Who's Afraid of the Measurement Problem?
On the Incompatibility between Scientific Realism and Quantum Mechanics

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Abstract

Call 'the realism problem' the problem of providing realist understandings of quantum theory. Scientific realists usually claim that this problem is settled by solving the measurement problem. Nonetheless, people disagree about which is the best solution. In this paper I argue that the disagreement among certain views can be tracked down to the fact that there are different views about what the realism problem is supposed to be. I distinguish between an adequacy problem, a precision problem (which is the measurement problem), and a completeness problem. I argue that the reason why some people disagree is that they have different realist commitments: 'relaxed' realists like proponents of the information-theoretical interpretation of quantum theory, think it is enough to solve the adequacy problem, 'modest' realists like wavefunction realists instead believe that there is also a precision problem, while 'robust' realists like primitive ontologists insist that quantum theory, even if it solves the precision problem, still needs to be suitably completed. These attitudes are explained by the type of theories one finds satisfactory: while relaxed realists favor principle theories, robust realists prefer constructive theories, and modest realists provide non-constructive dynamical hybrids as long as they preserve locality and separability. This clarifies why the proponents of the information-theoretical approach endorse standard quantum mechanics with the collapse rule, wavefunction realists favor the many-worlds theory or GRW, and primitive ontologists support the pilot-wave theory.

Keywords: constructive and principle theories, quantum mechanics, measurement problem, scientific realism, information-theoretical quantum theory, primitive ontology, wavefunction realism.

1. Introduction

Quantum theory, while being so successful, suffers from what we can call the *realism problem*: the theory is incompatible with scientific realism, as it cannot provide, in its standard textbook formulation, a picture of reality. Traditionally scientific realists think that one can deal with the realism problem by solving the *measurement problem,* namely the problem of precisely suppressing the unobserved macroscopic superpositions predicted by the theory. Solutions of the measurement problem include the GRW theory, the pilot-wave theory, and the many-worlds theory. Even in a realist framework, people disagree about which solution is best. In this paper I focus on the disagreement between primitive ontologists and wavefunction realist: the former favor the pilot-wave theory while the latter either GRW or many-worlds. In the comparison I introduce the information-theoretic (IT) approach because, as we will see, it provides a nice contrast. I argue (section 2) that these approaches disagree about which is the best realist quantum theory because they disagree about why standard quantum theory, the one in physics textbooks, is unsatisfactory from a realist perspective. That is, they disagree about which problem is the realism problem. Proponents of the IT approach think that the realism

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problem is an adequacy problem, wavefunction realists instead focus on a precision problem, and primitive ontologists maintain that the problem to solve is a completeness problem. A quantum theory which solves the adequacy problem is one which makes empirically adequate predictions. Instead, a theory which solves the precision problem (which is the measurement problem) not only is empirically adequate but also has an ontology whose dynamics is unique and precisely defined. Finally, solving the completeness problem amounts to being empirically adequate and having a unique and precise dynamics for a microscopic spatiotemporal ontology. I also show how the reason why proponents of the IT approach, wavefunction realists and primitive ontologists look at these distinct problems is that they have diverging realist commitments (section 3), because they think of theories differently (section 4). I maintain that those who think the realism problem is the adequacy problem endorse a relaxed realist attitude, as they think that a theory should objectively systematize the phenomena in terms of principles constraining the behavior of their macroscopic ontology. Instead, those who think that quantum theory is incomplete have in mind a robust realist understanding, where a theory explains the phenomena constructively, in terms of the dynamics of the microscopic constitutes of the world. Finally, those who think that the precision problem is the one to be solved endorse a modest version of realism, which combines an interest in the reality behind the phenomena with a non-constructive understanding guided by the desire of keeping a local and separable ontology. In section 5, I conclude with some remarks about each of these approaches. First, it is unclear why relaxed realists such as the proponents of the IT approach are really realists, given that they focus on accommodating appearances. Even granting that they are, their argument that principle theories should be privileged is unconvincing. Moreover, I discuss how their proposal could be improved by reformulating it in terms of a non-epistemic wavefunction. As for the primitive ontologists, I argue that it does little sense for them to discuss the other solutions of the measurement problem other than the pilot-wave theory. Moreover, they should avoid thinking of the wavefunction as an unanalyzable primitive and of laws as constraints because they are in tension of their constructive approach. As for the wavefunction realists, first, I show that the type of explanations they provide seems to undermine their motivation for looking for a better theory than standard quantum theory. Moreover, they need to allow for a constructive as well as a non-constructive type of explanation without an independent reason for why that has to be the case. I summarize and conclude in section 6.

2. Quantum Problems

When discussing standard quantum mechanics, the one presented in physics books, it is often pointed out that it is merely a recipe for predicting experimental results. As such, it is incompatible with scientific realism, the view that theories can give us information about the nature of the world beyond the appearances. As anticipated, let us call this incompatibility *the realism problem*. Traditionally, it is argued that the realism problem is the measurement problem. If so, solving the measurement problem generates quantum theories amenable to a realist interpretation, namely theories which could reliably guide us in discovering the metaphysics of the quantum world. As is known, the measurement problem arises when we assume that the wavefunction, the main object of standard quantum mechanics, evolves in time according to a suitable evolution equation, the Schrödinger equation. Since a solution of this equation describes possible states of affairs of the world, and since the Schrödinger equation is linear, also any sum of solutions (superpositions) describes possible situations. If one also assumes that every system is completely described by such wavefunction, then there will be 'superpositions of states' at all scales, such as a cat in a superposition state of 'living' and 'dead.'

2.1. The Adequacy Problem

For what we just saw, it is clear that the first problem of standard quantum theory is that it is *not empirically adequate*: it fails to predict something we observe. We observe no macroscopic superpositions, no superpositions' of cat states, which instead are predicted by the theory. This problem is solved in physics books by postulating the collapse rule, in addition to the Schrödinger evolution. When we observe something, we make a measurement on it, and in virtue of that the wavefunction no longer evolves linearly according to the Schrödinger evolution but rather randomly and instantaneously collapses into one of the terms of the superposition: the cat is either dead or alive.

The collapse rule works for an anti-realist perspective: it reproduces measurement data. Nonetheless, there are some realists who think that there is no realism problem left. Standard quantum theory with the collapse rule lays out a set of constraints imposed on the empirical data. However, these data exist objectively and mind-independently, so one could be realist about those, and not give too much importance of what is going on at the microscopic level. Proponents of the information-theoretic (IT) approach can be thought as providing an example of this reasoning.[2] Similarly, QBists think of quantum theory as providing constraints on measurement outcomes.[3] Moreover Rainforest Realism, according to which objects, both at the microscopic and the macroscopic level, are seen as real patterns, defined by their usefulness, seems to fit this profile.[4]

2.2. The Precision Problem

However, many are not convinced, and find the collapse rule unsatisfactory: it is unclear when one is supposed to apply it (what is a measurement?), and why it applies (why is a measurement process not a particular type of physical interaction?). In other words, some identify the realism problem as a *precision problem*: the unobserved macroscopic superpositions

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[2] Bub and Pitowsky (2010). They write: "On the information-theoretic interpretation, no assumption is made about the fundamental 'stuff' of the universe."

