constancy of the velocity of light (in vacuum for all inertial frames). This theory explains relativistic effects (such as length contraction and time dilation) as the physical phenomena compatible with the theory's principles. By contrast, since Lorentz's theory (1909) derives the relativistic transformations and the relativistic effects from the electromagnetic properties of the ether and its interactions with matter, is a constructive theory.[5]

According to Bub and Pitowsky, Lorentz's constructive theory came first, then only later Einstein formulated his (principle theory of) special relativity: Minkowski provided kinematic constraints which relativistic dynamics has to obey, and then Einstein came up with an interpretation for special relativity. Bub and Pitowsky also claim that we should take the fact that Einstein's kinematic theory has been preferred over Lorentz's dynamical theory as evidence that such type of theories are to be preferred in general. In addition, they argue that the fact that Lorentz's theory can constructively explain Lorentz

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[4] Here's how Balashov and Janssen put it:"In a theory of principle […] one explains the phenomena by showing that they necessarily occur in a world in accordance with the postulates. Whereas theories of principle are about the *phenomena*, constructive theories aim to get at the underlying *reality*. In a constructive theory one proposes a (set of) model(s) for some part of physical reality […]. One explains the phenomena by showing that the theory provides a model that gives an empirically adequate description of the salient features of reality" (Balashov and Janssen 2003).

[5] Again in the worlds of Balashov and Janssen: "Consider the phenomenon of length contraction. Understood purely as a theory of principle, SR explains this phenomenon if it can be shown that the phenomenon necessarily occurs in any world that is in accordance with the relativity postulate and the light postulate. By its very nature such a theory-of-principle explanation will have nothing to say about the reality behind the phenomenon. A constructive version of the theory, by contrast, explains length contraction if the theory provides an empirically adequate model of the relevant features of a world in accordance with the two postulates. Such constructive-theory explanations do tell us how to conceive of the reality behind the phenomenon" (Balashov and Janssen 2003).

invariance justified a realist interpretation of special relativity as a principle theory. But after this initial use, the constructive counterpart is *no longer necessary*. Similarly, Bub and Pitowsky argue that IT is kinematic theory in that it provides constraints on the phenomena without explaining them dynamically. That is, Hilbert space should be recognized as a "*the kinematic framework for the physics of an indeterministic universe*, just as Minkowski space-time provides the kinematic framework for the physics of a non-Newtonian, relativistic universe" (Bub and Pitowsky 2010, emphasis in the original text). Because of this, no other explanation for the experimental results is necessary.[6] More in detail, "the information-theoretic view of quantum probabilities as 'uniquely given from the start' by the structure of Hilbert space as a kinematic framework for an indeterministic physics is the proposal to interpret Hilbert space as a constructive theory of information-theoretic structure or probabilistic structure" (Bub and Pitowsky 2010)

As a consequence, we should reject the first dogma to obtain a kinematic theory, not a dynamical one. According to Bub and Pitowsky, the 'big' measurement problem is a dynamical problem, and as such a pseudo-problem when considering kinematic theories like theirs: as relativistic effects, such as length contraction and time dilation, are a problem for Newtonian mechanics but ceases to be such when looking at the geometry of Minkowski space-time and thus at the kinematics, here the 'big' problem dissolves when looking at the constraints that the Hilbert space structure imposes on physical events, given by experimental outcomes.

The next step is to observe that by rejecting dogma 1, the wavefunction can only be connected to experimenters' degrees of belief, rather than representing something real. Because of this, therefore, it is argued that we should also reject dogma 2. In other words, the rejection of the first dogma allows to make quantum theory a kinematic theory, which in turns dissolves the 'big' measurement problem, while the role of the rejection of the second dogma is to find a place for the wavefunction in the interpretation. That is, it allows to answer the question: if measurements are primitive, what is the wavefunction?

Be that as it may, in the next section we will start discussing some criticism raised against the IT account.

4. Objections to the Explanatory Superiority of Kinematic Theories

The IT framework has been criticized for mainly two reasons: on the one hand, objections have been raised against the alleged superiority of kinetic theories, therefore undermining the rejection of dogma 1; and on the other hand, people have pointed out the difficulties of considering the wavefunction as epistemic, as a consequence of the

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[6] "There is no deeper explanation for the quantum phenomena of interference and entanglement than that provided by the structure of Hilbert space, just as there is no deeper explanation for the relativistic phenomena of Lorentz contraction and time dilation than that provided by the structure of Minkowski space-time" (Bub and Pitowsky 2010).

rejection of dogma 2. In this section, we will review the first kind of criticisms, while in Section 9 we will discuss the ones based on the nature of the wavefunction.

First of all, Timpson (2010) argues that the dogmas Bub and Pitowsky consider are not dogmas at all, as they can be derived from more general principles like realism. In fact, regarding dogma 1, a realist recognizes measurement results and apparatuses as merely complicated physical systems without any special physical status. Regarding dogma 2, we just proceed as we did in classical theories: there's a formalism, there's an evolution equation, then one is realist about what the equation is about, which, in the case of quantum mechanics, is the wavefunction. However, I think Timpson misses the point. The dogmas are dogmas *for the realist*: the realist is convinced that she has to accept them to solve the measurement problem. What Bub and Pitowsky are arguing is that realist does not have to accept these dogmas: they in fact provide a realist alternative which does not rely on them. Timpson is on target in that a realist will likely endorse dogma 1 (what's special about measurements?), but Bub and Pitowsky argue that that is not the only option. Namely, one can recognize dogma 1 as being a dogma and therefore may want to reject it. One advantage of doing so, as we saw, is that in this way quantum theory becomes a kinematic theory, if one believes in the explanatory superiority of these type of theories. This leads one to recognize dogma 2 also as a dogma, and then to reject it as well.

Moreover, let me notice that Timpson also points out that Bub and Pitowsky provide us with no positive reason why one should be unhappy with such dogmas. I will present in Section 9 reasons for being extremely suspicious of dogma 2. Indeed, as I will argue later, one can restate the situation as follows: a realist, based on the reasons Timpson points out, *at first* is likely to accept *both* dogmas. However, upon further reflection, after realizing that by accepting dogma 2 one needs to face extremely hard problems, the realist should reject it.

