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Many-Worlds: Why Is It Not the Consensus?

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Abstract: In this paper, I argue that the many-worlds theory, even if it is arguably the mathematically most straightforward realist reading of quantum formalism, even if it is arguably local and deterministic, is not universally regarded as the best realist quantum theory because it provides a type of explanation that is not universally accepted. Since people disagree about what desiderata a satisfactory physical theory should possess, they also disagree about which explanatory schema one should look for in a theory, and this leads different people to different options.

Keywords: interpretations of quantum mechanics; Everettian quantum mechanics; many-worlds theory; primitive ontology; principle and constructive theories

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1. Introduction

Quantum mechanics is known to be resistant to a realist understanding, as it is unclear what picture of reality it provides us. Nonetheless, a variety of realist quantum theories have been proposed, and among these, one finds the many-worlds theory, also known as Everettian quantum mechanics. There are various readings of this theory, but they all have in common that all there is in the theory is a quantum state, evolving according to the Schrödinger unitary evolution equation, which produces experimental results distributed according to the Born rule. Other notable realist quantum theories are the spontaneous localization theory, also known as GRW theory, and the pilot-wave theory, or de Broglie–Bohm theory or Bohmian mechanics. Nonetheless, according to many advocates of Everettian quantum mechanics, there should be no debate over which quantum theory is best: the many-worlds theory is the simplest most straightforward interpretation of the quantum formalism, as it does not require any modifications of the mathematics of the theory. Moreover, it is maintained, it is consistent with how physicists use the theory as well as its relativistic extensions. Therefore, one question arises naturally: why is it not the consensus? Why are all people not Everettians?

According to some (Wallace p.c.), Everettian quantum mechanics is the implicit consensus, at least among practicing physicists; when they perform calculations, they use the Born rule, they never write down the guidance' equation for the waves, and they never need to modify the unitary evolution. That is, they implicitly adopt the many-worlds theory. However, *pace* Wallace's optimism, I think this is not exactly how most physicists characterize what they are doing. When informally asked, many of them say that they use standard quantum mechanics, namely the unitary evolution and the collapse rule, rather than unitary evolution alone, and they do not believe that they and their labs are continuously 'splitting' into infinitely many worlds. Indeed, some of them will not even see the point of 'adding' these worlds on top of the empirical adequacy of the standard theory. If the many-worlds theory makes the same predictions of standard quantum mechanics, but also postulates an infinity of unobservable worlds on top of the one we experience, then why should one prefer this theory to standard quantum mechanics? In any case, among philosophers of physics, the situation is certainly very different: many do not find Everettian quantum mechanics satisfactory or the best alternative, and even among those who do, they have their own ways of formulating the view.

Vaidman [1] argues that the many-worlds theory is not the consensus due to its revolutionary, groundbreaking metaphysics. He writes: “We would like to think that we are the center of the Universe: that the Sun, together with other stars, moves around Earth, that our Galaxy is the center of the Universe, and we are unhappy to accept that there are many parallel copies of us which are apparently not less important”. He also blames technical difficulties that the theory faces, such as the justification of the Born rule or the preferred basis problem. Moreover, he thinks that the fact that some understand the theory as fundamentally not in spacetime obscures “the connection between ontology and our experience”. While I think that these are important issues, I disagree that they are the fundamental reasons why the many-worlds theory is not universally accepted.

In this paper, I argue that there is no consensus because people favoring different theories have profoundly different motivations guiding their search for a satisfactory theory, which leads them to favor specific explanatory structures. The paper is organized as follows. In the next section, I provide a brief overview of standard quantum theory, the measurement problem, and the distinction between principle and constructive theories, as well as between frameworks and interaction theories, which will help me compare the various approaches. To make my case that disagreement is connected with theory desiderata and preferred explanatory types, first, I contrast the information-theoretic (IT) approach of quantum mechanics with the primitive ontology approach. I discuss the former in Section 3, and I argue that the proponents of this approach are satisfied with an empirically adequate theory. This fits well with an explanation in terms of principles, without requiring a microscopic ontology, and this naturally leads them towards standard quantum theory. In Section 4, I analyze the primitive ontology approach, and I argue that the proponents of this view are guided by a constructive understanding. This requires a theory to possess a spatiotemporal microscopic ontology, and the pilot-wave theory is the simplest theory of this kind. Then, in Section 5, I move to Everettian approaches, which aim at reading physics at face value, thereby conceiving of quantum theory as a framework, which could fit different theories. Consequently, they argue that Everettian quantum mechanics is the only option which describes the entire framework, rather than a single theory. In contrast, wavefunction realism, which is discussed in Section 6, is guided by finding a theory with a local and separable ontology. This leads them to think of the various quantum theories as interaction theories, which describe how the basic ontology, provided by the non-spatiotemporal wavefunction, behaves. I summarize and conclude in Section 7.

2. Setting the Stage

Quantum mechanics, as it is found in physics textbooks (‘standard quantum mechanics’ for short), is presented axiomatically, in terms of postulates. The first of them is that possible states of any physical system are described by quantum states, which are rays in a Hilbert space. When written as a function of position, the quantum state is called the wavefunction. In addition, it is postulated that the measurable properties of a physical system (often called ‘observables’) are represented by self-adjoint (Hermitian) operators. There is a preferred observable, the Hamiltonian, which generates the dynamical evolution of the quantum state in terms of the (linear and deterministic) Schrödinger equation (sometimes called unitary dynamics). Since the Schrödinger equation is linear, superpositions of solutions will be solutions, and they will propagate macroscopically, even in situations in which we do not observe any, as in the infamous example of the Schrödinger cat. That is, the theory is, as is, empirically inadequate: it fails to predict what we observe (lack of macroscopic superpositions). One can fix this problem by adding the so-called von Neumann collapse rule, which kicks in when a measurement of a given observable is performed. This rule states that the wavefunction randomly and instantaneously ‘collapses’ into one of the possible solutions of the Schrödinger equation for that measurement situation. That is, the possible values of the observable associated with some operator are given by the eigenvalues of that operator, and the wavefunction collapses into the eigenstate corresponding to that eigenvalue. This is the so-called eigenvalue–eigenstate rule (EER). Finally, it is stipulated that the probability to find a particular measurement result is provided by the Born rule: the probability of obtaining some eigenvalue is given by the scalar product of the initial state and the eigenvector corresponding to that experimental result.

With these postulates, even without specifying whether matter is made of particles or waves or something else, standard quantum theory can account for the known phenomena, and it can make novel predictions.

Classical mechanics instead is very different. As it is taught in physics books, it starts from a stipulated and clear metaphysical hypothesis, namely that everything is composed of point particles, which evolve in time according to Newton's second law, moving in space, which is suitably described by having a three-dimensional Euclidean structure. In contrast with the quantum case, the classical formalism does not require any interpretation, as it is clear what the various mathematical objects correspond to: x is the particle's position, v is its velocity, m is mass, and so on. Furthermore, as every physics student is taught, there are abstract spaces without a physical meaning only to ease computation, like in the case of Lagrangian and Hamiltonian mechanics, and these are not to be taken ontologically seriously.