[3] Fuchs (2010); Fuchs, Mermin, and Schack (2014); Fuchs (2017) and references therein. Here is an interesting quote: "What is the stuff of the world? QBism is so far mostly silent on this issue, but not because there is no stuff of the world. The character of the stuff is simply not yet understood well enough. Answering this question is the goal, rather than the premise" (DeBrota, and Stacey 2019).

[4] Ladyman and Ross (2007, 2013); Ladyman, (2016). This view follows the ideas of Dennet (1991) and Wallace (2003, 2012).

predicted by the theory need to be accounted for *without mention of observers or measurements*. The wavefunction should evolve according to one dynamics, not two, and this dynamics should be precisely defined without appealing to vague concepts like the ones of measurement or observer. This is the measurement problem as usually understood. Its solutions need to be more than just empirically adequate: they also have to have a unique and precisely defined dynamics. As a consequence, empirically adequate quantum theories which are not precise in this sense, such as standard quantum theory, will have to be discarded. The most promising solutions of this problem are recognized to be: the many-worlds theory, in which all terms of the superpositions exists but never interact with one another;[5] the pilot-wave theory, in which the complete state of the system is specified by the wavefunction and by the particles' position;[6] the GRW theory in which the wavefunction collapses a as matter of law.[7] All these theories are empirically adequate (GRW's deviations are currently undetectable) and have a unique and precise dynamics.

These theories are taken to be theories about the wavefunction, with the exception of the pilot-wave theory which also has particles. There are different views about how to think about the wavefunction. The view I will focus on is called *wavefunction realism*, according to which the wavefunction is understood as a physical field in configuration space (which is a space with $3N$ dimensions, if there are N three-dimensional particles).[8] As such, therefore, the wavefunction is not an entity in spacetime. In this paper, I am going to focus on wavefunction realism.[9] For them, quantum theory needs to have a clear ontology and a precise dynamics, in addition of being empirically adequate. So, quantum theories which solve the precision problem would qualify as suitable realist quantum theories.

2.3. The Completeness Problem

Others instead have argued that one needs more that an empirical adequate theory with a clear ontology and a precise dynamics: one also needs the ontology to be in spacetime. Since the wavefunction is not a spatiotemporal object, then *all 'wavefunction-only' quantum theories are fundamentally incomplete*. That is, under this understanding, not all solutions of the precision problem are satisfactory, as GRW and many-worlds are purely wavefunction theories. They need to be re-thought as theories with a spatiotemporal ontology, which needs to be specified independently of their solving the measurement problem. In this sense, they need to be

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[5] Everett (1957).

[6] Bohm (1952).

[7] Ghirardi, Rimini and Weber (1987).

[8] Albert (1996, 2013, 2015), Ney (2012, 2013, 2015, 2017, 2021) and references therein.

[9] There are other views about how to think of the wavefunction. When the wavefunction is taken to be a vector in Hilbert space, it is called *vector space realism or Hilbert space fundamentalism* (see Carroll 2022 and references therein). If the wavefunction, or better the quantum state, is instead taken to be in its own category of existence, then one talks about *quantum state fundamentalism* (Maudlin 2019). In the many-worlds framework, some also have endorsed a view called *spacetime state realism*, which takes the states associated to spacetime regions as fundamental (Wallace and Timpson 2009). For a comparison between spacetime state realism, the many-world theory, and the primitive ontology approach, see Allori (2023).

completed with a spatiotemporal ontology. This attitude can be historically tracked down for instance to Lorentz, who objected to Schrödinger that his wavefunction was physically unacceptable because it is a field in configuration space, rather than in three-dimensions like electromagnetic fields.[10] Similar concerns were raised by Einstein,[11] (at least) an early Schrödinger,[12] and de Broglie.[13] Even Heisenberg expressed similar worries, which arguably pushed him toward anti-realism.[14] This idea has recently implicitly resurfaced in the primitive ontology framework.[15] Proponents of this approach require that in all quantum theories material entities are not represented by the wavefunction but by the *primitive ontology*, which represents a suitable spatiotemporal fundamental ontology. There are different ways of completing quantum theory: with different spatiotemporal ontologies (particles, waves, spatiotemporal events or 'flashes', and so on) and different evolution equations. In any case, the pilot-wave theory seems straightforwardly the simplest way of doing this: the simplest type of ontology (particles), and the simplest evolutions (deterministic). But one could propose different ontologies governed by a Schrödinger-evolving wavefunction as well as by a GRW-evolving wavefunction. Examples of the latter include GRWp (in which particles evolves stochastically and nonlinearly with a law induced by a GRW-evolving wavefunction),[16] GRWm (in which the ontology is a matter field defined in terms of a GRW-evolving wavefunction, which therefore inherits a dynamics with the same stochastic and nonlinear features),[17] GRWf

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[10] Here is what Lorentz writes to Schrödinger: "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" (Lorentz in Przibram, 1967).

[11] Einstein in a letter to Lorentz dated May 1st, 1926, writes: "Schrödinger's conception of the quantum rules makes a great impression on me; it seems to me to be a bit of reality, however unclear the sense of waves in n-dimensional q-space remains." Similarly, here is an excerpt from a June 18th, 1926 letter that Einstein sent to Paul Ehrenfest: "Schrödinger's works are wonderful – but even so one nevertheless hardly comes closer to a real understanding. The field in a many-dimensional coordinate space does not smell like something real." Both these quotes are taken from Howard (1990).

[12] "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."[12] Also: "Of course this use of the q-space is to be seen only as a mathematical tool, as it is often applied also in the old mechanics; ultimately [...] the process to be described is one in space and time" (Schrödinger 1926).

[13] Before settling for the pilot-wave theory, in which there are particles guided by the wavefunction, de Broglie worked on what he called 'the theory of the double solution,' in which particle behavior was supposed to be interpreted as singularities of a physical wave u guided by an abstract wave ψ in configuration space. He wrote: "Physically, there can be no question of a propagation in a configuration space whose existence is purely abstract: the wave picture of our system must include N waves propagating in real space and not a single wave propagating in the configuration space" (de Broglie 1927, reprinted in de Broglie 1956).

[14] Heisenberg has been reported to have said, very vividly, referring to Schrödinger's work: "Nonsense, […] space is blue and birds fly through it"(Bloch 1976). This expresses his refusal to accept a theory with no fundamental three-dimensional fields and with no fundamental three-dimensional physical space.

[15] Dürr, Goldstein, and Zanghí (1992); Dürr, Goldstein, and Zanghì (1997); Allori *et al.* (2008); Allori (2013a,b). For a review, see Allori (2015); Allori (2019).

[16] Allori (2020a).

[17] Benatti, Ghirardi and Grassi (1995).