Brown and Timpson (2006) point out that the first dogma was not a dogma at all for Einstein.[7] In this way, they criticize the historical reconstruction of Bub and Pitowsky for their argument for the superiority of kinematic theories. In the view of Brown and Timpson, Einstein's 1905 theory was seen by Einstein himself as a temporary theory, to

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[7] In fact, discussing his theory of special relativity he wrote: "One is struck that the theory […] introduces two kinds of physical things, i.e., (1) measuring rods and clocks, (2) all other things, e.g., the electromagnetic field, the material point, etc. This, in a certain sense, is inconsistent; strictly speaking measuring rods and clocks would have to be represented as solutions of the basic equations (objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities. However, the procedure justifies itself because it was clear from the very beginning that the postulates of the theory are not strong enough to deduce from them sufficiently complete equations […] in order to base upon such a foundation a theory of measuring rods and clocks. […] But one must not legalize the mentioned sin so far as to imagine that intervals are physical entities of a special type, intrinsically different from other variables ('reducing physics to geometry', etc.)" (Einstein 1949b).

be discarded once a deeper theory would make itself available.[8] Indeed, they point out, Einstein introduced the principle/constructive distinction to express *his own dissatisfaction* of the theory at the time. According to them, it was Einstein's view that kinematic theories are typically employed when dynamical theories are either unavailable or too difficult to build.[9] In this way, they argue that it is too much of a stretch to argue that Einstein would have encouraged a kinematic theory interpretation of quantum mechanics, as Bub and Pitowsky propose. However, even if I think that Brown and Timpson are correct, it is not clear why this should be an issue for Bub and Pitowsky. In fact, the charge at this stage is merely that Einstein did not consider dogma 1 as such, and that he did not like kinematic explanations. And to this Bub and Pitowsky can simply reply that they disagree with Einstein, and insist that there is value in kinematic theories, contrarily to what Einstein himself thought.

Therefore, let's move to the more challenging charge. Brown and Timpson argue against the explanatory superiority of kinematic theories by pointing out that only dynamical theories provide insight of the reality underlying the phenomena.[10] That is, regularities and constraints over the possible experimental findings lack explanatory power because we still do not know why these constraints obtain. A reason is provided only by a dynamical, constructive theory, in which one is told the mechanism, or the microscopic story, that gives rise to the observed behavior. For instance, it has been argued that the economy of thermodynamic reasoning is trumped by the insight that statistical mechanics provides (Bell 1976, Brown and Timpson 2006).[11]

Whether dynamical theories are actually more explanatory than kinematic theories remains a controversial issue, and certainly more should be written in this regard.[12] Nonetheless, even if one were to accept that in some contexts (such as in special relativity or thermodynamics) that dynamical theories are better, Bub (2004) has argued that a kinematic quantum theory is superior to any dynamical account. In fact, while Einstein's

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[8] "The methodology of Einstein's 1905 theory represents a victory of pragmatism over explanatory depth; and that its adoption only made sense in the context of the chaotic state of physics at the start of the 20th century" (Brown and Timpson 2006).

[9] For according to Einstein, "when we say we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question" (Brown and Timpson 2006).

[10] See also Brown (2005), and Brown and Pooley (2006).

[11] "The beauty of thermodynamics is in its economy of reason, but the insight it provides is limited in relation to the messier story told in statistical mechanics" (Brown and Timpson 2006).

[12] See Flores (1999), who argues that principle theories, in setting out the kinematic structure, are more properly viewed as explaining by unification, from the top-down, a model of explanation in the Friedman (1974)/Kitcher (1989) sense. Moreover, see Felline (2011) for an argument against Brown's view in the framework of special relativity. See also van Camp (2011) who argues that it is not the kinematic feature of Einsteinian relativity that makes it preferred to the Lorenzian dynamics but the constructive component, in virtue of which the theory possesses a conceptual structure.

theory of Brownian motion, which led to the acceptance of the atomic theory of matter as more than a useful fiction, showed the *empirical* limits of thermodynamics and thus the superiority of the dynamical theory, no such advantage exists in the quantum domain. Bub in fact argues that such an advantage is given *only* when a dynamical theory can provide some 'excess' in empirical content. Since dynamical constructive quantum theories (such as the pilot-wave theory) are empirically equivalent to a kinematic quantum theory, then (unlike kinetic theory) no dynamical quantum theory can ever provide more insight than a kinematic one. Critics could point out immediately that there are dynamical quantum theories such as the spontaneous collapse theory, which are not empirically equivalent to quantum mechanics. Moreover, it is not obvious at all that the only reason to prefer dynamical theories is because they can point to new data.[13]

Therefore, it seems safe to conclude that an important step in Bub and Pitowsky's argument for their view rests on controversial issues connected with whether a kinematic explanation is better than a dynamical one. Since the issue has not been settled, I think it constitutes a serious shortcoming of the IT interpretation, and it would be nice if instead it could be grounded on a less controversial basis. Indeed, this is what I aim to do in Section 6. Before doing this, however, I will present in the next section the most popular realis approach which accepts the second dogma.

5. Accepting the Second Dogma: Wavefunction Realism

Part of Bub and Pitowsky's reasoning is based on their willingness to dissolve the 'big' measurement problem. So let's take a step back and reconsider this problem again. As is widely known, quantum theory has always been regarded as puzzling, at best. As recalled by Timpson (2010), within classical mechanics the scientific realist can read out the ontology from the formalism of the theory: the theory is about the temporal evolution of a point in three-dimensional space, and therefore the world is made of point-like particles. Similarly, upon opening books on quantum theory, a mathematical entity and an evolution equation for it immediately stand out: the wavefunction and the Schrödinger equation. So, the natural thought is to take this object as describing the fundamental ontology. Even if we have just seen how it can be readily justified, as we have seen, Bub and Pitowsky think it is a dogma, in the sense that it is something that a realist has the option of rejecting. Here I want to reinforce the argument that this is indeed a dogma, and that this dogma should be rejected.

As emphasized by Schrödinger when discussing his cat paradox to present the measurement problem (1935), assuming the second dogma makes the theory empirically

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[13] Indeed, as Brown and Timpson (2006) write, "it is very doubtful whether Einstein advocated recognition of boosted rods and clocks as 'moving atomic configurations' in SR because he thought such a view might ultimately lead to a violation of one or more of this 1905 postulates. It is more plausible that he did so because it made sense conceptually."

inadequate. In fact, superposition states, namely states in which 'stuff' is both here and there at the same time, are mathematically possible solutions of the Schrödinger equation. This feature is typical of waves, as the wavefunction is in virtue of obeying Schrödinger's equation (which is a wave equation). However, if the wavefunction provides a complete description of the world, superpositions may exist for everything, including cats in boxes being alive and dead at the same time. The problem is that we never observe such macroscopic superpositions, and this is, schematically, the measurement problem: if we open the box and we measure the state of the cat, we find the cat either dead or alive. The realist, keeping the second dogma true, traditionally identified their next task in finding theories to solve this problem. That is, the realist concluded that, in Bell's words, "either the wavefunction, as given by the Schrödinger equation, is not everything, or it is not right" (Bell 1987, 201). Maudlin (1995) has further elaborated the available options by stating that the following three claims are mutually inconsistent: A) the wavefunction of a system is complete; B) the wavefunction always evolves to the Schrödinger equation; and C) measurements have determinate outcomes. Therefore, the most popular realist quantum theories are traditionally seen as follows: the pilot-wave theory (Bohm 1952) rejects A, the spontaneous collapse theory (Ghirardi Rimini and Weber 1986) denies B, while the many-world theory (Everett 1957) denies C.