Nonetheless, dissimilarities aside, both classical and quantum mechanics have enjoyed an enormous amount of success, albeit the type of success they have is very different. For instance, while the predictions of quantum theory have shown an unprecedented amount of precision and accuracy, we no longer have a clear understanding of the underlying microscopic reality. In other words, while standard quantum mechanics enjoys incredible predictive success, classical mechanics also had a type of explanatory power which quantum theory completely lacks. That is, classical mechanics could provide a pictorial image of, say, what water is. Water is a two-hydrogens-one-oxygen molecule, in which the atoms are kept together by a polar bond. On top of that, one could also picture hydrogen and oxygen as small balls with peculiar appendages, which would allow them to fit together, and water could be imagined to be a collection of such composites held together by some sort of loose rubber band. This pictorial understanding could explain, say, why water at a given temperature becomes solid: the composites are stuck in the corner of a hard, geometrical, crystalline structure. In other words, in classical mechanics, one could have explanatory illustrations: one can draw pictures of the physical phenomena to understand them better. Instead, standard quantum theory does not provide any microscopic picture of the reality underlying the phenomena. There are pictures in the textbooks, but one is always warned not to take them too seriously. For instance, the orbitals of the electrons around the nucleus are not like the planetary orbits around the Sun. Rather, the orbitals are to be understood as 'probability clouds'; we are told that they represent a surface where the probability per unit of volume of finding an electron is constant. Similarly, the interference pattern in a two-slit experiment with electrons is not generated, as one would have understood classically, by a physical wave passing through both slits and interfering with itself. Rather, it is a 'probability wave': the interference pattern expresses the probability to find the electron when measured. That is, standard quantum mechanics does not allow us to draw or to picture in our mind what an electron does or how it moves. Nonetheless, it seems too much to say that standard quantum theory does not explain anything. It can explain, but in a different way: standard quantum theory can explain why one observes the two-slit experiment interference pattern, not in the sense that it tells us where the electron has gone and, thus, where it will be detected, but in the sense that the observed distribution of detections is the one predicted by the theory.

It has been argued that we cannot have anything better than this: standard quantum mechanics cannot provide a coherent microscopic picture of reality. That is, someone providing such a description would run into contradictions. For instance, the two-slit experiment performed with entities so far understood as particles, such as electrons, shows that they inexplicably behave like waves because they interfere. Alternatively, the photoelectric effect shows that light, so far understood as a wave, inexplicably behaves as a particle, because the observed intensity of the emitted light is compatible with a particle rather than a wave ontology. But how is it possible? It is because of examples like these that some people became convinced that a coherent microscopic picture of the quantum world was impossible and many more decided to ignore questions about ontology. They instead decided to focus on formulating the theory as to make contact directly with macroscopic observable quantities rather than microscopic unobservable entities. That resulted in the axiomatic quantum theory presented above: the postulates are about measurement results, and they are expressed in terms of 'abstract' entities, rather than in terms of the motion of unobservable microscopic entities, as in the classical theory. As such, the theory has been taken to be incompatible with scientific realism, the view that theories can give us information about the nature of reality beyond the phenomena.

2.1. The Measurement Problem

Some have argued that this is the true quantum revolution: our classical desire of understanding is doomed to fail, so perhaps we should become anti-realist. Nonetheless, one may think this is too harsh. Perhaps we did not think enough about the possibility of making standard quantum mechanics compatible with a realist reading. Indeed, what would be required from a realist quantum theory? It is usually maintained that such a theory would have to solve the so-called measurement problem.

One of the things which seems to make the standard theory unsuitable for a realist reading is the fact that there are two evolution equations, and that they are expressed in terms of measurement: the Schrödinger evolution holds when no measurements are performed, and the collapse rule when a measurement takes place. As noted, the collapse rule is needed to eliminate unobserved macroscopic superpositions produced by the linear evolution, but this is at the expense of promoting measurement processes to a privileged status, as whether a measurement happens or not determines which evolution the wavefunction would follow. This is bad news for the realists, as they would like to think of measurements as merely special types of physical processes. If so, then it is natural to assume that the wavefunction is the fundamental ontology of everything, and its fundamental evolution is given by the Schrödinger equation. As a result, however, there will be 'superpositions of states' at all scales, which we never observe. Therefore, the measurement problem is the problem of dealing with unobserved macroscopic superpositions without postulating a measurement-dependent double dynamics, as the standard theory does.

The measurement problem is sometimes formulated by stating that three claims are incompatible [2]: (1) the wavefunction provides the complete description of any physical system; (2) the wavefunction evolves according to the Schrödinger equation; (3) measurement outcomes are unique (which is to say that there are no unobserved macroscopic superpositions). Solutions of the measurement problem are often portrayed as denying one of these three claims: the pilot-wave theory denies that the description provided by the wavefunction is complete; the GRW theory denies that the wavefunction evolves according to the Schrödinger dynamics; and the many-worlds theory allows for superpositions at all scales. Usually, the solutions of the measurement problem are taken to be the realist quantum theories, namely the quantum theories that realists should look at in their investigations about the nature of the quantum world.

There are too many ways of understanding the metaphysics of quantum mechanics to analyze them all. In any case, one can group them depending on which is their favorite theory. On the one hand, we have primitive ontologists, who favor the pilot-wave theory (or some versions of GRW) and, on the other hand, we have wavefunction realists who favor either the many-worlds theory (or other versions of GRW). Oxford Everattians, championed by Wallace, also favor the many-worlds theory, which is also defended by Vaidman.

In the next sections, I analyze these different approaches, and I argue that people disagree because they require different desiderata for a theory to be successful: they have different motivations, connected to different understandings of explanation, which lead them to favor a given type of theoretical structure, and this translates into naturally favoring different quantum theories over others. I discuss different theoretical structures in the next subsection.

2.2. Constructive Explanations, Principle Theories, Interactions, and Frameworks

Not all physical theories are of the same sort: thermodynamics is different from classical mechanics, which is different from optics, which is different from electromagnetism, and so on. Some have dynamical equations, while some others have principles, some have forces, while some others have constraints, *et cetera*. Therefore, one may think it is not surprising that quantum and classical mechanics are different: they are just another pair in the list. Nonetheless, one could recognize shared features among the various theories. Some theories are what Einstein [3] called constructive theories. For one thing, these theories have a microscopic ontology, which constitute the building blocks of everything else. Constructive theories allow one to understand the phenomena compositionally and dynamically: macroscopic objects are composed of microscopic particles, and the macroscopic behavior is completely specified in terms of the microscopic dynamics. Therefore, the type of explanation these theories provide is bottom-up, rather than top-down. According to Einstein, there is another type of theory, which he dubbed principle theory. Theories of this type, also called kinematic theories, are formulated in terms of principles, which are used as constraints on physically possible processes: they exclude certain processes from physically happening. In this sense, principle theories are top-down: they explain the phenomena identifying constraints the phenomena need to obey to. They are 'kinematic' theories because the explanations they provide do not involve dynamical equations of motion and they do not depend on the interactions the system enters into. Instead, by definition, constructive theories involve dynamical reductions in macroscopic objects in terms of the motion and interactions of their microscopic three-dimensional constituents. Flores [4] argued that this distinction could be expanded in terms of framework theories, which deal with general constraints, and interaction theories, which explicitly invoke interactions. He thought that framework theories are principle theories while interaction theories include a larger set of theories than constructive theories. Furthermore, he connected framework theories with unification and interaction theories with mechanistic explanation (see also [5,6]).

I think that, contrary to Flores, the two distinctions do not capture the same idea, as I discuss in Section 6. In any case, I am going to use them both to characterize the different motivations and explanatory strategies of the various approaches. While the constructive-principle distinction is useful to contrast the primitive ontology approach with the IT approach, the interaction-framework characterization will be helpful in the comparison between wavefunction realism and Everettian quantum mechanics.

Be that as it may, an example of a principle theory is thermodynamics (e.g., "energy is conserved" is a principle), and an example of constructive theory is statistical mechanics, which reduces the behavior of gases to the motion of atoms. Another example of principle theory (which motivated Einstein's distinction in the first place) is the 1905 theory of special relativity (before the introduction of Minkowski spacetime), as it was formulated in terms of two principles: the principle of 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 was proposed to explain the same phenomena, but it does it constructively: it derives the relativistic effects from the electromagnetic properties of the ether and its interactions with matter.