(which has a flashes ontology whose distribution is governed by a GRW-evolving wavefunction).[18] Examples of the latter turn out to be theories with a many-worlds character: for instance in Sm the matter field inherits the superpositions generated by the Schrödinger-evolving wavefunction.[19]

Others have emphasized the importance of spacetime for a satisfactory ontology. For instance, Maudlin (e.g. 2016) has argued that satisfactory theories have local beables: "those which (unlike for example the total energy) can be assigned to some bounded space-time region."[20] Also, Norsen (2010) has proposed that we should actively look for a theory entirely formulated in terms of spatiotemporal ontologies, without a wavefunction in high dimensional space. This turns out to be technically difficult, but perhaps the essence of this can be saved by understanding the wavefunction as a multi-field, or poly-wave, in three-dimensional space. This multi-field is an extension of the concept of field, as it assigns a number to a set of locations, rather than only one location, in the three-dimensional space.[21] Arguably, one could think of these views as solving the completeness problem, as all of them effectively add a spatiotemporal ontology to quantum theory.[22]

3. Quantum Realisms

I have argued in the previous section that there is a disagreement about what the realism problem is supposed to be. That is, there is disagreement about what ingredients and features a quantum theory should have in order to be a reliable guide to discover the metaphysics of the quantum worlds. That is, there is disagreement about what being a scientific realist means. In general, a scientific realist believes that theories provide descriptions of the world which we are entitled to believe to be approximately true in virtue of the theory's explanatory success. However, one can disagree about what a such a description should amounts to, and what is meant by explanatory success of a theory. The reason why people disagree about which is the realism problem is that they disagree about the features that a satisfactory dynamics and a satisfactory ontology are supposed to have, and they disagree about what counts as a good explanation. In this section, I discuss different requirements for the ontology, which constrain the type of realism on endorses. In the next section, I discuss different explanatory strategies compatible with these realist commitments.

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[18] This theory was first proposed by Bell (1987b), and then adopted in Tumulka (2006), who developed a relativistic extension.

[19] Allori *et al.* (2008, 2011), Allori (2019), and references therein.

[20] Bell (1987).

[21] Forrest (1988), Belot (2012), Chen (2017), Hubert and Romano (2018), Romano (2020).

[22] The disagreement between these views and primitive ontologists has to do with symmetries properties, as discussed in Allori (2021a).

3.1. Relaxed Realism

The approaches which take the realism problem to be the adequacy problem, such as the IT interpretation, QBism and Rainforest Realism, think that quantum theory with the collapse rule is more than just a recipe for predicting results. Rather, realists could interpret it as a theory with a macroscopic ontology of measurement outcomes. If so, it does not matter whether the collapse rule is precise or not, because in IT and QBism measurements are unanalyzable primitives, while in Rainforest Realism nothing is primitive. Once the collapse rule is in place, the realism problem 'dissolves:' the theory becomes empirically adequate.

Usually, these attempts are taken to be not realist enough: Aren't realists supposed to care about more than just empirical adequacy? Should they not discover reality beyond the appearances? However, while anti-realists will presumably say that physical theories are not the kind of things which can give us a description of what is unobservable, the proponents of these approaches acknowledge that there are many possible microscopic descriptions for the same macroscopic phenomena but, because of underdetermination concerns, one should remain agnostic about which the correct one is. Or even that no microscopic description is needed to have a satisfactory explanation. So, they do not deny that a microscopic reality exists, just that it is neither possible nor necessary to provide a description of it in order for a theory to be amenable to a realist interpretation. Let's call this perspective *relaxed realism*. According to relaxed realists, a satisfactory theory has *some spatiotemporal ontology*. Namely, it is about something objective and mind-independent, which is in spacetime, but it does not need to be microscopic.

3.2. Modest Realism

Those who care about the precision problem (dealing with macroscopic superpositions with a unique and precisely defined dynamics) think that solving the adequacy problem is not enough: they also care about having all physical objects and processes being governed by a unified, precise dynamics. For instance, wavefunction realists care about having the same dynamics for all scales (unlike the relaxed realists), as well as a clear ontology. However, they do not insist on the fundamental ontology to be in spacetime (unlike primitive ontologists). On the contrary, they are open to other theories which do not complete quantum theory but otherwise deal with the unobserved macroscopic superpositions using a theory with a unique dynamics. That is, they take all solutions to the measurement problem to be viable realist quantum theories. Indeed, they favor theories, such as GRW and many-worlds, in which the ontology is the wavefunction (and not like the pilot-wave theory, in which you also have the particles). Their reason to prefer fundamental ontologies not in spacetime is that, in contrast with spatiotemporal ontologies, they allow for locality and separability in the fundamental space (Ney 2021). Locality is a property of the interaction, namely that influence travels at finite velocity. Instead, separability is a property of the ontology, namely that the whole can be seen as the sum of its parts. These assumptions seems both commonsensical and needed to do physics. Locality is intuitive because it allows us to make sense of physical action: if nonlocality were true then how can we say that this object acted on this other object? Moreover, separability is intuitive because it preserves Humean supervenience, as in the high dimensional space of the wavefunction, all properties are determined locally. To preserve Humean supervenience is desirable because it is simple, as we do not have to postulate any additional (relational or otherwise) fact to account for the phenomena.[23] However, quantum nonlocality has threatened them both: arguably the violation of Bell's inequality has shown that any theory reproducing the quantum predictions has not be nonlocal.[24] Ney has argued that the only fundamental ontology which is local and separable in the fundamental space is the one provided by wavefunction realism, because the fundamental space is high dimensional.[25]

Consequently, wavefunction realists endorse a *modest* form of realism. According to a *modest realist,* a realist quantum theory has *a local and separable ontology in the fundamental space.* They are more realists than the relaxed realists because they want more than empirical adequacy: for them a satisfactory quantum theory would also need a precisely define unique dynamics for the ontology of the theory. However, the ontology for this dynamical law is not required to have special features, like being microscopic or in spacetime, as long as it is local and separable. So, as we will see in the next subsection, they are less realist than primitive ontologists, hence the name.

3.3. Robust Realism

Let us now discuss primitive ontologists who think that quantum theories with only the wavefunction are fundamentally incomplete. As we have seen in the previous section, they require the fundamental ontology to be in spacetime. In this, they agree with relaxed realists. However, they require more than empirical adequacy, which you can get with a macroscopic ontology. Rather, primitive ontologists are driven by the idea that macroscopic objects should be thought as composed of some fundamental (spatiotemporal) ontology.[26] They have in mind a *Lego bricks picture* of reality, similar to the classical understanding, in which the objects of our experience are built from the fundamental ontology. In order to make sense of such a picture, the fundamental ontology needs to be spatiotemporal, but also suitably microscopic. In the case of a particle ontology, this is rather straightforward: the individual Lego bricks (the particle fundamental ontology) used to build a castle (a macroscopic object) are in the same space as the castle (spacetime) and they are smaller than the castle (they are microscopic). Notice that waves can be a suitable ontology for robust realists too, even if they are delocalized objects and, strictly

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[23] See Ney (2021) for more.

[24] See, e.g., Goldstein *et al.* 2011. and references therein.

[25] If you have a spatiotemporal ontology, like in the pilot-wave theory, objects may be though as separable (they are made of particles), but they interact nonlocally (through the wavefunction). If instead you have a spatiotemporal ontology in a many-worlds theory (like in the case of spacetime state realism), the theory may be seen as local (the state of any spatiotemporal region depends only on the state of some cross-section of its past light cone) but it is non-separable (the intrinsic properties of a localized region of space are represented by a density operator, and the density operators of two subsystems do not determine the density operator of their union).