Notice that it is surprising that even if dogma 2 has been challenged or resisted in the 1920s by de Broglie, Heisenberg, Einstein and Lorentz (see next section),[14] the physicists proposing the realist quantum theories mentioned above did not do so. Indeed, the view which accepts the second dogma has been the accepted view among the realists for a very long time. In this sense it was a dogma, as Bub and Pitowsky rightly call it, until it was recently recognized to be an assumption and the name of *wavefunction realism* was given to the view which accepts dogma 2.

Even if it is not often discussed, most wavefunction realists acknowledge that the measurement problem leads to another problem, the so-called *configuration space* problem. The wavefunction by construction is an object that lives on configuration space. This is classically defined as the space of the configurations of all particles, which, by definition, is a space with a very large number of dimensions. So, given that for dogma 2 the ontology is given by the wavefunction, if physical space is the space in which the ontology lives, then physical space is configuration space. Accordingly, material objects are represented by a field in configuration space. That is, the arena in which physical phenomena take place seems to be three-dimensional, but fundamentally it is not; and physical objects seem to be three-dimensional, while fundamentally they are not. Thus, the challenge for the wavefunction realist is to account for the fact that the world appears

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[14] See Bacciagaluppi and Valentini (2009) for an interesting discussion of the various positions about this issue and others at the 1927 Solvay Congress.

so different from what it actually is.[15] According to this view, the realist theories mentioned above are all taken to be theories about the wavefunction, aside from the pilot-wave theory which had both particles and waves. In contrast, since in all the other theories everything is 'made of' wavefunctions, particles and particle-like behaviors are best seen as emergent, one way or another.[16]

Be that as it may, the configuration space problem, after it was ignored since the 1920s, started to be recognized and discussed only in the 1990s, and at the moment it is acknowledged that it has *no universally accepted solution*.[17] Regardless, strangely enough, most people keep identifying the measurement problem (who has been solved) and not the configuration space problem (which has not) as the problem for the realist.[18] In the next section I will present a proposal to eliminate such a problem once for all.

6. Why Realists Should Reject the Second Dogma

In the last two decades or so, some authors have started to express resistance to the characterization of the quantum theories in terms of having a wavefunction ontology.[19] They propose that in all quantum theories material entities are not represented by the wavefunction but by some other mathematical entity in three-dimensional space (or four-dimensional space-time) which they dubbed the primitive ontology (PO). The idea is that the ontology of a fundamental physical theory should always be represented by a mathematical object in three-dimensional space, and quantum mechanics is not an exception. Given that the wavefunction is a field in configuration space, it cannot represent the ontology of quantum theory.

This view constitutes a realist approach, just like wavefunction realism. In contrast with it, however, the configuration space problem never arises because physical objects are not described by the wavefunction. In this way, not only the pilot-wave theory but also the spontaneous collapse and many-worlds are 'hidden variable' theories, in the sense that matter needs to be described by something else (in three-dimensional space) and not by the wavefunction. For instance, primitive ontologists talk about GRWm and GRWf as spontaneous localization theories with a mass density m and an event ('flash')

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[15] See most notably Albert (1996, 2013, and 2015); Lewis (2004, 2005, 2006, and 2013); Ney (2012, 2013, 2015, 2017, forthcoming); North (2013).

[16] See Albert (2015) and Ney (2017, forthcoming) for two different approaches to this.

[17] With this I do not mean that there are not proposals but simply that these proposals are work-in-progress, rather than full-blown solutions.

[18] The fact that there is more than one solution is what makes people say that the measurement problem has not really been solved, since one may think that it would be solved only if we had a unique answer to it. While this is certainly true, the sense in which it has been solved (albeit not uncontroversially so) is that all its possible solutions are fully developed, mature accounts, in contrast with the proposals to solve the configuration space problem, which are only in their infancy. This is therefore the sense in which the configuration space problem is more serious than the measurement problem.

[19] Dürr, Goldstein and Zanghí (1992), Allori et al (2008), Allori (2013a, and 2013b).

ontology f, as opposed to what they call GRW0, namely the spontaneous localization theory with merely the wavefunction (Allori et al 2008).[20] The proponents of this view therefore, contrarily to Bub and Pitowsky, do not deny the first dogma: measurement processes are 'regular' physical processes analyzable in terms of their microscopic constituents (the PO). Nevertheless, like the IT interpretation, they reject the second dogma: they deny the wavefunction representing physical objects. As we will see in Section 8, however, they do not take the wavefunction as epistemic: this view rejects the second dogma in the sense that the wavefunction is not material but not in the sense that it does not represent some objective feature of the world.

In this framework, one of the motivations for the rejection of dogma 2 is the conviction that the configuration space problem is a *more serious problem* than the measurement problem. The measurement problem is the problem of making sense of unobserved macroscopic superpositions which are consequences of the formalism of the theory. I wish to argue now that one important reason why one should drop the second dogma comes from the recognition that, even if the realist solves the measurement problem, the corresponding realist theories would still face the configuration space problem, which is arguably much harder to solve and which can be entirely avoided if one rejects the second dogma.

First, take the wavefunction-only theories, like the spontaneous localization and many-worlds theories. If one could keep the wavefunction in three-dimensional space, then both these theory could identify a 'particle' as a localized three-dimensional field given by the wavefunction (the superposition wavefunction spontaneously localizes in the spontaneous localization theory, and decoherence separates the different braches in Everett's theory). This would solve the measurement problem. However, these theories would need a wavefunction in configuration space to be empirically adequate, and therefore one ends up facing the configuration space problem. So, in order to solve one problem, wavefunction realists create a new problem. In the case of the pilot-wave theory, moreover, the argument for the rejection of the second dogma is even clearer, because the theory does not even solve the measurement problem from the point of view of the wavefunction realist. In fact, in this view the matter would be made by both particles and wave. That is, the cat is both made of waves and of particles, and because of its wave-like nature, she can be in unobserved macroscopic superposition. The measurement problem is solved only when one considers the theory a theory of particles only, without the wave-counterpart representing matter. This is how indeed the theory is often discussed: there are particles (which make up the cat), which are pushed around by the wave. This is however still misleading because it assumes that some wave physically exists, and this becomes problematical as soon as one realizes that this wave is in configuration space:

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[20] Notice however, that they are hidden variable theories only in the sense that one cannot read their ontology in the formalism of quantum mechanics, which is, in this approach, fundamentally incomplete.