One can read standard quantum mechanics as a theory of principles, as the axioms presented above constrain the phenomena. This is arguably one of the reasons why Einstein disliked this theory. In fact, Einstein maintained that "most [theories in physics] are constructive. They attempt to build up a picture of the more complex phenomena out of the materials of a relatively simple formal scheme from which they start out. Thus, the kinetic theory of gases seeks to reduce mechanical, thermal, and diffusional processes to movements of molecules". Moreover: "When we say that 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" (*ibid.*). As mentioned above, Einstein introduced the distinction to explain why he was not happy about his theory of relativity being a principle theory. He did not accept Lorenz's constructive relativity because Einstein did not think we had the right understanding of the theory of matter involved (an atomistic understanding of the Lorentz contraction was unavailable). According to Einstein, principle theories are provisional in nature. That is, we usually accept principle theories when we do not have other explanations of the phenomena. Einstein believed that physics should look for constructive theories and that we accept principle theories only when we have no other option. Arguably, then, he could have said something similar for quantum theory, as 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, which is, however, in need of a constructive explanation in terms of a still-unknown more fundamental theory expressed in terms of 'hidden variables'.

Nonetheless, some have argued that there is nothing wrong with explanation in terms of principles. Let us turn to this approach in the next section.

3. The IT Approach: Standard Quantum Mechanics as a Principle Theory

Some have argued that one can provide a realist understanding of standard quantum mechanics even without solving the measurement problem. For instance, according to the proponents of the IT approach, it is a matter of being careful in choosing the fundamental ontology for standard quantum theory [7]. They claim that it is a dogma that the fundamental ontology of a theory should be microscopic: it is a dogma that measurement should be understood in terms of other, more fundamental, microscopic processes. Rather, if one takes measurement results as primitive and unanalyzable, one can consider them to be standard quantum theory's fundamental macroscopic ontology.

3.1. Motivation: Empirical Adequacy

The main motivation for this approach is empirical adequacy. That is, a satisfactory theory is one which adequately reproduces the phenomena at the macroscopic level. Thus, one should be content with a theory which predicts the measurement outcomes, understood as the fundamental ontology of the theory. As discussed earlier, unitary quantum theory, namely the theory of a Schrödinger evolving wavefunction, is not empirically adequate: it fails to predict that there are no macroscopic superpositions. This problem is solved by standard quantum theory introducing the collapse rule and allowing for a double dynamics, depending on whether a measurement is performed or not. The proponents of the IT approach are not bothered by not having a unique, not measurement-dependent dynamics, because they actually do not understand the two evolution equations as dynamical laws at all. They provide the specification of what we should expect in terms of measurement outcomes. It happens that this specification is conveniently provided in terms of the collapse rule and the Schrödinger equation, but one should not really take these specifications too seriously, ontologically speaking. Other formulations could be possible, and perhaps more convenient. What is important is that they are effective in correctly reproducing the data and in adequately predicting what we should expect to observe. That is, what is important is for the theory to predict what to expect in terms of its principles. In fact, given that compositionality fails, explanation cannot be constructive. Standard quantum theory (with the Schrödinger equation and the collapse rule) provides that, and in virtue of that, they find nothing wrong in having the collapse rule. Consequently, for them, there is no need to solve the measurement problem: there is no need to have a unique dynamics for the microscopic entities because they are not what the theory is about.

3.2. Explanations as Kinematic Top-Down Systematizations

According to the IT approach, standard quantum theory is best understood as a principle theory. As mentioned, principle theories provide a top-down explanation, in the sense that they explain the phenomena identifying constraints they need to obey. More specifically, in the case of standard quantum mechanics, Hilbert space is thought of 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" [7]. This type of explanation is fundamentally different from the one provided by classical mechanics: quantum theory lays out a set of constraints imposed on the empirical data, rather than specifying some microscopic story about how a given result comes about.

In general, supporters of the IT approach maintain that in order to provide a satisfactory explanation, one does not need a deeper, dynamical account: "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 certain physical situation, so does standard quantum theory. There is no reason and no need to ask for more. In fact, they do not say this, but one could maintain that this approach is to be preferred because principle theory explanations are independent on the detailed assumption about the structure or the constitution of matter.

Be that as it may, also, QBists think of quantum theory as providing constraints on measurement outcomes (see [8] and references therein). However, in contrast, QBists leave open the possibility for a deeper understanding: "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" [9]. In addition, Pragmatist quantum realism (see [10] and references therein; see also [11]) agrees with the IT approach that standard quantum mechanics is a principle theory: the Born rule assigns phenomena probabilities of happening, and these probabilities express our degrees of belief that a given phenomenon will happen.

It is important to underline that all these proposals characterize themselves as not anti-realist: they do believe that standard quantum theory with the collapse rule tells us something objective about the world. It does not matter that the collapse rule does not specify what measurements are because in these approaches, measurements are unanalyzable primitives. Moreover, since they believe that standard quantum theory is about experimental results, they are realist about measurement outcomes. They exist objectively and mind independently. In other words, these attitudes are realist, in the sense that theories are taken to be objectively informative about the world: the description they provide is independent from us.

However, from a theory, they require very little: they think that it is enough to provide an accurate description at the macroscopic level and an explanation in terms of principles constraining the phenomena. They do not require a unique dynamics for all levels of description: in these approaches, the two equations are seen as principles, rather than dynamical laws. Correspondingly, since their explanation is not constructive, they do not have to require a microscopic ontology. In this approach, as long as the principles make the theory empirically adequate, the theory is amenable to a realist interpretation.

A realist approach similar to the one described here rainforest realism [12]. Rainforest realism is a view, according to which objects, both at the microscopic and the macroscopic level, do not fundamentally exist. All there is at the fundamental level is structure. This is a radical structuralist position in which all objects are eliminated from the fundamental level but are seen non-fundamentally as real patterns, defined by their usefulness. What we call 'particles' are neither fundamental nor composed entities. Rather, they are merely useful fictions: they allow us to conveniently express certain regularities at a given level of description. The same is true for chemical compounds, molecules, tables, chairs, and measurement devices. They are not analyzed in terms of more fundamental entities, because they are not composed entities. Rather, they are understood as effective descriptions. This position is realist: theories talk about the word, and at all levels, many types of entities emerge. This approach fits nicely with the idea that a theory explains the phenomena in terms of principles rather than dynamically. Moreover, in this case, the fact that the collapse rule is vague does not create a problem for rainforest realism because measurement devices and measurement outcomes are patterns, and patterns are vague.

4. Primitive Ontology: The Pilot-Wave Theory as a Constructive Quantum Theory

If the proponents of the IT approach think of standard quantum theory as a principle theory and, in virtue of that, they argue that there is no need for a microscopic description of reality, primitive ontologists instead defend the constructive point of view that principle theories always need a microscopic explanation (see, to start with, [13–16]).

4.1. Motivation: Constructive Explanation

According to primitive ontologists, a satisfactory explanation is a constructive explanation. Here is a quote:

> " ... in the classical framework we have a clear and straightforward scheme of explanation: given the primitive ontology at the microscopic level, one can employ standard methods to determine the properties of familiar macroscopic objects. Since in classical theories this is possible because the theories have a primitive ontology, for any other fundamental physical theory with a primitive ontology, like the quantum theories we just discussed, we could employ an explanatory scheme derived along the lines of the classical one". [16]

We had a constructive account in classical theory, but we do not have one in quantum theory. Quantum and classical mechanics are two proposals for fundamental physical theories, but they have barely anything in common. They both have 'mechanics' as part of their names, but what that amounts to in the two theories is very different, aside from very generally conveying the idea that both theories deal with the motion of physical bodies in terms of forces, potentials, and energy. In classical mechanics, it is arguably clear what matter is made of, how it behaves, and how one recovers the macroscopic behavior we observe from these ingredients: macroscopic objects are composed of microscopic particles, whose position in time and whose mutual interaction are described by Newton's laws. Primitive ontologists think that this precise microscopic picture allows one to account for the observed macroscopic properties and phenomena. For instance, water is liquid at a given temperature and solid at another because the interaction between water's molecules accordingly changes with temperature. Accordingly, they think that we should construct a constructive counterpart to standard quantum theory. A theory in which the quantum phenomena are explained constructively, namely a theory in which macroscopic objects are composed of microscopic entities and their properties, is dynamically understood in suitable scale limits (see below).