[26] This is explicit in Allori (2013a, b, 2015, 2019).

speaking, they are not microscopic, as long as the following conditions are met. First, they are oscillating in (three-dimensional) space, evolving in time, and also they superimpose to form stable and localized wave-packets to reproduce particle-like observed behavior. These conditions being satisfied would make waves effectively microscopic. As a consequence, one could think of the Lego brick being (three-dimensional) wave-packets instead of particles. Thus, they are *robust realists*: a satisfactory quantum theory not only is empirically adequate, has a clear ontology and a precise dynamics, but also a suitably *microscopic (spatiotemporal) fundamental ontology*.

In any case, standard quantum theory falls short in this respect in at least two ways: it has two dynamical evolutions, and it has no clear ontology. The IT approach has a macroscopic ontology, but it stops there: it does not think of macroscopic objects or processes in terms of a microscopic picture, so they do not need a microscopic fundamental ontology. Moreover, they do not interpret measurement as physical processes, so they do not care about the non-unique vague dynamics. Instead, primitive ontologists care about both. In their Lego bricks picture, not only Lego bricks need to be suitably microscopic, but also they need to describe all physical processes, including measurement processes, so they need to have the same dynamics for all scales. Modest realists instead privilege a local and separable ontology in the fundamental space, and this leads them to a non-spatiotemporal ontology to which the Lego brick picture cannot be applied.

To summarize, then:

1) relaxed realists require a spatiotemporal fundamental ontology which makes discussing about empirical adequacy straightforward, but require neither a unique nor a precise dynamics;
2) modest realists require a precise dynamics but do not require the fundamental ontology to be spatiotemporal if it can make the theory local and separable;
3) robust realists require a theory to have a precise dynamics as well as an effectively microscopic spatiotemporal fundamental ontology.

4. Quantum Explanations

Wavefunction realists, *contra* primitive ontologists, argue that GRW, say, needs no completion: the theory solves the measurement problem not by completing standard quantum theory but by changing the dynamics making it nonlinear (and stochastic). Primitive ontologists disagree, I have argued, because they think that even if a theory solves the measurement problem it may not solve the realism problem. In fact, a theory is compatible with realism if it solves the completeness problem. In other words, for them GRW is not satisfactory because, even if it solves the measurement problem, it does not solve the completeness problem, and thus the realism problem. This is due to the type of realism the primitive ontologists endorse: robust realism requires an effectively microscopic (spatiotemporal) ontology, and GRW, being about the wavefunction, does not have it. In contrast, wavefunction realists are modest realist, and are willing to sacrifice a spatiotemporal ontology for a local and separable theory. Proponents of the IT interpretation are even more flexible, as they do not even care about having a unique and precise dynamics or a microscopic ontology. That's what makes them relaxed realists.

In this section I discuss how the type of realism one endorses goes hand in hand with a specific type of explanatory strategy. I show how relaxed realists favor explanations provided by principle theories, how robust realists instead look for constructive theories, while modest realist end up endorsing a hybrid type of explanation.

According to Einstein, theories are either constructive or they are theories of principles.[27] *Principle (or kinematical) theories* are formulated in terms principles, which are used as constraints on physically possible processes. They spell out principles that the phenomena need to conform to, and they are 'kinematic' theories because the explanations they provide do not involve equations of motion and they do not depend on the interactions the system enters into. Instead, by definition *constructive theories involve the dynamical reduction* of macroscopic objects in terms of the motion and interactions of their microscopic constituents. An example of a principle theory is thermodynamics (it has principles such as e.g. "energy is conserved"), and an example of (the corresponing) constructive theory is statistical mechanics (its goal is to reduce the behavior of gases to the motion of atoms). Another example of principle theory is the 1905 theory of special relativity (before the introduction of Minkowski spacetime), as it was formulated in terms of the two principles: the equivalence of inertial frames for all physical laws, and the principle of constancy of the velocity of light. This theory explains relativistic effects (such as length contraction and time dilation) as the physical phenomena compatible with the theory's principles. By contrast, Lorentz's 1909 theory is a constructive theory, as it derives the relativistic effects from the electromagnetic properties of the ether and its interactions with matter.

4.1. Principle Theories

Some have argued that principle theories are preferable. For instance, Bub and Pitowsky (2010) have argued that quantum theory is best understood as a principle theory. They maintain that to explain is to constrain the phenomena without the need of a dynamical account. More specifically, Hilbert space is thought as "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"(*ibid*.).They believe that we should favor explanations given in terms of principle theories: "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"(*ibid*.). As relativity explains the phenomena when it tells us what we should expect in a

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[27] Einstein (1919).

certain physical situation, so does standard quantum theory with the collapse rule. There is no reason and no need to ask for more. They do not explicitly say it but one could argue that a principle type of explanation is to be preferred to a constructive one because it provides a framework which is independent on the detailed assumption about the structure or the constitution of matter. Moreover, Flores (1999) has convincingly argued that principle theories are explanatory because, being top-down, they unify.[28] So if one thinks that to explain is to unify, all things being equal they will likely prefer principle theories, and they will find no reason to modify standard quantum theory with the collapse rule.

Be that as it may, the preference of the proponents of the IT approach for principle theories fits well with their relaxed realism and their idea that to solve the realism problem one needs no more than solving the adequacy problem: for them, a satisfactory theory only needs to systematize the phenomena, and this can be successfully done using principles, no dynamical explanation is necessary.

4.2. Hybrid Theories

What type of explanation do modest realists advocate? Wavefunction realists favor GRW and many-worlds over the pilot-wave theory because the pilot-wave does not really fit in their schema: they want a high dimensional ontology, while in the pilot-wave theory there are also particles (Ney 2021). Moreover, they favor many-worlds over GRW, because they are both theories about the wavefunction, and GRW adds nothing more that its stochastic nonlinear dynamics. Starting from a local and separable ontology in high dimensional space, this approach has three steps to complete in order to account for the macroscopic phenomena: first, it needs to recover three-dimensional space from the fundamental high dimensional space; then it needs to recover a microscopic non-fundamental ontology from the fundamental wavefunction; and finally, it needs to account for the macroscopic behavior. As far as the first step is concerned, the strategy of wavefunction realists is to show that three-dimensional space suitably emerges from the fundamental high dimensional space. There are various wavefunctionalist strategies, but they all have in common that they are based on principles. For example, Albert uses the principle that the privilege the dimensions in which the Hamiltonian is written. In other words, the fundamental Hamiltonian of the world contains the potential a function of three-dimensional space. This fact constrains the phenomena by privileging three-dimensions over others. In this sense, the structure of the Hamiltonian explains why we expect to see a three-dimensional world. Ney instead uses the principle that privilege the dimensions that respect the fundamental symmetries of the dynamics. She notices that the dynamics of the wavefunction has certain symmetries, and she argues that only three-dimensions can preserve these symmetries. This is the sense in which symmetries explain why we should expect a three-dimensional world.[29] These approaches use principles in the second step as well, namely for the

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[28] Friedman (1976), Kitcher (1989).

