Quantum Ontology and Intuitions

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Abstract

Among the various proposals for quantum ontology, both wavefunction realists and the primitive ontologists have argued that their approach is to be preferred because it relies on intuitive notions: locality, separability and spatiotemporality. As such, these proposals should be seen as normative frameworks asserting that one should choose the fundamental ontology which preserves these intuitions, even if they disagree about their relative importance: wavefunction realists favor preserving locality and separability, while primitive ontologists advocate for spatiotemporality. In this paper, first I clarify the main tenets of wavefunction realism and the primitive ontology approach, arguing that seeing the latter as favoring constructive explanation makes sense of their requirement of a spatiotemporal ontology. Then I show how the aforementioned intuitive notions cannot all be kept in the quantum domain. Consequently, wavefunction realists rank locality and separability higher than spatiotemporality, while primitive ontologists do the opposite. I conclude that however, the choice of which notions to favor is not as arbitrary as it might seem. In fact, they are not independent: requiring locality and separability can soundly be justified by requiring spatiotemporality, and not the other way around. If so, the primitive ontology approach has a better justification of its intuitions than its rival wavefunction realist framework.

Keywords: wavefunction realism, primitive ontology, intuitions, locality, separability, spacetime, constructive and principle theories.

1. Introduction

As originally proposed, in quantum theory the complete state of a physical system is given by the so-called quantum state, a vector in Hilbert space (a vector space with inner product) whose position representation is called the wavefunction. The quantum state evolves in time according to the deterministic and linear Schrödinger equation. Because of linearity, superpositions of solutions will also be solutions. This generates unobserved macroscopic superpositions, such as a cat being in a superposition of 'being dead' and 'being alive' or a particle 'being here' and 'being there.' This is the so-called measurement problem: if the wavefunction is complete and it evolves according to a linear equation, then there are no single-valued experimental outcomes (Schrödinger 1935). This problem has been historically solved by postulating that, upon measurement, the wavefunction collapses, instantaneously and randomly, in one of the terms of the superpositions (von Neumann 1932). However, this solution is unsatisfactory from a scientific realist perspective, according to which our best theories can guide our metaphysics, since it is not clear what makes a physical process a measurement, and why it is special. This is why several other theories which solve the measurement problem without invoking the concept of measurement at the fundamental level have been proposed. I will dub these 'realist quantum theories.' The most promising of them are the spontaneous localization theory (also known as GRW theory, from Ghirardi, Rimini, and Weber 1986), the many-worlds theory (also dubbed Everettian mechanics, from Everett 1957) and the pilot-wave theory (which also goes under the

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name of de Broglie-Bohm theory, or Bohmian mechanics, from Bohm 1952). In GRW and Everett, the quantum state provides the complete description, but evolves according to different laws. More precisely, in the many-worlds theory the state evolves according to the Schrödinger dynamics, and to avoid the measurement problem the theory allows the existence of infinitely many unobservable and non-interacting emergent 'worlds' each corresponding to a single possible term of the superposition the state could be in. Instead, in GRW the Schrödinger evolution is modified nonlinearly and stochastically as to make macroscopic objects collapse in a very short time. Finally in the pilot-wave theory the state of the system is not given by the Schrödinger-evolving wavefunction alone, but it is completed by the particles positions, who themselves evolve according to an equation which contains the wavefunction.

While these theories allow for a realist interpretation, nonetheless they are not known to be intuitive, and indeed they seem very revolutionary: for instance, the many-worlds theory asks us to believe in the existence of an infinity of unobservable worlds; GRW, being stochastic, needs us to re-think the notion of causation; the pilot-wave theory, since the wavefunction at a given time depends on all the particle positions at that instant, seem to require an instantaneous 'spooky action at a distance'.
Moreover, there are different views about what the ontology of even the same quantum theory is supposed to be. To begin with, some argue that the quantum state represents matter, some others deny that. In the former camp there is disagreement about how to think of the quantum state: wavefunction realists think of it as a wavefunction in the high-dimensional configuration space (Albert 1996, Ney 2021, and references therein), while others argue that it should be seen otherwise. These latter approaches include spacetime state realism (according to which the ontology is a spatiotemporal object depending on the wavefunction, Wallace and Timpson 2010), Hilbert space realism (which maintains that the quantum state should be seen as a ray in Hilbert space, Carroll 2023), the multi-field approach (which proposes that the quantum state is a field assigning a unique value to an n-tuple of points in three-dimensional space, Hubert and Romano 2018) and various types of monism (e.g. priority monism, Ismael and Schaffer 2020, and relational holism, Teller 1986, which they all have in common that the quantum state describes the whole three-dimensional universe). In contrast, the primitive ontology approach maintains that the ontology of matter is in spacetime, while the wavefunction plays a different role in the theory (Allori *et al.* 2008, Allori 2013).