As observed earlier in the case of Einstein, traditionally, physicists have looked for constructive theories. Pauli, among others, explicitly favored constructive theories, even if he rejected Lorentz theory:

> "Should one, [...] completely abandon any attempt to explain the Lorentz contraction atomistically? We think the answer to this question should be No. The contraction of a measuring rod is not an elementary but a very complicated process. It would not take place except for the covariance with respect to the Lorentz group of the basic equations of the electron theory, as well as of those laws, as yet unknown to us, which determine the cohesion of the electron itself.

> We can only postulate that this is so, knowing that then the theory will be capable of explaining atomistically the behaviour of moving rods and clocks". [17]

Some have argued that principle theories are not explanatory: "Explanations are about the reality behind the phenomena (be it about their causes or about their nature). Principle theories [. . .] are agnostic about that" [18]. Others have argued that constructive theories are better, as they provide insight about the reality underlying the phenomena:

> "In a theory of principle, one starts from some general, well-confirmed empirical regularities that are raised to the status of postulates (e.g., the impossibility of perpetual motion of the first and the second kind, which became the first and second laws of thermodynamics). With such a theory, 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 (e.g., the kinetic theory modeling a gas as a swarm of tiny billiard balls bouncing around in a box). One explains the phenomena by showing that the theory provides a model that gives an empirically adequate description of the salient features of reality". [19] (see also [20–22])

I take this to mean that to explain constructively seems deeper: constructive explanations not only account for the phenomena, as they also explain where the phenomena come from. In other words, a principle explanation provides a reason why one should expect a phenomenon to happen, while a constructive explanation also explains why it happens. Constructive theories not only predict the correct results, but they also give you a reason why these predictions come about and thus why you should expect certain results and not others.

What is required for a constructive explanation? The essence of this type of explanation is to be bottom-up. That is, it explains compositionally and dynamically: it is a Lego brick style of explanation, in which there are fundamental entities which build up the rest of the non-fundamental entities. In order to have such an explanation, one needs a fundamental spatiotemporal ontology which is suitably microscopic. This is because both of them are requirements to make sense of this Lego bricks picture: the individual Lego bricks (the fundamental ontology) used to build a castle (the macroscopic phenomena) are in the same space as the castle (spacetime) and they are smaller than the castle (microscopic). As in classical mechanics, with an ontology of particles, one could think of macroscopic objects as composed of microscopic particles and account for their properties in terms of the microscopic dynamics. A quantum constructive explanation would then require such a spatiotemporal microscopic ontology.

Standard quantum theory falls short of constructive explanation in at least two ways: it has two dynamical evolutions, and it has no clear ontology. The IT approach has a macroscopic ontology, but that does not allow for constructive explanation. Moreover, they do not interpret measurements as physical processes, while constructivists should. Since a constructive quantum theory provides us with a microscopic spatiotemporal picture of the world, it should describe measurement processes in terms of such fundamental spatiotemporal microscopic ontology and its (unique) dynamics, valid for all scales. Therefore, the way to go to obtain a constructive quantum theory is to recognize that we should treat standard quantum theory as we treated 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. According to the constructivist, one can (and should!) reduce thermodynamics in terms of classical mechanics: if one thinks of gases as collections of microscopic particles, one obtains a deeper explanation of the behavior of the gases. In contrast with the case of thermodynamics, in which we already had the more fundamental microscopic theory, in the quantum case, we still do not have it. Therefore, the constructivist should look for it.

Through this theory, one would be able to understand quantum systems in terms of a more fundamental ontology and to arrive at a deeper understanding of why quantum phenomena happen, rather than merely settling for accounting for what we should expect. In this way, as it would be absurd to use a gas ontology for classical mechanics to reduce thermodynamics, one should not use the wavefunction as the ontology of the reducing constructive quantum theory. Since the wavefunction 'belongs' to the reduced theory, it does not make sense to use it as the ontology for the reducing one. In addition, the wavefunction is not defined in spacetime, which allows for constructive explanation. Rather, it is defined in a high dimensional space, usually called configuration space. Since constructivists require a spatiotemporal fundamental ontology, the obvious choice is the one of particles. For once, they seem more compatible with the empirical evidence of tracks in detectors. Nonetheless, waves can also be a suitable ontology for a constructive approach, but they at least need to be oscillating in (three-dimensional) space, evolving in time. Furthermore, waves need to superimpose to form stable and localized wave packets to reproduce particle-like observed behavior. This, however, would require a nonlinear dynamics, like the one in theories such as GRWm, where the fundamental spatiotemporal ontology is given by a matter density field, defined in terms of a wavefunction evolving according to the GRW (nonlinear stochastic) evolution [23]. Alternatively, one could try to develop de Broglie's double solution program, in which the fundamental ontology is a wave oscillating in three-dimensional space, guided through a nonlinear equation by another wave in configuration space (the wavefunction), which has "only a statistical and subjective meaning" [24] (for a review, see [25]).

Be that as it may, notice that this constructive attitude is the attitude that all realist physicists have always had, even when standard quantum theory was initially proposed. It can arguably be 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 a three-dimensional field such as electromagnetic fields. He 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" (Lorentz in [26]). Similar concerns were raised by Einstein. In a letter to Lorentz dated 1 May 1926, he 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 18 June 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 [27]). In addition, de Broglie and an early Schrödinger were skeptical about interpreting the wavefunction as a physical field. 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". 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" [28]. Moreover, de Broglie 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" [29]. Interestingly, even Heisenberg expressed his refusal to accept a theory with no fundamental three-dimensional fields and with no fundamental three-dimensional physical space. He has been reported to have said, very vividly, referring to Schrödinger's work: "Nonsense, [. . .] space is blue and birds fly through it" [30]. This attitude has been inherited by the primitive ontologists who, therefore, propose that any satisfactory theory should have a spatiotemporal suitably microscopic ontology. Accordingly, primitive ontologists think that standard quantum theory as well as all solutions of the measurement problem except the pilot-wave theory are fundamentally incomplete because, otherwise, constructive explanation would fail, given that they all lack a spatiotemporal ontology (this is explicit in [15,16,31,32]). In fact, the many-worlds theory and GRW are usually seen as theories of the wavefunction, which is in configuration space. That is, for primitive ontologists, solving the measurement problem is not enough to generate a satisfactory theory because not all solutions of the measurement problem are amenable to a constructive understanding. For them, there are different satisfactory quantum theories, depending on the choice of the microscopic spatiotemporal ontology. The pilot-wave theory is arguably the simplest among the options: it has the simplest type of ontology (particles) and the simplest evolution equations (linear and deterministic).

Nonetheless, some stochastic nonlinear constructive quantum theories have been recently proposed, arguably because they seem to be more compatible with relativity than the pilot-wave theory: GRWm, which we saw above, and GRWf, which is a theory of a set of spatiotemporal events ('flashes'), are defined in terms of a GRW-evolving wavefunction [33]. These theories each have a relativistic extension, which uses only relativistic spatiotemporal structures (see, respectively, [34,35]) rather than a preferred spatiotemporal foliation, as it happens for relativistic extensions of the pilot-wave theory [36]. For more discussion about the alleged advantage of GRW-type theories, see [37].

In addition to primitive ontologists, others have emphasized the importance of space-time or three-dimensionality for a satisfactory ontology. For instance, Maudlin [38] popularized Bell's idea of local beables: "those which (unlike for example the total energy) can be assigned to some bounded space-time region" [33]. Moreover, Norsen [39] 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 multifield is an extension of the concept of field, as it assigns a number to a set of locations, rather than only one location, in three-dimensional space [40–44]. Arguably, these approaches can all be seen in constructive terms: just like classical electromagnetism has, in addition to particles, electric and magnetic fields oscillating in three-dimensional space, in quantum theory, the wavefunction is seen as a suitable field also oscillating in three-dimensional space.