What kind of physical entity is it? How does it interact with the particles? A better way of formulating the theory avoiding all this is to say that cats are made of particles and the wavefunction is not material, therefore rejecting the second dogma.[21]

Regardless, what's so bad about the configuration space problem? According to the proponents of the PO approach, it is extremely hard to solve, if not unsolvable.[22] Let us briefly see some reasons. One difficulty was recognized already by de Broglie, who noticed that, since for the wavefunction realist there are no particles at the fundamental level, "it seems a little paradoxical to construct a configuration space with the coordinates of points which do not exist" (de Broglie 1928). Interestingly, this argument can be tracked down historically also to Heisenberg, who very vividly said to Bloch (1967), referring to configuration space realism: "Nonsense, […] space is blue and birds fly through it", to express the ultimate unacceptability of building a theory in which there was no fundamental three-dimensional space.[23] Also, as already noticed, in wavefunction realism the traditional explanatory schema of the behavior of macroscopic entities in terms of microscopic ones needs to be heavily revised: contrarily to the classical case, tables and chairs are not macroscopic three-dimensional objects composed of microscopic three-dimensional particles; rather, as already noticed, they are macroscopic three-dimensional objects 'emerging from' high-dimensional wavefunction. And this problem has to be solved in absence of a truly compelling argument to so. In fact, what is the positive argument for dogma 2? The one we already saw is that we should do what we did in Newtonian mechanics, namely extract the ontology from the evolution equation of the theory. However here the situation is different. Newton started off with an *a priori* metaphysical hypothesis and built his theory around it, so there is no surprise that one has no trouble figuring out the ontology of the theory. In contrasts, quantum mechanics was not developed like that. Rather, as it is known, different formulations have been proposed to account for the experimental data (Heisenberg matrix mechanics and Schrödinger wave mechanics) without allowing ideas about ontology to take precedence. Just like Bub and Pitowsky claim, before the solution of the measurement problem, the theory is a kinematic theory: just like thermodynamics, it put constraints on possible

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[21] This is implicit in Dürr, Goldstein and Zanghí (1992).

[22] Allori et al (2008), Allori (2013a, and 2013b).

[23] Similar concerns have been expressed by Lorentz, who in a 1926 letter to Schrödinger wrote: "If I had to choose now between your wave mechanics and the matrix mechanics, I would give the preference to the former, because of its greater intuitive clarity, so long as one only has to deal with the three coordinates *x, y, z*. If, however, there are more degrees of freedom, then I cannot interpret the waves and vibrations physically, and I must therefore decide in favor of matrix mechanics" (Przibram 1967). Similarly, Schrödinger wrote: "The direct interpretation of this wave function of six variables in three-dimensional space meets, at any rate initially, with difficulties of an abstract nature" (1926a, p.39). Again: "I am long past the stage where I thought that one can consider the w-function as somehow a direct description of reality" (1935a). This is also a concern heartfelt by Einstein, who expressed this view in many letters, e.g.: "The field in a many-dimensional coordinate space does not smell like something real" (Einstein,1926).

experimental outcomes *without* investigating how and why these outcomes come about. The main difference between the PO and the IT approaches is that the former provides a framework of constructive quantum theories based on the microscopic PO, which can be seen as the dynamical counterpart of the latter, in which measurements are fundamental.[24]

Recently, a more compelling argument for wavefunction realism has been defended, namely that wavefunction realism is the only picture in which the world is local and separable.[25] The idea is that, since fundamentally all that exists is the high dimensional wavefunction, there are no other facts that fail to be determined by local facts about the wavefunction. First, let me notice that this is true also for the IT account, in which what is real are the (three-dimensional) experimental outcomes. However, while a more thorough analysis of this should be done somewhere else, let me point out that it is an open question whether the notions of locality and separability used in this context are the ones which have been of interest in the literature. Einstein first proposed the EPR experiment to discard quantum mechanics because it would show three-dimensional nonlocality. Arguably[26], Bell instead proved that the locality assumption in EPR was false and that nonlocality is a fact of nature. In other words, to show that the world is separable and local in configuration space seems to give little comfort to people like Einstein who wanted a world which is local and separable in three dimensional space.

Be that as it may, a further reason to reject the second dogma is that, if we accept it and somehow we can solve the configuration space problem, still we would lose important symmetries.[27] However, this is not the case if we drop the second dogma. In fact, the law of evolution of the wavefunction should no longer be regarded as playing a central role in determining the symmetries of the theory. Indeed, they are determined by the ontology, whatever it is (the PO in the PO approaches, and measurement outcomes in the IT framework). If one assumes that the wavefunction does not represent matter, and wants to keep the symmetry, then one can allow the wavefunction to transform as to allow this.[28]

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[24] For more on the comparison between the PO approach and the IT framework, see Dunlap (2015).

[25] See Loewer (1996) and Ney (forthcoming) and references therein.

[26] See Bell and Gao (2016) and references therein for a discussion of Bell's theorem and its implications.

[27] See Allori et al.(2008) and Allori (2018, 2019). For instance, quantum mechanics with wavefunction ontology turns out not Galieli invariant. In fact the wavefunction is a scalar field in configuration space, and as such will remain the same under a Galilean transformation: $\psi(r) \to \psi(r - vt)$. In contrast, invariance would require a more complicated transformation: $(r, t) \to e^{\frac{i}{\hbar}\left[mvr - \frac{1}{2}mv^2 t\right]}\psi(r - vt, t)$. A similar argument can be drawn to argue that if one accepts the second dogma then the theory is not time reversal.

[28] See respectively Allori (2018) and Allori (2019) for arguments based on Galilean symmetry and time reversal symmetry that the wavefunction is best seen as a projective ray in Hilbert space rather than a physical field.