[29] A similar strategy is employed in vector space realism, in which three-dimensionality is recovered in terms of the energy eigenvalues of the Hamiltonian. See Carroll (2022).

emergence of non-fundamental microscopic objects. Albert and Loewer (1996) propose to modify the so-called EER (eigenvalue-eigenstate rule) of standard quantum mechanics as to define particles as suitably emergent. The EER is used to connect observables (i.e. physical properties) with the wavefunction: an observable has a well-defined value for a given system if and only if its wavefunction is an eigenstate of that observable. Albert and Loewer's proposal is to define 'particles' as follows: "particle x is in region R if and only if the proportion of the total square amplitude of x's wavefunction which is associated with points in R is greater than or equal to $1 - p$," where the parameter p is a conventional matter. It is a supervenience rule, since it is a rule that explains how our talk about macroscopic objects and properties (the macroscopic talk) supervene on the talk in terms of wavefunction (the microscopic talk). In this sense, it is a principle, just like the EER was. In this way, they say, it is possible to non-fundamentally recover what we usually mean when we talk about localized spatiotemporal objects. Later, Albert (2015) proposed that particles as we experience them are to be understood as emerging as 'functional shadows' of the high dimensional fundamental wavefunction. The idea is that it is possible first to define functionally what it means to be effectively a three-dimensional object, and then it is possible to show that the wavefunction can play that role. With this functional reduction microscopic objects are understood non-fundamentally. Once we have this microscopic non-fundamental ontology, we can understand macroscopic objects as composed of them. So, in order to complete step two (recovering the non-fundamental spatiotemporal ontology at the microscopic level), Albert uses principles, but in step three (recovering the non-fundamental spatiotemporal ontology at the macroscopic level), he employs a constructive explanation. Ney (2021) has a different proposal. First, she derives microscopic (spatiotemporal) particles as the derivative parts of the wave function, which is the fundamental whole. In her view, there is a particle when there is a 'bump' in the squared of the wave function. Understood in this way, a particle location is indeterminate, as the wave function may be spread out. Particles may partially instantiate different locations to different degrees, given by the squared amplitude of the wave function in that point. Having defined particles in this way, step three is carried out not in terms of compositionality. That is, in contrast with Albert, Ney does not think of macroscopic objects as composed of microscopic particles. Rather, she thinks that decoherence, namely the interaction of the environment, is responsible for the emergence of macroscopic, classically behaving patterns, along the lines of strategies adopted by supporters of the many-worlds theory.[30]

The explanatory strategies developed by modest realists we just discussed are not constructive in the sense that the macroscopic phenomena are not explained in terms of the fundamental spatiotemporal microscopic dynamics. Rather, they seem much closer to the type of explanation provided by principle theories. Albert uses the Hamiltonian and functionalism, Ney uses

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[30] See Wallace (2012).

symmetries and partial instantiation to establish the derivative reality of three-dimensional reality, thereby providing principles that constrain the phenomena.

On the other hand, these are not entirely principle explanations. In fact, we know that modest realists, in contrast with relaxed realists, care about the dynamics in virtue of wanting to solve the precision problem, which the problem of having a unified and precise dynamics. Moreover, Albert's functionalist account takes the dynamics into account using the form of the Hamiltonian (rather than its solutions) to recover three-dimensional objects. Similarly, Ney's focus on symmetries can be understood as taking the dynamics seriously, as well as her appeal to decoherence. So, at the end, the type of explanation provided by wavefunction realism is a hybrid between principle, compositional and dynamical explanation.

4.3. Constructive Theories

In contrast with the proponents of the IT approach and wavefunction realism, primitive ontologists favor constructive theories. They follow Einstein, who believed that physics should look for constructive theories, and accept principle theories only when one has no other option.[31] Brown (2005) has argued that constructive theories are more explanatory than principle theories because in contrast with kinematical theories they provide insight of the reality underlying the phenomena.[32] Not only they accounts for what we should expect to happen, but they also account for why it happens.

The essence of constructive explanation is to explain top-down, compositionally and dynamically. As we have seen, the essence of this type of explanation is to have an effectively microscopic ontology that plays the role of Lego bricks and that evolves according to a unique and precise dynamics that can allow to adequately reproduce the observed macroscopic behavior. So, primitive ontologists treat standard quantum theory as thermodynamics. They are both principle theories: the quantum recipes describe the phenomena by specifying the statistics of the experimental results, just as thermodynamics provides constraints on macroscopic phenomena. As such, they have a constructive counterpart, to which we can reduce them. The constructive counterpart of thermodynamics is classical mechanics. Thermodynamics can be constructively understood in terms of classical mechanics, by thinking of gases as collections of particles, thereby obtaining an explanation of why the laws of thermodynamics hold. Unlike the case of thermodynamics, we do not have a constructive counterpart for standard quantum mechanics. Through this theory one would be able to understand quantum systems in terms of a more fundamental ontology and to arrive to understand not only why quantum principle hold, but why they do. Notice therefore that, as it

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[31] He thus expressed his own dissatisfaction for the theory of special relativity at the time. However, he could have said something similar for quantum theory: his preference for constructive theories is compatible with his idea that quantum mechanics is incomplete. Moreover, it fits well with his statistical interpretation of quantum theory, as it is a principle theory by constraining the phenomena with suitable rules.

[32] See also Brown (2005), Brown and Pooley (2004), Brown and Timpson (2006). See Flores (1999) and Felline (2011) for a connection with Salmon's mechanistic view of explanation (1984).

would be absurd to use a gas ontology for classical mechanics to constructively explain thermodynamics, *one should not use the wavefunction as the ontology* of the constructive quantum theory: since the wavefunction 'belongs' to the principle theory, it does not make sense to use it as the ontology for the constructive one. In addition, the wavefunction is not defined in spacetime, which is the space which allows for constructive explanation. Since constructive explanation requires a spatiotemporal fundamental ontology, the obvious choice is the one of particles. For once, particles seem more compatible with the empirical evidence of tracks in detectors. If so, the straightforward constructive counterpart of standard quantum mechanics, namely the theory with a microscopic fundamental ontology and a unique and precise dynamics that explains why we obtain the results predicted by standard quantum mechanics, is the pilot-wave theory.

5. Final Remarks

So far, we have compared the choices of the proponents of the IT interpretation, of wavefunction realists and of primitive ontologists. I have argued they have a different understanding of what to do to make quantum theory compatible with realism, which constrain their choice of the ontology and the dynamics and reflect favoring distinct explanatory strategies. For each approach I have identified the driving motivation: preserving principle explanation, preserving locality and separability, and preserving constructive explanation. In this section, I wish to evaluate these accounts in their own terms.

5.1 Puzzles for Relaxed Realists

Usually, as anticipated, relaxed realist attempts are taken to be *not realist enough*. For example, Egg (2019) has put forward a set of arguments that some implementations of this type of realism do not deserve to be labelled realist. In my opinion, when people object that these approaches are not realist, they have in mind that in order to be a realist one needs to go behind the phenomena, they need to do more than merely systematize the data and providing us with an effective rule to tell us what we should expect to observe next. It is more than just to say that the theory is empirically adequate. To be realist, in this view, is to talk about unobservable entities, to connect this to the observable phenomena in a way which allows us to not only explain what to expect but also to tell us why we should expect it. In other words, to be realist is to look for a constructive rather than a principle explanation. Einstein has indeed argued that principle explanations are fine when we have nothing better, but true understanding of the world is given by the constructive theories. In response, while anti-realists will presumably say that physical theories are not the kind of things which can give us a description of what is unobservable, proponents of the IT approach deny, as we have seen, that we need constructive understanding. However, many remain unconvinced that we should settle for principle type of explanations, especially if one could have also a constructive understanding.