4.2. Explanations as Dynamical Bottom-Up Constructions

In the constructive understanding, once the fundamental spatiotemporal microscopic ontology is specified, compositionality and dynamics can be used to explain the macroscopic phenomena, along the classical lines. In this way, the entities of the microscopic fundamental ontology aggregate into composites: quarks and gluons form protons and neutrons, which form atoms, which form molecules, which, depending on how they interact, form liquids, gases, complex proteins, or crystalline structures, viruses, bacteria, animals, stars, and nebulas. These non-fundamental entities constitute the non-fundamental ontology of high-level sciences. These non-fundamental ontologies have the remarkable feature of being autonomous at certain scales. For instance, one can formulate a theory of chemical elements to explain their behavior as if atoms are effectively the ontology, without the need of specifying their detailed microscopic composition in terms of subatomic particles. That is, atoms may be thought of as the effective ontology of the theory valid at that scale, even if such an ontology could be explained in terms of a more fundamental ontology at a smaller scale, such as protons and neutrons. This is, for instance, what thermodynamics does for gases, hydrodynamics does for fluids, or rigid body dynamics does for solid bodies: gases, fluids, and rigid bodies behave autonomously, independently of their composition, and one has laws to describe how they behave. Nonetheless, the constructivist thinks that identifying the microscopic compositions of these non-fundamental entities can explain why these theories are successful (in addition to why, under certain circumstances, these theories fail). Thermodynamics and the other theories can be understood in terms of particle dynamics. Indeed, the fact that such theories exist is what has made it possible for us to come to know anything at the unobservable scale; if we want to explain regularities at one level in terms of regularities at a lower level, we have to come up with a lower-level theory which does that, even if our observation is at a higher level.

Another interesting feature is that while the fundamental ontology is precisely defined, the non-fundamental effective ontology may be vague: while water is precisely defined as having two hydrogen atoms and one oxygen atom, we do not need to specify how many molecules a tiger has in order to identify her as a tiger. In other words, up to a certain scale, the effective ontology is precisely defined. Instead, at a more macroscopic level, the precision of the definition becomes less relevant and arguably unnecessary in order to be explanatory. Indeed, a macroscopic effective ontology is defined functionally: a tiger is what a tiger does. Presumably, at that level, the tiger effective ontology is explanatory because it is vague rather than precise, and this is presumably because, at the macroscopic level, the type of explanation we adopt is more teleological in nature, in terms of desires and intentions, rather than forces or properties. When we observe an electron turning right in a magnetic field, we explain that behavior in terms of its charge and the direction of the magnetic field. Instead, when we observe a tiger hunting a deer, we explain this behavior in terms of the fact that she is a carnivore and that she needs to eat every such-and-such number of hours. Be that as it may, the point is that high-level sciences have effective ontologies that can be reduced, compositionally and dynamically, to the fundamental microscopic ontology. This is compatible with the fact that high-level sciences are explanatory in virtue of the fact that they use a macroscopic rather than a microscopic language.

5. Everettians: Unitary Quantum Mechanics as a Framework

Usually, the attempts described in Section 3 are taken to be 'not realist enough'. For example, Egg [45] puts forward a set of arguments that some implementations of this type of realism do not deserve to be labelled realist. Others, as anticipated, have complained that what seems wrong is having two evolution equations, for a variety of reasons. First, if one thinks of measurements as physical processes, then there is little justification for a double dynamics. Otherwise, one may complain that the theory is not simple or elegant enough. Indeed, Everett did not like the von Neumann collapse rule, which he found was inconsistent [46]. Therefore, he took the unitary wave dynamics seriously and embraced the consequences.

Let us call Everettians those who follow Everett's steps and favor a pure wave dynamics. There are at least two prominent approaches: Oxford Everettians, championed by David Wallace, and Lev Vaidman's approach. There are differences, but there are also many things in common. Here, I will focus on the commonalities.

5.1. Motivation: Practice in Physics

I think that the driving motivation for Everettians is to make realist sense of quantum theory, as practiced. This is, at least, Wallace's explicit position [47], but I believe this is also what Vaidman thinks (p.c.). If one considers what is involved in a typical physicist's daily job, they never invoke the collapse rule, they never use the stochastic nonlinear GRW evolution, and they never solve the guidance equation for the Bohmian particles. Rather, they use the Schrödinger dynamics, operators as observables, and the Born rule. These practices reveal something objective about the world, so, the Everettians ask: How can we make realist sense of standard quantum mechanics without the collapse rule? That is, how can we take the unitary quantum dynamics at face value? Their response is that we need to embrace superpositions at all levels. That is, the unitary Schrödinger dynamics without the collapse is compatible with realism, as long as one recognizes that the superpositions produced by such a linearly evolving wavefunction describe multiplicity. Vaidman's approach is similar in the sense that he cares about having a precise and simple mathematical formalism, which neither modifies nor adds anything to the formalism of quantum theory, just like it is used by physical practitioners.

> "This, in short, is the Everett interpretation. It consists of two very different parts: a contingent physical postulate, that the state of the Universe is faithfully represented by a unitarily evolving quantum state; and an a priori claim about that quantum state, that if it is interpreted realistically it must be understood as describing a multiplicity of approximately classical, approximately non-interacting regions which look very much like the 'classical world'". [47]

First, decoherence, namely the interactions with the environment, guarantees that there is a preferred way of writing the quantum state as the wavefunction. Then, the superposition terms of the wavefunction are taken to suitably represent 'worlds'. Finally, the various worlds are effectively non-interacting: because of decoherence, the interference terms between the different terms of the superposition are effectively and consistently suppressed. In this way, the quantum state effectively describes an emergent branching structure of non-interfering quasi-classical 'worlds'. Vaidman also sees 'words' as vague entities, which classically and autonomously evolve up to the next splitting time. However, he disagrees with Oxford Everettians about the role of decoherence in this. In any case, these words need to be suitably 'weighted' by the probabilities as defined by the Born rule. These weights are necessary to reproduce quantum predictions and are justified by Oxford Everettians in terms of rationality constraints (see [47,48] and references therein). Otherwise, Vaidman takes the Born rule as an additional principle, which we are justified to assume because it makes the theory empirically adequate.

Wallace's argument to favor Everettian mechanics over the alternative is that this theory better respects the practice of physics before and after quantum theory [49,50]. He maintains that classical mechanics is not a constructive theory after all. To have a constructive theory, one needs to have a single theory, taken to describe the behavior of the fundamental building blocks of the physical world. However, Wallace thinks it is a mistake to think that there is a single classical theory. Usually, when people talk about classical mechanics, they mean point-particles classical mechanics, which I described above. Nonetheless, Wallace thinks this is just one of many other theories, which we should also call classical mechanics. For instance, the dynamics of a spring, the vibrations of a rigid body, the flow of a fluid, and the behavior of fields are all 'classical mechanics' in virtue of having a common formalism. They are all formulated in some sort of phase space with a common mathematical structure, whose elements represent physical systems and in which the Hamiltonian generates the dynamics, and which is such that separability holds: the state of a composite system decomposes into the state of the composites. In other words, Wallace thinks that classical mechanics is a framework, in Flores' sense. Unitary quantum theory is also a framework, a set of formal rules: there is a Hilbert space, whose elements represent physical systems and in which the Hamiltonian generates the dynamics. The main difference with the classical case is that this time separability does not hold. That is, the state of a composite system does not decompose into the state of the composites. Many theories can fit the quantum framework: theories of particles, of fields, and so on. Everettian mechanics is the only quantum theory that describes the whole framework, not specific theories. Consequently, it is misguided to ask what 'the' ontology of Everett is, in general, because it depends on the specific framework-fitting theory we are discussing.