Another reason to reject the second dogma, even assuming the configuration space problem is solved, is the so-called problem of *empirical incoherence*. A theory is said to be empirically incoherent when its truth undermines our empirical justification for believing it to be true. Arguably, any theory gets confirmation by spatiotemporal observations. However, wavefunction realism rejects space-time as fundamental so that its fundamental entities are not spatiotemporal. Because of this, our observations are not spatiotemporal observations, and thus provide no evidence for the theory in the first place.[29]

Moreover, it seems to me that insisting on holding on to dogma 2 at all costs would ultimately undermines the original realist motivation. In fact, the realist, in trying to make sense of the puzzles and paradoxes of quantum mechanics, as we have seen, would try to find the ontology with methods that worked in the past. That is, she will look at the evolution equation and she will identify the wavefunction as the ontology of the theory. This move gives rise to the measurement problem. To solve this problem the wavefunction realist develops theories with have an evolution equation for an object in configuration space. Thus, she needs also to solve the configuration space problem. Assuming a solution is possible, it will be radically different from the familiar constructive theories since it would involve emergence of the three-dimensional world from the multidimensional configuration space, rather that the dynamical explanation of the three-dimensional macroscopic data in terms of the three-dimensional microscopic ontology. However, the quest for a dynamical explanation, typical of proponents of constructive theories, in which macroscopic objects are thought of as composed of microscopic entities, motivated the whole realist approach to quantum theory to start with. To put it in another way, the wavefunction realist assumes that realist quantum theories (which solve the measurement problem) are satisfactory as they are, and looks to their fundamental equation to find the ontology. However the cost of assuming this amounts to ending up with a theory which will certainly not involve a dynamical explanation of the phenomena, which however is the view that motivated the realist to solve the measurement problem to start with. In contrast the primitive ontologist recognizes the disanalogy with classical mechanics (as mentioned earlier in this section), in which the strategy of looking at the evolution equation to find the ontology worked because Newton had already an ontology in mind when he constructed the theory. Thus, she rejects dogma 2 by dropping the idea that the various realist theories are satisfactory as they are:[30] the wavefunction never describes matter, and therefore *never* provides the complete description of a physical system, *contra* Bell's characterization of the

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[29] Barrett (1999), Healey (2002), Maudlin (2007). For responses, see Huggett and Wüthrich (2013) and Ney (2015).

[30] Notice that there is nothing strange in this: the wavefunction realist did not accept quantum mechanics as it was is it was because it suffered from the measurement problem, and in order to solve it, she finds it acceptable to, for instance, change the theory by modifying the Schrödinger equation.

measurement problem. Physical objects have a different ontology, which (to avoid the configuration space problem) is postulated to be in three-dimensional space. In this way, one can have a dynamical explanation of the phenomena in terms of the fundamental ontology. In this sense, the PO approach provides with constructive dynamical theories corresponding to the kinematic theory given by the IT interpretation.

Before concluding this section, let me make some remarks. First, it is interesting to note how the discussion above, in which we have motivated the rejection of the second dogma with multiple arguments, provides a response to Timpson, who complained that Bub and Pitowsky provide no reason why one would be unhappy with dogma 2.

In addition, let me mention another theory which accepts the second dogma, as well as the first, which has been proposed to avoid the configurations space problem. The idea is to think as the wavefunction as a multi-field in three-dimensional field. That is, the wavefunction is 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.[31] Even if it has the advantage of having no configuration space problem without dropping the second dogma, however this approach is problematical because it loses important symmetry properties, given that the multi-field transforms differently from how a classical field would (Belot 2012).[32]

On a different note, observe that the reasons I provided for the rejection of dogma 2 are not connected with dogma 1. On one hand, one can reject it as well together with dogma 2, as in the IT approach, and have a macroscopic ontology of measurement results without having the measurement problem. The existence of the IT interpretation, which I think is best seen as a refinement of Bohr's original account, is thus the counterexample to the claim that a scientific realist cannot solve the measurement problem by rejecting both dogmas. On the other hand, PO theories solve the measurement problem by rejecting only the second dogma. Criticisms to theories which reject the first dogma has been put forward. Most notably Bell (1987) argues that by taking measurements as primitive one introduces a fundamental vagueness in the theory connected with characterizing what a measurement is. This, it is argued, makes the theory hardly satisfactory. Moreover, Egg (2018) argues that rejecting the first dogma is incompatible with standard accounts of scientific realism, according to which reality is more than what we can observe or measure. In the next section we will discuss in a little more detail the

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[31] Forrest (1988), Belot (2012), Hubert and Romano (2018).

[32] Moreover, a new formulation of the pilot-wave theory has been proposed (Norsen 2010) in which to each particle is associated a three-dimensional filed given by a conditional wave-function, namely 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, and this makes the theory hardly satisfactory.

different options open to the realist, and the factors which are likely to be relevant in making a choice among the alternatives.

7. The Dogmas, Scientific Realism, and the Role of Explanation

Let's summarize some of the points and draw some partial conclusions. A scientific realist thinks it is possible to explain the manifest image of our senses in terms of the scientific image given to us by our best theories (Sellars 1962). We have different possibilities:

1- Reject dogma 2: a microscopic ontology in three-dimensions, as advised by the PO approach;
2- Reject both dogmas: a macroscopic ontology in three-dimensions, as advised by the IT interpretation; and
3- Accept both dogmas: a non-three-dimensional ontology, as in wavefunction realism. [33]

In the first case, one can provide a constructive and dynamical explanation of the manifest image, both of the experimental results and the properties of macroscopic objects. In the second case, instead, the only thing to explain is why certain statistical patterns are observed, and this is done using kinematical constrain on the possible physical events, not in a dynamical way. In the third case the situation is more complicated: one needs to explain both the empirical statistics and the 'emergence' of macroscopic objects in a way which is neither (obviously) kinematic nor dynamics, neither constructive nor using principles. No such account has been proven so far as being uncontroversial or fully developed. Because of this, and the other problems discussed in the previous section, all other things being equal, at this stage one can argue that the first two alternatives are to be preferred over the third.

So, which of the first two should we chose? This is going to depend on whether one prefers dynamical to kinematic explanations. That is, Bub and Pitowsky find option 1 unnecessary, while the proponents of the PO approach find 2 lacking explanatory power. If so, we have found a new role for the kinematic/dynamic distinction. In the original argument by Bub and Pitowsky the distinction came in the first step of the argument to reject the first dogma on the basis of which dogma 2 was later rejected. Because the superiority of kinetic theories is a controversial matter, however, I think this argument is

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[33] Interestingly, there's logically a fourth option, namely a theory which rejects dogma 1 without rejecting dogma 2. This would be a theory in measurement outcomes are left unanalyzed and the wavefunction represents physical objects. I am not sure who would hold such a view, but it seems to me that such a theory would presumably not appeal many people: while it solves the measurement problem (by rejecting dogma 1) it does not solve the configuration space problem (since it accepts dogma 2). Moreover, this theory leaves a mystery what the relation between the wavefunction and measurement processes is. Regardless, it nicely shows the relation between the two dogmas, with dogma 2 being in my opinion the one responsible for the problems for the quantum realist.

not likely to convince anyone already inclined to prefer dynamical theories to drop dogma 2. In contrast, in the argument I proposed, the reasoning against dogma 2 is independent of this distinction, which only plays a role in selecting which of the alternatives theories which *already reject* dogma 2.