Here's another feature of these approaches that contributed to some confusion. Principle theorists aims at providing an objective description of the phenomena in terms of the kinematic framework provided by Hilbert space. In this approach, the wavefunction is not seen as 'ontic,' namely as describing some physical entities or some physical facts, because only measurement results are taken ontologically seriously. As a consequence, these approaches make the move of thinking of *the wavefunction as epistemic*: roughly, it encodes what we know about the system we are analyzing. I think this is not a wise move on their part: it threatens the objectivity of the approach, as it makes the approach mind dependent. By considering the wavefunction as epistemic, one is more or less explicitly stating that the description it provides is not complete. In fact, in order for a theory to completely describe the world, it needs to specify what any system will do, given the initial conditions. That is, the theory should be formulated in objective terms describing the system, not in terms of our knowledge about it. Classical mechanics is formulated in that way: all ingredients are necessary and sufficient to predict physical behavior. When we are asked at what time a train going at uniform velocity v will arrive at distance d, we do the calculation and obtain the result $t = d/v$. That is, we know everything there is to know about the train and the rest. If instead for some reason we cannot answer, it is not because the theory is incomplete, but rather because the information we had was insufficient (for instance, say, we did not know the velocity of the train). That is, our knowledge was incomplete, not the theory. In contrast, if you have a theory which contains in its definitions something which expresses your lack of complete information about the system, you are simply acknowledging the fact that the theory you currently have is incomplete. It would become complete we would obtain perfect knowledge. Principle theorists like the proponents of the IT approach and QBists do exactly this: they specify the Hilbert framework but then they introduce the wavefunction which, if seen as epistemic, makes standard quantum theory incomplete. There is something out there to be known, which currently however we do not know. Notice that this is in tension with their claim that a theory needs to provide an objective and mind independent account of the phenomena. So, on the one hand they want a mind independent account, but on the other hand they make their approach mind dependent by considering the wavefunction as epistemic. Some people have taken this as evidence for the wavefunction being ontic. Since these approaches are inconsistent with that, it is claimed, they need to be discarded. However, I do not think this is correct. In fact, in these approaches the wavefunction does not represent physical objects. Nonetheless*, it does not follow that because of the wavefunction does not represent physical systems then the wavefunction cannot be ontic* and therefore the wavefunction has to be epistemic. In fact, the label 'ontic' here just means objective: it is an objective ingredient of the framework. In order to be objective, the wavefunction does not have to represent a physical system. For instance, it could also represent some other objective fact, for instance a fact describing the interaction between systems, like the one expressed by the Hamiltonian function. This is straightforwardly compatible with these principle approaches, and it does not imply that the wavefunction should be taken as epistemic.[33]

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[33] See Allori (2020b, 2021b).

5.3 Puzzles for Modest Realists

An initial, not very deep, puzzle for wavefunction realism is their focusing on GRW. If they care about having a high dimensional ontology, why do not favor many-worlds, which does not have the nonlinear stochastic dynamics of GRW?

A second, more serious problem, has to do with their motivation. As we have emphasized, wavefunction realists want more than empirical adequacy but less than constructive explanation because they care about preserving separability and locality. That is, they are willing to give away constructive explanation if they can save locality and separability. So, the first puzzle is: how do they justify their attachment to separability and locality? As anticipated, their answer is that they are intuitive. However, the locality in wavefunction realism is locality in the space of the wavefunction, namely high dimensional space, so quantum theory is still nonlocal in three-dimensional space. The wavefunction realist points out that locality is needed to explain physical action. Nonetheless, *this move is effective only if we think of three-dimensional locality.* In fact, the way in which we understand physical action which conflicts with nonlocality is through three-dimensional space: we see, three-dimensionally, stuff acting on other stuff, and that's why we do not understand how something over here, three-dimensionally speaking, is affecting something over there remaining the same object localized here. Traditionally, people have wanted locality because this was compatible with relativity theory. To cut a long story short, since in relativity there is a maximum velocity, the speed of light, there cannot be instantaneous action at a distance. However, this is three-dimensional locality, so this argument cannot be used in favor of wavefunction realism. Moreover, people assumed locality, the three-dimensional one, because it is what seems to make physics possible: it is only assuming locality that we seem to be able to account for causes and effect. Rather similarly, the wavefunction realist cares about separability because it preserves our intuitive notion of compositionality: if separability is true, composed systems can be broken down into simpler ones so that the features of the composite are understood as sums of the features of its parts. Nonetheless, it seems again that the separability we intuitively care about is in three-dimensions: it is what it is familiar to us, we model and manipulate systems under the assumption that the world is separable in three-dimensions, as in the case of locality. People always cared about separability because thinking about macroscopic objects as composed of microscopic ones has worked very well in the past. But of course, this is true for three-dimensional separability, not necessarily for the corresponing high dimensional notion.

A third problem is the following. Within wavefunction realism phenomena are not accounted from entirely in a constructive way. In fact, as we have seen, since the wavefunction is a field in configuration space, one first has to derive three-dimensionality, then particles, and then macroscopic objects. Each of these steps (except the last, in the case of Ney's approach) involves some sort of principle. In this respect, then they are similar to relaxed realists. However, as noted already, wavefunction realists want more than what relaxed realists want: they want to deal with macroscopic superposition in a precise way, with a theory with a unique and precise dynamics. Arguably, they care about having the same dynamics for all levels of description because they do not want to no privilege some middle level description, as for instance the one that involves measurements. One way to go away from the middle level is to push the privileged description at the microscopic level, and account for all the other descriptions in terms of that. This is what constructive theories do. However, this is not what wavefunction realists propose (because of their desire to keep locality and separability): they have a high dimensional ontology and propose principles to go from there down to spacetime. In this way however wavefunction realists end up leaning too much towards relaxed realism: their approach reproduces appearances by systematizing the phenomena. But, didn't they claim that they wanted more? Didn't they claim that they wanted to find a unified understanding of the fundamental reality? However, if both relaxed and modest realists essentially systematize the phenomena, then it means that the only difference between the two is that the wavefunction realists systematizes the data precisely (the theory is empirically adequate, and it has a precise and unique dynamics), while the proponents of the IT approach do it rather vaguely (namely the theory is empirically adequate because of the collapse rule). In other words, wavefunction realists think that a satisfactory theory needs a precise and unique dynamics, while the proponents of the IT approach think that the dynamics of a satisfactory theory does not need to be unique or defined in terms of precise notions. At this point, however, one may wonder why we should care about precision at all. In other words, if it is the case that wavefunction realism ends up systematizing the phenomena as relaxed realists do, one may wonder *what the point of solving the measurement problem actually is*. That is, what is it to be gained by systematizing the phenomena precisely, with a theory with a unique and precise dynamics, if you can do it with vague notions, like the collapse rule? Macroscopic phenomena are vague, after all. Why would one want to explain such vague macroscopic phenomena in terms of principles formulated in terms of a precise, rather than vague, dynamics? Why don't wavefunction realists simply take standard quantum mechanics with the collapse rule and interpret it as a theory of the wavefunction, if they end up systematizing the phenomena using principles? The point of solving the measurement problem was that there was value in having a precise dynamics for the wavefunction. But why would one want a precise rule if they only care about reproducing the appearances? It seems one would care about the precision of the dynamics ultimately if they cares about the dynamics: it is because one wishes a unified dynamics which is applicable at all scales that one is interested on theories that solve the measurement problem. In fact, wavefunction realists do not provide a pure principle explanation: wavefunction realists use the dynamics (for instance in the form of decoherence) to show that macroscopic objects create and persist. However, the way wavefunction realists rely on the dynamics is not constructive: for instance, they use the symmetries of the Hamiltonian to recover three-dimensional appearances, while a constructive theorist would have used the solutions of the Hamiltonian, as they represent a possible way the world could be. Be that as it may, even granting that the dynamics is important to them, still it is unclear why that is. That is, *why is the wavefunction realist interested in the dynamics, if they provide a non-dynamical explanation*? Having a non-constructive explanation and giving importance to the dynamics seem to pull in opposite directions: the former pushes towards relaxed realism, while the latter towards a robust realism, making wavefunction realism a peculiar hybrid. There is a tension between the desire of the wavefunction realist of a robust kind of realism, and the kind of explanation wavefunction realism actually provides, which is not constructive: the wavefunction realist starts as off a robust realist, but she ends up (too) close to the relaxed realist. One can defend wavefunction realism (at least in the case of Albert) by observing that, as a matter of fact, the principles are needed to recover three-dimensionality and microscopic objects, but once these emerge, we can think of macroscopic objects effectively as if they are composed of microscopic entities. That is, constructive explanation still holds. That is, it is not the only step needed to recover the phenomena, but one of the two: principles first, constructive explanation next.