Wallace does not say that, but, given the close connection between principle theories and frameworks, I think that if the Everettians' motivation is a comprehensive understanding of physical practice, then understanding standard quantum mechanics as a principle theory makes it also more compatible with the common understanding of relativity theory as a principle theory. For similar compatibility reasons between quantum and relativity theory, it is important for them to have a local quantum theory. In fact, even if it is not a required ingredient of the quantum framework, locality is, arguably, the spirit of relativity.

In this respect, also for Vaidman the many-worlds theory has the advantage, over the alternatives, of being local, in addition of being deterministic. Locality, or local causality, is the idea that interactions propagate continuously. This is something that physicists always assumed, because otherwise it seems impossible to think of systems as isolated.

Notice that Newton's theory violates locality, as forces between objects act instantaneously. Nonetheless, the intensity of the interaction quickly decreases with the relative distance of the systems in question, so that, for all practical purposes, one can forget about objects that are sufficiently distant from the system under examination. The theory of relativity, however, imposes a new limit to local causality, namely that interaction can travel, at most, at the velocity of light. However, standard quantum mechanics is nonlocal, due to the collapse rule, which instantaneously collapses the quantum state, regardless of the relative distance of the superposition terms. Bell's inequality and its violation arguably show that any theory which reproduces the predictions of quantum theory has to be nonlocal, if we assume that the so-called hypothesis of statistical independence is true (see [51] for a review of Bell's theorem and [51] for a critical review of some ways of avoiding nonlocality denying statistical independence). In a many-worlds picture, one arguably could recover locality within a branch: "A believer in the MWI (Many Worlds Interpretation) witnesses the same change, but it represents the superluminal change only in her world, not in the physical universe which includes all worlds together, the world with probability 0 and the world with probability 1. Thus, only the MWI avoids action at a distance in the physical universe" [1]. Wallace agrees that Everettian mechanics is local: "the quantum state of any region depends only on the quantum state of some cross-section of the past light cone of that region. Disturbances cannot propagate into that light cone" [47].

Be that as it may, perhaps more importantly, the Everettians' desire to understand quantum field theories as relativistic extensions of standard quantum mechanics, together with their understanding of relativity as fundamentally a theory about spacetime, requires them to have a spatiotemporal understanding of the quantum state. Wallace and Timpson [52] propose the so-called spacetime state realism, which puts spacetime back into the quantum picture: "just take the density operator of each subsystem to represent the intrinsic properties which that subsystem instantiates, just as the field values assigned to each spacetime point in electromagnetism represented the (electromagnetic) intrinsic properties which that point instantiated" [47]. Vaidman does not propose such an argument but agrees on the centrality of spacetime. He thinks that while interference experiments have shown that matter is wave-like, as opposed to particle-like, the mathematical description of the phenomena provided by the wavefunction is contingent: other descriptions, in terms of density matrices or similar, may be useful or convenient in other contexts. What is essential instead is that this wave-like object cannot live in three-dimensional space; because of entanglement, it has to live in $3N$ dimensional space. Therefore, I think that Vaidman claim that 'reality is only wavefunction' is merely a slogan to convey that 'reality is wave-like, and such a wave is entangled'. He believes that, in order to explain our experiences, three-dimensional space and some three-dimensional 'properties' (such as the matter density field or the particle density field) have to be extracted from the wavefunction and should be considered as fundamental [1,53,54]. Therefore, in this respect, Vaidman is similar to spacetime state realism, or perhaps to the multi-field interpretation of the wavefunction (even if he would disagree with the latter that there is something special about the description of reality given by the wavefunction aside from describing a wave-like object displaying entanglement). Indeed, his view seems to also share some similarities with the matter density theory ontology proposed by primitive ontologists which has been dubbed Sm [55]. Vaidman leaves unspecified which of these fields should be extracted from the wavefunction to explain our experience, but he is adamant that these are what need to be looked at.

5.2. Explanations as Dynamically Emerging Structures

What type of explanation does the many-worlds approach provide? To respond, let us first discuss their fundamental ontology. They do not have a macroscopic ontology, such as IT or QBism. In fact, it is not needed, because superpositions are dealt with by multiplying the worlds. While IT needs the collapse rule to effectively eliminate unobservable macroscopic superpositions, Everettians embrace them at face value. Worlds and macroscopic objects are seen as emerging from the fundamental ontology of the theory, namely the quantum state. Aside from their differences, Vaidman and Oxford Everettians both agree that their theory needs to be rooted in spacetime. They have this requirement in common with primitive ontologists, but their motivations are very different: primitive ontologists require a spatiotemporal ontology because they wish to preserve compositionality, while Everettians do not care about that but care about relativity. Moreover, they also do not require microscopicality. This is because they do not recover macroscopic phenomena in terms of the dynamics of some microscopic ontology, and they do not think of macroscopic objects as composed of microscopic entities, as primitive ontologists would do. Rather, they understand theories as framework and they use principles to constrain the phenomena: as we have seen above, for instance, they use principles of rationality to account for probabilities. Moreover, they adopt structuralist techniques to define what a world or an object is. This is achieved using what Wallace calls the Dennett's criterion [56]: "A macro-object is a pattern, and the existence of a pattern as a real thing depends on the usefulness—in particular, the explanatory power and predictive reliability—of theories which admit that pattern in their ontology" [47]. In this approach, objects are also seen as emergent patterns: "So a cat is a subsystem of the microphysics structured in cattish ways" (*ibid*.). One could see these patterns as defined in terms of principles, but Wallace prefers to think of them as objective emerging structures: "there are structural facts about many microphysical systems which, although perfectly real and objective (try telling a deer that a nearby tiger is not objectively real), simply cannot be seen if we persist in describing those systems in purely microphysical language. Zoology is of course grounded in cell biology, and cell biology in molecular physics, but the entities of zoology cannot be discarded in favour of the austere ontology of molecular physics alone. Rather, those entities are structures instantiated within the molecular physics, and the task of almost all science is to study structures of this kind" (*ibid*.). Therefore, Wallace thinks these structures are needed to account of the explanatory power of higher-level sciences: biology, say, is explanatory because at that level of description, the explanation is in terms of DNA, seen as an emerging autonomous structure.

Everettians and primitive ontologists agree that biology is explanatory, even if it is not expressed in the fundamental language of physics. They also agree that at a certain scale, such as the level of tigers, the effective ontology may be vague and functionally defined. However, they disagree in their understanding of the higher-level ontology. Everettians propose a top-down approach, starting from the quantum state and then reading off from that the non-fundamental structure (worlds, objects, tigers, DNA, etc.). Instead, as described in Section 4, the primitive ontologist constructive understanding is bottom-up: at certain scales, some collections of the microscopic entities will show autonomous behavior.

In addition, in the Everettian account, similarly to the primitive ontologists and unlike pure principle theories, the dynamics is important: these structures emerge in virtue of decoherence, which is a dynamical process. Therefore, there is a sense in which they justify their structures dynamically: at the fundamental level, one has the quantum state; the dynamics, through decoherence, selects a spatiotemporal ontology; the unitary of the dynamics then allows for the formation of superpositions, and, again, decoherence dynamically ensures that the emerging worlds are effectively non-interacting, and that the emerging structures are effectively autonomous and stable. Therefore, even if the explanation provided by this approach is bottom-up, such as principle theorists, here, principles and structures have a dynamical justification.

When Everettians ask for a realist quantum theory, they want a theory with a spatiotemporal ontology from which physical phenomena dynamically emerge. Therefore, there are two ingredients: a spatiotemporal ontology and a structuralist explanation. These requirements are independent from one another. In fact, one could have a structuralist understanding without a spatiotemporal ontology. In fact, as we have seen, rainforest realists understand everything structurally, including the fundamental ontology. Alternatively, one could maintain that worlds are structurally emerging directly from a high-dimensional quantum state. This is, indeed, how one may decide to implement a structuralist version of wavefunction realism (see next section). Moreover, as primitive ontologists do, one can have a spatiotemporal ontology and a compositional explanation: macroscopic objects are not emerging as structures, but they are literally composed of microscopic fundamental entities.