8. On the Status of the Wavefunction

Before discussing the objections to the IT interpretation based on the epistemic account of the wavefunction, let us take another step back. The different accounts of the nature of the wavefunction are usually classified as either '*ontic*' or '*epistemic*'. Let's see what this means, and review some of the main objections to the ontic accounts, while we will leave the criticism to the epistemic accounts to the next section.

An account is said to be ontic when the wavefunction (or the density matrix which may also define the quantum state) represents some sort of objective feature of the world. In contrast, an account is epistemic if the wavefunction (or the density matrix) has to do with our knowledge of the physical system. Each view has their own sub-classification. As we have seen, wavefunction realism and the wavefunction as multi-field are ontic approaches in that they regard the wavefunction as a physical field. However, there are other approaches that could be labelled as ontic which do not have this feature. One of these ontic interpretations is the view according to which the wavefunction is a law of nature. This is a peculiar account because it has been formulated in the PO framework, which denies the second dogma. Roughly put, the idea is that since the wavefunction does not represent matter but has the role in governing the behavior of matter, then the wavefunction has a nomological role and thus is best understood as a law of nature.[34] Notice that this account of the wavefunction is still ontic (the wavefunction expresses some nomic feature of the world) even if the second dogma is rejected (the wavefunction does not represent material entities), and thus one can dub this view as 'ψ-non-material' rather than 'ψ-ontic', which does not seem sufficiently specific (another non-material view is the one that the wavefunction is a property, see below). Perhaps the most serious problem[35] of this approach is that one usually thinks of laws as time-independent entities, while the wavefunction evolve itself in time.[36] Another challenge for the view is that while laws are taken to be unique, the wavefunction is not. Replies have been provided, relying on a future quantum cosmology in which the wave function would be static.[37] However, they have been received with skepticism, given that one would want to get a handle on the nature of the wavefunction in the current situation, without having to wait for a future theory of quantum cosmology.

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[34] Dürr et al. (1992, 1997); Goldstein and Zanghì (2013).

[35] For more objections, see Belot (2012); Callender (2015); Esfeld et al. (2014), Suárez (2015).

[36] Brown and Wallace (2005).

[37] Goldstein and Teufel (2001).

Perhaps a better way of capturing this idea can be found in a Humean framework, regarding the wavefunction as part of the Humean mosaic.[38] Nonetheless, many still find the account wanting, most prominently because they find Humeanism with respect to laws misguided for other reasons. A different but connected approach that can be thought as nomological is to think of the wave function as a dispositional property or more generally as a property of the ontology.[39] Not surprisingly, even if these approaches do not have the time-dependence problem, they nevertheless are not immune to criticisms, given that the dispositional properties are notoriously a tough nut to crack and moreover the wavefunction does not behave like a regular property.[40]

Moving on to the epistemic approaches, they have in common the idea that the wavefunction should be understood as describing our incomplete knowledge of the physical state, rather than the physical state itself. One of the motivations of the epistemic approaches is that they immediately eliminate the measurement problem altogether. In fact, schematically, in a Schrödinger cat type of experiment, the cat is never in a superposition state; rather, it is me who does not know what its state is. When I open the box and find the cat alive, I simply have updated my knowledge about the status of the cat, who now I know to always have been alive during the experiment.

The epistemic approaches can be distinguished into the 'purely epistemic', or neo-Copenhagen, accounts, and the ones that invoke hidden variables, which one can dub 'realist-epistemic' approaches. The prototype of the latter type is Einstein's original 'ignorance' or 'statistical' interpretation of the wavefunction (Einstein 1949a), according to which the current theory is fundamentally incomplete: there are some hidden variables which describe the reality under the phenomena, and whose behavior is statistically well described by the wavefunction.[41] For a review of the first epistemic approaches, see Ballantine (1970).[42] In contrast, the neo-Copenhagen approaches reject that the above mentioned hidden variables exist, or are needed. The wavefunction thus describes our knowledge of measurement outcomes, rather than of an underlying reality. This view has a long story that goes back to some of the founding fathers of the Copenhagen school as one can see, for instance, in Heisenberg (1958) and in Peierls (1991), who writes that the wavefunction "represents our knowledge of the system we are trying to describe".

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[38] Miller (2014), Esfeld (2014), Callender (2015), and Bhogal and Perry (2017).

[39] Suàrez (2007, 2015), Monton (2013), Esfeld et al. (2014), and Gao (2014b).

[40] For an assessment, see Suàrez (2015).

[41] Einstein was convinced that "assuming the success of efforts to accomplish a complete physical description, the statistical quantum theory would, within the framework of future physics, take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of this type; but the path will be lengthy and difficult" (Einstein 1949).

[42] For a more modern approach, see Spekkens (2007).

Similarly, Bub and Pitowsky write: "quantum state is a credence function, a bookkeeping device for keeping track of probabilities".[43]

A crucial difference between the ontic and the epistemic approaches is that while in the former the description provided by the wavefunction is objective, in the latter it is not. This is due to the fact that different agents, or observers, may have different information about the same physical system. Thus, many epistemic states may correspond to the same ontic state.

9. Objections based on the Wavefunction Being Epistemic

As we anticipated, since the IT interpretation rejects the first dogma and takes measurements as primitive and fundamental, one is left with the question about what the wavefunction is. According to Bub and Pitowsky, the wavefunction (or the density matrix) is not fundamental. Thus, they spend not too much time in discussing what the nature of the wavefunction is, and Timpson (2010) finds this troublesome. However, it seems natural for them to consider the wavefunction as epistemic, given their overall approach: the wavefunction adds no empirical content to the theory, and thus is best seen not as a description of quantum systems but rather as reflecting the assigning agents' epistemic relations to the systems.

One epistemic approach which shows important similarity with Bub and Pitowsky's view is the one put forward by Healey (2012, 2015, and 2017). According to him, physical situations are *not* described by the wave function itself. Rather the wave function prescribes how our epistemic attitudes towards claims about physical situations should be. For instance, in a particles interference experiment, an experimenter uses the Born rule to generate the probability that the particle is located in some region. The wavefunction therefore prescribes what the experimenter should believe about particle location. This view is epistemic in the sense that the wavefunction provides a guide to the experimenter's beliefs. Moreover, it is pragmatic in the sense that concerns about explanation are taken to be prior to representational ones. In this sense, the wavefunction has an explanatory role. This explanatory role is also shared by Bub and Pitowsky's account, since in their account the wavefunction allows the definition of the principles of the theory which constrain the possible physical phenomena, including interference.