Notice that having at least one constructive step is important. In fact, consider thermodynamics and statistical mechanics. According to many, the laws of thermodynamics could be constructively accounted for in terms of classical statistical mechanics, Lego bricks style. If the wavefunction realist does not have a constructive step in their explanation of the phenomena, then it becomes difficult to see how they can accept statistical mechanics. That is, we can think of macroscopic objects like gases as composed by particles only if these particles emerge microscopically. The principles need to be used only to go from the high dimensional space to the three-dimensional one, and not after the microscopic particles have emerged, otherwise it would be impossible to think of a gas as composed of the microparticles. In other words: if someone wishes quantum theories to be explanatory in terms of principles only, then they should not be too attached to a constructive understanding in general, not only in quantum theory. However statistical mechanics constructively explains thermodynamics, and this arguably extends also to quantum statistical mechanics. But if the explanation provided by wavefunction realism is non-constructive, then there is a tension. How are these two explanations compatible?

5.2 Puzzles for Robust Realists

As we have seen, according to the robust realist, the wavefunction, being a non-spatiotemporal object, cannot represent physical objects, as this would make constructive explanation impossible. In other words, robust realists require a microscopic ontology, and consequently for them the realism problem is a completeness problem: in a robust realist quantum theory the description provided by the wavefunction is never complete, and the fundamental ontology of the theory is spatiotemporal and microscopic. As we have seen, this is straightforwardly accomplished by the pilot-wave theory. Nonetheless, robust realists such as primitive ontologists engage with other quantum theories, and they seem to treat them as equally acceptable robust realist alternatives. That is, *instead of starting from the completeness problem, they focus on the measurement problem.* They say that in order to have a quantum theory amenable to a realist interpretation, the theory needs to solve the measurement problem. But this is puzzling, as they also argue that all robust realist quantum theories have to have a spatiotemporal ontology, and two out of three ways of solving the measurement problems do not respect such requirement: GRW and many-worlds do not solve the completeness problem. These theories the solve the measurement problem in ways other than completing standard quantum theory. So why are they even an option for the primitive ontologists?

Admittedly, primitive ontologists insist that these theories need to be supplemented by a spatiotemporal ontology. As seen above, they discuss various GRW and many-worlds type of theories with a spatiotemporal ontology. However, such theories are bound to be artificial, as *they were meant to solve the measurement problem without solving the completeness problem*. In fact, GRW was developed to unify a wavefunction dynamics which could eliminate unobserved macroscopic superpositions without appealing to measurements, while the many-worlds theory was developed to maintain the Schrodinger dynamics, which consequently lead to recognize the existence of macroscopic superpositions. What is it to be gained in taking these theories and then turning them into solutions of the completeness problem by supplementing them with a spatiotemporal ontology, especially given that one already has the simplest way of doing that, namely the pilot-wave theory?

Primitive ontologists reply that many-worlds and GRW theories with a spatiotemporal ontology have been presented as examples of theories which could begin to be considered constructive theories (because at least they have a spatiotemporal ontology), not as real alternatives to the pilot-wave theory: they lack either simplicity or motivation. For instance, take a many-worlds theory like theory like Sm. This theory predicts macroscopic superpositions because the matter density field inherits the superpositions of the wavefunction. There is no reason for the primitive ontologists to endorse a theory with a many-worlds character, as it is in contrast with the spirit of constructive explanation. So, Sm is not a real contender. Since the many-worlds character of Sm results from the linearity of the Schrodinger evolution, which is inherited by the evolution of the matter field, arguably a theory like GRWm has not the same many-worlds character, at least not macroscopically. Anyway, less controversial is the case for GRWp of GRWf, since particle or spatiotemporal events cannot superimpose. Nonetheless, why do primitive ontologists need such theories, which have a nonlinear and stochastic evolution for the ontology of matter, when the pilot-wave theory provides a much simpler constructive picture with a linear dynamics? In a recent paper, I have explained that the value of looking at GRW-type theories with a spatiotemporal ontology is to explore the *compatibility with quantum mechanics and relativity*.[34] To cut a long story short, in addition to the Lorentz invariance of the laws, people disagree about what it means that a theory is compatible with relativity. One possibility has to do with locality: a theory is compatible with relativity when influence propagate at finite speed. However, given Bell's theorem, arguably no quantum theory can be local. Otherwise, one could say that a theory is compatible with relativity if it is formulated only with relativistic spatiotemporal structure. For instance, if a theory has a preferred foliation,

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[34] Allori (2020a).

namely a preferred spatiotemporal slicing, then it is in tension with relativity. Lorentz invariant extensions of the pilot-wave theory have been proposed but they all have such a foliation, so they are regarded to be in tension with relativity.[35] This is not so for Lorentz invariant extension of GRW theories with a spatiotemporal ontology (like GRWm and GRWf): they are Lorentz invariant and have no preferred foliation. This is the sense in which they are more compatible with relativity than the pilot-wave theory.[36] Because of this reason, it is argued, GRW-type theories are worth exploring as constructive theories. However, in a more recent paper I have changed my mind and I have argued that it is unclear whether GRW theories with a spatiotemporal ontology can substantially bring quantum theory closer to relativity.[37]

On another front, consider the wavefunction: in this framework, the wavefunction does not represent physical objects, but what is it? According to Maudlin (2019), the quantum state, represented by the wavefunction, represents some objective fact about the world. Since it does not represent physical objects, it is better understood as unanalyzable and belonging to belonging to its own ontological category. That is, there are local beables, which represent matter, and then there are non-local beables, such as the quantum state, which are what they are. I think that this primitivist categorization of the quantum state does not straightforwardly fit with the constructive schema advocated by robust realists. Local beables are understood as the fundamental ontology of matter, but what can we say about the quantum state? What does it do? Why is it needed in the theory? How does it serve the constructive schema? A better fit with the constructive understanding, I think, are the approaches which regard the wavefunction as nomological. According to these views, "roughly speaking, the wave function tells the matter how to move."[38] Several proposals have been put forward to make this idea more precise. My suggestion, dubbed *wave-functionalism*, is that the wavefunction should be understood as one possible, convenient ways of realizing one of the ingredients needed to implement the dynamics for the fundamental ontology. In a slogan, the wavefunction is functionalized: the wavefunction is the functions it plays in the theory.[39] This view of the wavefunction is compatible with a constructive explanation: the wavefunction does not represent the Lego bricks the castle is made of, but it represents the rules in the booklet to guide us constructing the castle.