Having said that, the reason why Everettians want a spatiotemporal ontology is that they care about our best physical theories to cohere with one another, and a realist quantum theory for them would have to be compatible with relativity theory (as noted above). Notice that this spatiotemporal ontology would allow for a constructive explanation, if the ontology was one of particles (like in the pilot-wave theory) or with a wave ontology, with a nonlinear dynamics (like the GRW theory with a spatiotemporal ontology or de Broglie's double solution). However, both options would require a substantial modification of the standard theory, and Everettians do not want to go that way without additional reasons to do so. Therefore, they have to make sense of a linearly evolving wave ontology, because this is what unitary dynamics provides us with. A wave ontology and a linear temporal evolution together generate a many-worlds picture, because waves superimpose due to linearity. This, in turn, requires a non-compositional understanding of macroscopic objects, because waves spread. Instead, a particle ontology would certainly not have given rise to superpositions, and it would have allowed for a compositional understanding of macroscopic objects. Notice that if the waves were to combine to form stable wave-packets, which, from afar, look like particles, then one could have constructive explanation as if we had particles at the fundamental level. Nonetheless, this does not happen: there are superpositions at all levels, and this is why Everettians take the multiplicity of worlds seriously. Therefore, it is because of their choice of a wave ontology that they need a structuralist explanation: given the spatiotemporal fundamental ontology, macroscopic phenomena emerge as dynamical structures.

6. Wavefunction Realism: Quantum Theories as Interaction Theories

We have not exhausted the most preeminent proposals for quantum ontology, as we have not yet talked about wavefunction realism. According to wavefunction realism, all quantum theories, which are solutions of the measurement problem, are to be interpreted as theories of the wavefunction, understood as representing a physical field in configuration space (see, most notably, [57–60]). In this way, wavefunction realism is not an approach designed to favor one quantum theory over another, but it is intended as a general strategy for naturalistic metaphysics: given a theory, what should we conclude about the nature of reality? When considering the solutions of the measurement problem, what is the best way to interpret their formalism? The many-worlds theory and GRW are theories about the evolution of the wavefunction, an object in configuration space, while the pilot-wave theory is a theory in which there is a particle and a wave ontology. Straightforwardly, therefore, one is led to interpret these theories at face value, namely as theories in which the fundamental ontology is given by the wavefunction (or part of the ontology, as in the case of the pilot-wave theory). This is very similar to what the Everettians are doing. Ultimately, however, there is another, stronger motivation for some wavefunction realists, as discussed in the next subsection.

6.1. Motivation: Locality and Separability

Ney [60] argues that the best way to motivate wavefunction realism is to notice that this is the only view with a local and separable ontology. As we have seen, local causality is the idea that interaction travels continuously, so it takes time. The violation of Bell's inequality has arguably shown that all quantum theories are nonlocal (setting aside theories violating statistical independence). Therefore, how can wavefunction realism recover locality? There is a sense in which this nonlocality in spacetime is built in the wavefunction, since it is a function of all particle configurations. Therefore, it seems straightforward that if one were to restore locality for the fundamental ontology, one can do that by thinking that the fundamental ontology is the wavefunction understood as a field in configuration space.

That is, if configuration space is the fundamental space, and the wavefunction is a field in that space, then the wavefunction is local in the fundamental space.

If local causality is a property of the interaction, separability is a property of the ontology of matter: as we have seen before, in classical mechanics, the properties of the whole are given by a suitable combination of the properties of its parts. In quantum theory instead, given entanglement, separability fails. Even introducing multiple branches will not help, in contrast with locality. Nonetheless, one could argue that if the fundamental ontology is the wavefunction in configuration space, the properties of the whole would be determined by the properties of its parts: the wavefunction, the whole, is completely determined by the amplitude and phase in each point in the fundamental space. Separability is important for physical practice because it is connected with compositionality, namely that macroscopic objects are composed of microscopic, more fundamental, entities. However, this reason is not available to wavefunction realists because, as we will see later, their explanation is not fundamentally compositional. Otherwise, it is important because it is consistent with Humean supervenience [60], as in configuration space, 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.

Wavefunction realists, therefore, allow for non-spatiotemporal ontology because they care about locality and separability, and in a suitable high-dimensional space, they can recover these features, which are otherwise lost in spacetime. In fact, primitive ontologists and the proponents of the IT approach both have a spatiotemporal ontology, so that separability holds, but there are nonlocal interactions. Instead, even if also Everettian mechanics has a spatiotemporal ontology, given that there are the branches, in each branch, the interaction is arguably local but the object across branches is nonseparable. In contrast, if one allows for the ontology and the interaction to both be in high dimensions, like wavefunction realists suggest, then the theory is both local and separable.

Thus, the many-worlds theory as well as GRW should be understood as theories in which the fundamental ontology is a field in a high-dimensional space. It is unclear which of these two theories one should prefer, but certainly the pilot-wave theory fits less straightforwardly in this framework. In fact, the pilot-wave theory can be understood as a theory in which there is a wave and a particle in the high-dimensional space [57], or as a theory in which there are N particles in spacetime and a wave in configuration space. Either way, this approach seems to create more problems than it solves for the pilot-wave theory: for instance, what is matter made of, wave(s) or particle(s)? Why does the wave act on the particle(s) while the particle(s) does/do not?

6.2. Explanations as Non-Constructive Dynamical Hybrids

How does wavefunction realism explain the phenomena? In this view, neither three-dimensional space nor spacetime are fundamental, as the wavefunction is taken to be a material field in configuration space, which is a high-dimensional space. Thus, respectively, the fundamental physical space is represented by configuration space, not by three-dimensional space or spacetime. Three-dimensional space and the macroscopic objects we experience exist, albeit not fundamentally.

In order to explain what this means, that is, in order to provide an explanation for the phenomena, this approach is set to recover three-dimensional space from their fundamental space; then, to recover a microscopic ontology from the wavefunction; and finally, it needs to account for macroscopic behavior. As far as the first step is concerned, the strategy of wavefunction realists is to show that three-dimensional space suitably emerges as non-fundamental from the fundamental high-dimensional space. This emergence happens because of principles which suitably constrain the phenomena, even if these principles differ from proponent to proponent. For example, Albert uses the principle that the dimensions displayed in the Hamiltonian are privileged [57]. Ney instead uses the principle that dimensions that respect the fundamental symmetries of the dynamics are privileged [60]. A similar approach is Carroll's vector space realism, also called Hilbert space fundamentalism [61], even if perhaps it is not motivated by preserving locality and separability. He proposes, in the framework of Everettian quantum theory, to consider the wavefunction as representing a vector in Hilbert space, rather than a field in configuration space. To recover three-dimensional space, Carroll uses the principle that three-dimensionality, which allow for the simplest decomposition of the whole of Hilbert space into subsystems, should be privileged. That singles out three dimensions, and, in this sense, explains why we should expect to observe a three-dimensional world.

Moreover, these approaches use principles to recover a microscopic three-dimensional ontology from the wavefunction as well. Albert and Loewer [62] propose to modify the so-called EER (eigenvalue–eigenstate rule) of standard quantum mechanics as to define three-dimensional, microscopic particles as suitably emergent. Later, Albert [58] proposed that three-dimensional particles are 'functional shadows' of the high-dimensional wavefunction. The idea is that it is possible first to define functionally what it means to be a three-dimensional object, and then it is possible to show that the wavefunction can play that role. This functional reduction can give rise to microscopic three-dimensional objects, which then can be understood as usual; in particular, as composing macroscopic objects. Ney [60] has a different proposal but, I think, the essence is the same. She wishes to derive three-dimensional microscopic particles as derivative parts of the wavefunction, which is the fundamental whole. In her view, there is a particle when there is a 'bump' in the function described by the squared module of the wavefunction. Understanding particles in this way, a particle location may be indeterminate, as the function describing it may be spread out. Particles so-defined may partially instantiate different locations to different degrees, given by the squared amplitude of the wavefunction in that point. Having defined particles in this way, we can proceed to think of macroscopic objects as suitably composed of the non-fundamental three-dimensional ontology. In the many-worlds theory, this will include the use of decoherence, as proposed by the Everettians.