Anyway, because of its epistemic approach, the IT interpretation has received many criticisms, and the situation remains extremely controversial.[44] Let me review what the main criticisms are. First of all, it has been argued that the epistemic approaches cannot explain the interference phenomena in the two-slit experiment for particles: it seems that something wavelike needs to exist in order to explain the interference fringes, and the

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[43] Other neo-Copenhagen approaches also include Bayesian approaches (Fuchs and Peres 2000, Fuchs 2002, Fuchs and Schack 2009, 2010, Caves et al. 2002a, 2002b, 2007), pragmatist approaches (Healey 2012, 2015, 2017; Freidrich 2015), and relational ones (Rovelli 1996).

[44] See Gao (2017) for a review, and Leifer (2014) for a defense.

obvious candidate is the wavefunction (Leifer 2014, Norsen 2017). Moreover, in particle experiments with the Mach-Zender interferometer outcomes change depending on whether we know or not which path the particle has taken. This seems incompatible with the epistemic view: if the wavefunction represent our ignorance about which path has been taken, then by coming to know that would change the wavefunction but would not produce any physical effect (Bricmont 2016).

Moreover, the so-called no-go theorems for hidden variables (starting from the ones of von Neumann 1932, and Bell 1987) have been claimed to show that the realist-epistemic view is untenable, so that they can be considered no-go theorems for this type of approach. In fact, if the wavefunction represents our ignorance of an underlying reality in which matter has some property A, say, spin in a given direction, then the wavefunction provides the statistical distribution of $v(A)$, the values of A. Indeed, if this interpretation is true, $v(A)$ exists for more than one property, since it would be arbitrary to say that spin exists only on certain directions. However, the no-hidden variable theorems show that mathematically no $v(A)$ can agree with the quantum predictions. That is, one cannot introduce hidden variables to *all* observables at once.[45]

Recently, a new theorem called PBR theorem, from the initials of its proponents (Pusey, Barrett and Rudolph theorem 2012) has been proposed as a no-go theorem for the epistemic theories in general. This theorem is supposed to show that, in line of the strategy used by the other no-go theorems, epistemic approaches are in conflict with the statistical predictions of quantum mechanics by showing that if the wavefunction is epistemic, then it requires the existence of certain relations which are mathematically impossible. Therefore, if quantum mechanics is empirically adequate, then the wavefunction must be ontic (either material, or not).

This objections have been subject to an extensive examination, and proponents of the epistemic views have proposed several replies, which are however in the eyes of many still tentative.[46] Bub and Pitowsky respond that they can explain interference as a phenomenon constrained by the structure of Hilbert space, more specifically by the principle of 'no universal broadcasting'. Moreover, PBR's conclusion, as well as the conclusions of the other no-go theorems, applies only to theories that assume an underlying reality, which they reject. However, these answers appear unsatisfactory to someone who would want to know why these phenomena obtain, rather than having a mere description. So, without entering too much in the merit of these objections, in the view of many they pose a serious challenge to the epistemic views, and, accordingly, to the IT interpretation. Therefore, one can wonder whether it is possible to deny the second dogma while staying away from the epistemic views without endorsing the non-material

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[45] Notice that the pilot-wave theory circumvents this theorem because some, but not all, experiments reveal pre-existing properties (for more on this, see Bricmont 2016, Norsen 2017).

[46] Again, see Leifer (2014), Gao (2017), and references therein.

interpretations discussed in Section 8, given that they suffer from serious objections too. This is the enterprise I will take on in the next section.

10. The Wavefunction is as the Wavefunction Does

We have reviewed in the previous sections the various non-material accounts of the wavefunction (the nomological approach, which is non-material but ontic, and the epistemic ones) and their criticisms. In this section, I propose a new account of the wavefunction based on functionalism, which I argue is better than the alternatives and could be adopted both by the proponents of the Po approach and from Bub and Pitowsky.

Functionalism, broadly speaking, is the view that certain entities can be 'reduced' to their functional role. To use a powerful slogan, 'a table is as a table does'. Strategies with a functionalist core have been used in the philosophy of mind for a long time (starting from Putnam 1960), and they have been recently used also in philosophy of physics.

For instance Knox (2013, 2014) argues that spacetime can be functionalized in the classical theory of gravity. That is, spacetime can be thought of as non-fundamental (emergent) in virtue of the fact that spacetime plays the role of defining inertial frames. Interestingly, Albert (2015) defends wavefunction realism using his own brand of functionalism. He in fact argues that ordinary three-dimensional objects are first functionalized in terms of their causal roles, and the wavefunction dynamically uses these relations in a way which gives rise to the empirical evidence.[47] Lam and Wüthrich (2017) use functionalist strategies in quantum gravity. There are many proposals for how to articulate a quantum theory of gravity, however it has been argued that in all these theories spacetime is not fundamental, but rather it is emergent from some non-spatiotemporal structures (Huggett and Wuthrich forthcoming). They argue that in order for spacetime to emerge it suffices to recover only those features which are functionally relevant in producing observations. However, not surprisingly, this approach faces the same objections of wavefunction realism. An objection to this approach is that it is unclear how space and time can indeed emerge from a fundamental non-spatiotemporal ontology: first, it is unclear what a non-spatiotemporal fundamental could be; second, it is doubtful whether the right notion of emergence is this one (Lam and Esfeld 2013). In addition, there is the already mentioned problem of empirical incoherence, namely that the theory undermines its possibility of being believed. Arguably, any theory gets confirmation by spatiotemporal observations. However, a theory in which spacetime is functionalized is a theory whose fundamental entities are not spatiotemporal. Because of this, our observations are not spatiotemporal observations, and thus provide no evidence for the theory in the first place.[48]

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[47] Ney (2017) provides a criticism and discusses her own alternative. See also Ney (forthcoming).

[48] For responses, see Huggett and Wüthrich (2013), and Ney (2015, forthcoming).

As anticipated, my idea is that one should functionally define the wavefunction, similarly as how people wish to functionalize space, space-time and material objects, and define it in terms of the role it plays in the theory. That is, *the wavefunction is as the wavefunction does*. I am going to show that this view captures the appeals of the other accounts without falling prey of their objections. In other words, by thinking of the wavefunction functionally one can capture the intuitions that the wavefunction is law-like (as proposed by the nomological approach), and that it is explanatory rather than representational (as proposed by the epistemic and pragmatic approaches) avoiding the problem of time-dependence, non-uniqueness, and no-go theorems.

The wavefunction plays different but interconnected roles in realist quantum theories which reject the second dogma, which however all contribute to the same goal: to *reproduce the empirical data*. First, the wavefunction plays a nomological role. This is straightforward in the case of PO theories, where it is one of the ingredients necessary to write the dynamics for the PO, which in turn constructively accounts for the measurement outcomes.[49] In the case of the IT interpretation, the dynamics plays no role, but the wavefunction can be seen as nomological in the sense that allows the principles or the kinematic constraints of the theory to be expressed, which in turn limit the physically possible phenomena and thus explain the data.