As a final remark, there seems to be restrictions on the view of laws that a proponent of this approach can hold. Being the approach constructive, the laws should be seen as grounding the dynamical explanation. That is, they should be seen as *Fundamental Laws of Time Evolution* (FLOTEs): they describe the evolution of a physical system through time.[40] In other words, a

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[35] See most notably Berndl *et al.* (1996), Dürr *et al.* (1999), Dürr *et al.* (2013).

[36] See Tumulka (2006, 2020) for a Lorentz invariant GRWf without and with interaction; see Bedingham *et al.* (2014) for a Lorentz invariant GRWm theory.

[37] Allori (2022).

[38] Allori *et al.* (2008).

[39] Allori (2021b).

[40] Maudlin (2007).

constructive approach has two components: matter, understood in terms of Lego bricks, and the laws, understood as instructions about how these bricks can stick together. Instead, Chen and Goldstein (2022) have recently proposed an account of laws of nature as constraint: laws "govern the behavior of material objects by constraining the physical possibilities." They also write: "laws explain, but not by accounting for the dynamic production of successive states of the universe from earlier ones. They explain by expressing a hidden simplicity, given by compelling constraints that lie beneath complex phenomena." In this view, laws substantially play the role of principles: they exclude what cannot happen without further explaining why that is. This is opposed as a dynamical conception of laws, in which laws specify the temporal evolution of the fundamental ontology. If so, this view is in direct contrast with the constructive understanding, according to which laws govern the dynamics of matter, and explain what happens in terms of the permissible dynamics. This creates a tension for Goldstein, who in the past have defended the primitive ontology approach. In this paper I have motivated this approach on the basis that it allows for a constructive explanation of the phenomena. This approach relies on a dynamical conception of laws. If instead one endorses a different understanding of laws, in which laws are supposed to constrain the phenomena, they are undermining their case for a spatiotemporal ontology on the basis of constructive explanation. In fact, if the argument for a spatiotemporal ontology is that constructive explanation should be preferred to principle explanation, then on what basis does one claim that laws are constrains? Conversely, if one finds laws as constrains as not problematical, then there seems to be no reason why they should favor constructive explanation to start with.

6. Conclusion

I have argued in this paper that, contrarily of the common understanding, it is not obvious what problem one needs to solve to make standard quantum mechanics amenable to a realist interpretation. Wavefunction realists think it is the measurement problem, namely the problem of precisely eliminating unobserved macroscopic superpositions (what I have called the precision problem). Wavefunction realists, in their quest for a local and separable ontology, require theories to have a unique and precise dynamics, without requiring the ontology to be in spacetime, and end up rooting for many-worlds theory and GRW. I have argued that not everyone thinks that this is the correct strategy to follow to make quantum theory compatible with realism. In fact, they have different ideas about what being a realist means and what a satisfactory theory should provide. For instance, the proponents of the IT approach argue that standard quantum mechanics with the collapse rule can be interpreted from a realist perspective because, they think, a realist theory only needs to be empirically adequate in the sense of effectively systematizing the macroscopic data. In this relaxed type of realism, a theory explains in terms of principles and the microscopic description of the phenomena is not important. In contrast, primitive ontologists require a constructive explanation in terms of a microscopic fundamental ontology. This leads them to endorse a robust type of realism and to reject all theories in which there is no microscopic ontology. This implies that what needs to be done to make quantum mechanics amenable to a realist understanding is to complete it with a spatiotemporal entity, automatically selecting as preferred the pilot-wave theory.

The following table summarizes this conclusion.

Table 1:

Type of Realism	**Type of Problem**	**Type of Explanation**	**Acceptable Theory**
Robust	Completeness	Constructive/dynamical	Pilot-wave
Modest	Precision	Non-constructive/dynamical	GRW, many-worlds
Relaxed	Adequacy	Principle/kinematical	Collapse rule

In the last section, I have outlined several problems and puzzles for the various approaches. Even if I am partial to a constructive understanding, the point of this paper was not to argue for it. Rather, I wanted to present some prominent positions, their different motivations and guiding intuitions, because I thought this would help us make progress towards a common understanding of the quantum world. Certain commitments will be less likely to be changes, but many other can be dropped, if presented with the right argument.

In fact, by better understanding the disagreement between the various approaches, one can better fine tune their arguments, both for and against these different perspectives. For instance, to say to a proponent of the IT approach that they need a microscopic ontology because compositionality and constructive explanation fail in their approach will certainly not change their mind. In fact, they already think that principle explanations are better and that constructive explanations are not needed. Rather, if someone wants to convince them that they should adopt another view they need to argue, for instance, that principle theories are not explanatory enough, or that principle theories are not a good guide to ontology. Moreover, after having tried to distill the motivations behind the IT approach, I could make a better case for it by showing that one can have principle theories with a non-epistemic wavefunction. Similarly, it is going to be ineffective to point out to the wavefunction realists that they need a spatiotemporal ontology, because such an ontology will not preserve locality, which is their guiding principle. Instead, to convince them that they approach is not with it, for instance, one should argue that locality is less important that they think it is, or that their reason to keep it works in three-dimensions but not in high dimensions. Only in this way, they will let their guiding principle go and accept a constructive explanation. Also, proposing a local constructive theory (which would therefore have a spatiotemporal ontology) would convince them to drop their high dimensional ontology, presumably even if such proposal were retrocausal or superdeterministic.[41] Moreover, a better case for wavefunction realism could be made by motivating locality and separability differently, or justifying a high dimensional ontology in

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[41] See, for instance Ciepielewski, Okon and Sudarsky (2020).

some other way, other than via separability and locality. Finally, pointing out that the pilot-wave theory has a foliation is not going to help convincing the primitive ontologists that they are on the wrong path because they are going to argue that other theories with a spatiotemporal ontology do not have it. That is, it is not necessary to use principle theories to make quantum theory compatible with relativity. Instead, a better argument against the primitive ontology approach would be one which shows that constructive explanation is impossible for some reason. Conversely, one could improve the arguments for the primitive ontology approach by showing that this constructive understanding can be extended to more general theories like relativistic quantum field theories.

Be that as it may, the bottom line is that only after there is mutual appreciation of the alternative views, one can start making progress efficiently, avoiding situations in which the two sides talk past one another. Hopefully, with this paper I have contributed to this.

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