Therefore, wavefunction realists care more about microscopicality and compositionality than Everettians. They use principles to go from high-dimensional space to spacetime and, then, once they have a microscopic non-fundamental ontology they proceed with the usual compositional and dynamical explanation. That is, wavefunction realists use the dynamics from the non-fundamental three-dimensional microscopic ontology to the non-fundamental three-dimensional macroscopic ontology. Instead, Everettians use principles and structural and functionalist techniques to extract the non-fundamental macroscopic ontology from the fundamental spatiotemporal one. Notice that one could use structuralist or functionalist strategies to go directly from high-dimensional space to macroscopic three-dimensional space. Presumably, this is what priority monism does: according to this view, the entire universe is more fundamental than its components, and the parts still exist, even if in a derivative fashion [63]. Otherwise, relational holism holds that only the 'whole' exists and nothing else [64].

How does wavefunction realism correlate with other views? If the IT and the primitive ontology approach can be understood and contrasted as being the principle and constructive counterparts of one another, wavefunction realism emerges as the view obtained when one thinks of quantum theories as interaction theories, without thinking of them in constructive terms, while one can see Everettians as endorsing a framework approach. In fact, let me suggest the following about the alleged similarity between frameworks and principle theories. Principle theories are formulated in terms of constraints on the phenomena, but the phenomena are, obviously, physical processes. In fact, in the case of thermodynamics, the phenomena involve gases expanding, or heat being dissipated, or work being generated. Instead, frameworks are devoid of direct physical significance: they are empty mathematical structures, which could be interpreted freely. They are like argument forms, which are neither true nor false until one substitutes some sentences in place of the letters. As Wallace emphasizes, many different ontologies and theories can fit into the classical or into the quantum framework. So, simply looking at the framework, one cannot say what the ontology of the theory is, because what we are looking at is not a theory but a framework that needs to be filled by some ontology. Many theories, even with different ontologies, could fit that framework, while this is not true for principle theories. Flores contrasts framework theories with interaction theories, which are the ones that Wallace calls point-particle mechanics. Classical point-particle mechanics describes the dynamics of point particles in three-dimensional space, evolving according to Newton's second law. Quantum particle mechanics is the theory of 'particles' whose motion is specified by the wavefunction (namely, a function from the configuration space of those particles to the complex numbers, satisfying the Schrodinger equation). The physical content of the theory is given by the Born rule, which specifies the probability density, on measurement, of finding the particles in a given configuration at a given time. Therefore, while Everettians can be taken as endorsing Everettian mechanics because it describes the whole quantum framework, I think that wavefunction realists are better seen as thinking of quantum theory as a theory of interaction: it is about some fundamental ontology, which they take to be the wavefunction evolving to some dynamical equation. Notice that thinking of interactions in these terms does not require any need for a spatiotemporal microscopic ontology or any notion of compositional explanation. In fact, this is why wavefunction realists, in contrast with primitive ontologists, think of the wavefunction as a suitable ontology for the theory.

7. The Disagreement in a Table

Table 1 graphically shows where the disagreement rests. I have argued, in this paper, that there is no consensus in the foundations of quantum mechanics on which theory should be preferred by the realist because theory preference is connected to types of explanation, and there is no agreement on which one should be favored. Realists who favor principle explanations will likely find nothing objectionable about standard quantum theory with the collapse rule, as it will provide the necessary principles. Instead, constructivists like primitive ontologists want a microscopic spatiotemporal ontology to explain where these principles are coming from, and this naturally leads them to favor the pilot-wave theory. Instead, Everettians follow the attitude of making sense of physics as it is practiced. This leads them to think of quantum theory as a framework, where the unitary quantum theory is taken at face values, namely as suggesting the existence of superpositions at all levels. Also, this leads them to see objects as dynamically emerging patterns. Finally, wavefunction realists require the theories to be local and separable in the fundamental space. To do so, they allow for ontologies to be non-spatiotemporal, and they allow for a hybrid type of explanation.

Personally, I favor a constructive explanation of the phenomena, and I think that, if one has such inclinations, the pilot-wave theory should be the clear consensus. Nonetheless, even if I did not care about constructive explanations, I would still have some questions for both wavefunction realists and Everettians.

For one thing, how can wavefunction realists justify the importance they give to locality and separability? They claim that they are motivated to choose the ontology which would give them a local and separable ontology, but what they have is a local and separable ontology in the fundamental space, namely high-dimensional space. Why should one care about locality and separability in a space other than spacetime? One could argue that locality and separability are desiderata for a spacetime ontology. For instance, Einstein thought that failure of locality would make physics impossible, as it would be impossible to think of systems as isolated. A similar argument could be put forward for separability. However, this seems no longer important if the locality and separability in question are in some high-dimensional space (for more on the comparison between the explanatory strategies of the primitive ontology approach and wavefunction realism, see [65,66]).

Table 1. Different views have different motivations and require different types of explanations.

View	Motivation	Ontology	Explanation	Theory
IT approach QBism Pragmatists	Empirical adequacy	Macroscopic Ontology	Principle explanation: Macroscopic phenomena are explained in terms of principles constraining the phenomena.	Standard QM (unitary dynamics and collapse rule)
Primitive Ontology	Compositionality and dynamical reduction	Spatiotemporal & microscopic ontology	Constructive, dynamical explanation: macroscopic objects are composed of the fundamental microscopic entities, and macroscopic behavior is explained in terms of the microscopic dynamics.	Pilot-wave theory (GRW-x) x = some spatiotemporal microscopic ontology
Spacetime State Realism	Coherence with physical practice	Spatiotemporal ontology	Structuralist explanation: macroscopic phenomena are accounted for in terms of structures dynamically emerge from a spatiotemporal fundamental ontology. Functionalist explanation: objects are what they are because of what they do.	Many-worlds
Wavefunction Realism	Keep locality and separability	Local & separable (not necessarily in spacetime)	Non-constructive/dynamical explanation: principles are used to recover the nonfundamental spatiotemporal microscopic ontology from the fundamental high dimensional space, then constructive explanation is used to account for macroscopic objects and their behavior.	Many-worlds (bare GRW)

My main question to the Everettians is that it is unclear to me why one would insist on having a wave ontology, knowing that this inevitably leads to a many-worlds picture. After all, if one wants a spatiotemporal ontology already because of relativity, a particle ontology would also remove the multiplicity of worlds. Their likely reply is that this would amount to a radical departure from quantum mechanics as it is practiced by physicists, while a wave ontology would not. However, why should one care about quantum mechanics as it is used by physicists? One may argue that it is because it is incredibly successful. However, how is that connected with realism? One could argue that success is evidence for truth: the best explanation for a theory's success is that the theory is true. Nonetheless, quantum theory has been developed by instrumentalists, so it was not aimed at providing a fundamental description of reality. So, why should we follow the practices of scientists who only care about empirically adequate macroscopic description? Why should such a theory be the guide for the realists, especially if it leads us to adopt a revisionary metaphysics, which does not seem to have any empirical support? For instance, what is the evidence for the existence of the other words?

Setting these questions aside, this paper aimed to show that there is currently no consensus about which is the best realist quantum theory because there is no consensus about which should be a theory's desiderata. If so, not only is there no consensus now, but likely there will never be one in the future (at least if no new physics comes about).

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