Connected to this, the wavefunction does not represent matter but it has an explanatory role: it is a necessary ingredient to account for the experimental results. As we have seen, the PO approach and the IT interpretation differ in what counts as explanatory, the former favoring a dynamical account, and the latter a kinematic one. Accordingly, the explanatory role of the wavefunction in these theories is different. In the PO approach the wavefunction helps defining the dynamics for the PO, and in this way accounts for the empirical results constructively as macroscopically produced by the 'trajectories' of the microscopic PO. In the IT interpretation the wavefunction provides the statistics of the measurement outcomes via the Born rule, therefore explaining the probabilistic data by imposing kinematical constraints.

Notice that this explanatory role allows to be pragmatic about the wavefunction: it is a useful object to adequately recover the empirical predictions. Pragmatically, both in the PO approach and in the IT framework one uses the wavefunction to generate the probability outcomes given by the Born rule, but one *could have chosen another object*, like a density matrix, or the same object evolving according to another evolution equation.[50] The fact that quantum mechanics is formulated in terms of the wavefunction is contingent

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[49] In the context of the pilot-wave theory, the wavefunction can be taken as a force or a potential, but one should not think of it as material (even if Belousek 2007 argues otherwise).

[50] In the PO framework, for instance, see Allori, Goldstein Tumulka and Zanghi (2008) for unfamiliar formulations of the pilot-wave theory and the spontaneous collapse theory respectively with a 'collapsing' wave function and a non-collapsing one respectively.

to other super-empirical considerations like for example simplicity and explanatory power: it is the simplest and most explanatory choice one could have made.

This pragmatic take is compatible also with the nomological role of the wavefunction. In fact, as we have seen, the wavefunction is not a law of nature, strictly speaking, rather it is merely an ingredient in the law. Because of this the wavefunction does not have to be unique, like potentials are not unique, and can be dispensable: other entities, such as the density matrix, can play its role. In this way, the wave function plays a nomological role, but avoiding the usual objections to the nomological view.

Moreover, notice that this approach, even if pragmatic, is not epistemic: the wavefunction does not have to do with our knowledge of the system (*contra* Bub and Pitowsky's original proposal). As a consequence, it does not suffer from the usual problems of the epistemic approaches. Moreover, in the case of the IT approach, this view remains true to the ideas which motivated the interpretation, namely to reject both dogmas, and fits well with their ideas of quantum probability.

Also, I wish to remark that, since all the theories we are considering reject the second dogma, this view also avoids the objection of empirical incoherence of other functionalist approaches. In fact the problem originates only if the fundamental entities of the theory are not spatiotemporal, and this is not the case in the IT frameworks (in which measurements outcomes are fundamental and obviously are in three-dimensional space) and in the PO approach (in which the PO is a spatiotemporal entity).

To summarize, the wavefunction plays distinctive but interconnected roles which act together and allow the wavefunction to recover the empirical data. First, the wavefunction is an ingredient in the laws of nature, and as such contributes in determining the trajectories of matter. As such, it has an explanatory role in accounting of the experimental results, even if it is not representational one. Because of this, the wavefunction can be thought in pragmatic terms without considering it connected to our knowledge of the system. Formulated in this way, the view has the advantages of capturing the main motivations for the other views without falling prey of their main objections:

1. The wavefunction has a nomological role, without being a law; so it does not matter whether it is time-evolving or unique;
2. The wavefunction has an explanatory role without necessarily being uniquely defined or connected to the notion of dynamical explanation;
3. The wavefunction has a pragmatic role in recovering the empirical data without being epistemic, thereby avoiding the interference problem and the no-go theorems linked with the epistemic view.

These roles combine together to define the wavefunction functionally: the wavefunction is whatever function it plays, namely to recover the experimental results. This role can be accomplished either directly, in the IT framework, or indirectly, through the 'trajectories' of the PO, but always remaining in spacetime, therefore bypassing the configuration space problem and the worry of empirical incoherence. This account of the wavefunction thus is arguably better than the other taken individually, and accordingly is the one that the proponents of realist theories which reject the second dogma should adopt. In particular, it can be adopted by the proponents of the PO approach, as well as by Bub and Pitowsky to strengthen their views.

11. Conclusion

As we have seen, the IT interpretation rejects the two dogmas of quantum mechanics. First, it rejects dogma 1. Using the CBH theorem, which kinematically constrains measurements outcomes, they see quantum theory as a theory with measurements as primitive, and thus they reject the first dogma. However, if one rejects dogma 1, then what is the wavefunction? The IT interpretation naturally interpret it as epistemic, therefore rejecting the second dogma. It is argued that both dogmas give rise to the measurement problem, and that by rejecting them both it becomes a pseudo-problem.

Because of this sequence of arguments the IT interpretation has the following two features that could be seen as shortcomings:

1- The rejection of dogma1 is based on the superiority of kinematic theories, which is controversial;
2- The rejection of dogma 2 makes them endorse the epistemic view, which is also considered problematical.

My aim in this paper was:

A-To show that any realist should reject dogma 2, even if she may or may not reject dogma 1, and
B-To provide a functionalist approach to the wavefunction which captures some of the motivations of the other accounts, including IT, while avoiding their main objections.

Aside for standing for themselves, in doing A, I also have provided the IT interpretation with tools to avoid the first set of objections; while in doing B, a way to reject the second. In fact, first I have argued that Bub and Pitowsky should have rejected dogma 2 *independently* of dogma 1 (on the basis of the configuration space problem, the loss of symmetries, and empirical incoherence), thereby completely bypassing the connection with the alleged superiority of kinematic theories. Indeed, my reasons for rejecting dogma 2 are less contentious in the sense that even those who endorse dogma 2 (such as the wavefunction realists) recognize them as problems for the tenability of dogma 2. After rejecting dogma 2 for these reasons, someone may also drop dogma 1 to make quantum mechanics a kinematic framework (if they prefer them for independent reasons). However, one may decide otherwise: a realist who prefers constructive theories based on a dynamical explanation could still keep dogma 1. Thus, if the IT proponent follow the route proposed here (drop dogma 2 first) then they can avoid their first type of challenges. As we have seen, the second set of objections comes from them endorsing the epistemic view. However, my functionalist approach to the wavefunction, which has merits in its own right, is compatible with dropping both dogmas without committing us to an epistemic view of the wavefunction. Because of this, it can be adopted by Bub and Pitowsky to avoid the second set of problems.

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