In this paper I wish to focus on two approaches, namely the primitive ontology approach and wavefunction realism, which have distinguished themselves from the others (among other things) because, instead of arguing that we need to fully embrace the quantum weirdness, they have both maintained that we should try to be *the least revolutionary*. In fact, proponents of these views have both argued that their perspective best respects some notions, namely *spatiotemporality, locality and separability*, which have always been used in physical practice up to quantum mechanics. These notions are extremely entrenched in our ways of understanding the world, and thus they are *intuitive*. Proponents of both views argue that their approach is worth exploring, if not to be preferred, because they preserve most of these intuitions in their understanding of quantum theories. This is so even if in the quantum domain it is not possible to keep all these notions, and the two approaches disagree about which should be privileged: while the primitive ontologists require a spatiotemporal ontology even if it costs them locality, wavefunction realists advocate for a local and separable metaphysics even if they lose a spatiotemporal ontology.

In this paper I wish to compare and contrast these two approaches, and ultimately argue that the primitive ontology approach is better motivated by showing that the three intuitions are not independently justifiable. Rather, they have a hierarchy with spatiotemporality at the bottom: one is justified in privileging locality and separability only if she first requires spatiotemporality, not the other way around.

This is the roadmap of the paper. I start in sections 2 and 3 by presenting the main features of wavefunction realism and the primitive ontology approach. I state their main tenets and the arguments for each view, the best of which in both cases ultimately relies on notions which can be justified as intuitive, namely spatiotemporality, locality and separability.

First, I remind how wavefunction realism has been explicitly advocated in virtue of being the only approach which preserves locality and separability. Moreover, I show how the primitive ontology approach's preference for spatiotemporality is best motivated by noticing that spatiotemporality grounds a constructive explanatory schema which the primitive ontologists favor. In this way, both the primitive ontology approach and wavefunction realism can be seen as normative frameworks: when facing underdetermination, they respectively prescribe to "choose the theory providing a constructive explanation" and to "choose the theory with a local and separable metaphysics."

Then, in section 4, discussing in what sense the notions of spatiotemporality, locality and separability are intuitive, I recall how they have always been a part of physical theorizing and they have shaped the history and development of physics until the rise of quantum theory. Nonetheless, I clarify how they cannot all be held true at the same time in a quantum world: either there is a spatiotemporal ontology, or the notions of locality and separability would have to be defined in a high-dimensional space. Thus, primitive ontologists and wavefunction realists disagree about the relative importance of these three notions. In section 5 I argue that choosing which intuitions should be preserved in our theories, and thus which normative principle should be used in our theory choice, is not arbitrary, as one might think. In fact, spatiotemporality, locality and separability are hierarchically not independent: locality comes last, spatiotemporality first, after which separability comes for free. If this is the case, then the primitive ontology approach rests on more solid grounds than wavefunction realism, as it stands. I draw my conclusions in the last section.

2. Wavefunction Realism and Intuitions

Wavefunction realism is the view according to which, in the nonrelativistic quantum domain, the fundamental space is given by 'configuration' space and the fundamental ontology of the theory is given by a physical field living in that space, represented by the wavefunction. More precisely, according to wavefunction realism, the wavefunction in configuration space, namely the space of the locations of all the particles the system was thought to have, represents matter at the fundamental level. As such, the fundamental space is a high-dimensional space (with N 'particles,' each described by 3 coordinates, configuration space would have $3N$ dimensions), and fundamentally matter is represented by a high-dimensional physical field.

As discussed by Ney, there are three main arguments for this view, the most compelling of which is the last (2021, 2024). The first argument is a plausibility argument based on an analogy with classical mechanics (Lewis 2004): since the quantum state plays the same role as the configuration of particles plays in classical mechanics, then it can be regarded as the fundamental ontology of quantum theories. While in classical mechanics the complete state of a physical system is given by its position and velocity and the fundamental equation is Newton's law, which prescribes how particles move, in the quantum domain the quantum state consists of a vector in Hilbert space (at least partially)[2], whose position representation is called the wavefunction, and it evolves according to the Schrödinger equation (at least, partially).[3] By analogy, therefore, it seems natural to think that the quantum state is what fundamentally represents matter in the theory.

Nonetheless, this argument does not specify the reason why, among all the possible representation of the quantum state, we should privilege the wavefunction, which is its position representation as a field in configuration space.[4] One could provide such a reason by arguing that a wavefunction in configuration space provides a high-dimensional dynamics able to explain entanglement: an entangled state between, say, a pair of particles cannot be interpreted in terms of two three-dimensional fields, each corresponding to a particle of the pair, but it can straightforwardly be understood in terms of a field in the space of their configuration (North 2013).

However, this argument is unable to single out wavefunction realism, as other alternative approaches can also explain entanglement. In fact, any approach with the wavefunction in its ontology of matter, either as a field in configuration space or in some other reformulation, will be able to explain entanglement. That is, the alternatives to wavefunction realism in which the quantum state represents matter, such as spacetime state realism, Hilbert space realism, monist views, and the multi-field approach mentioned in section 1, can explain entanglement as well. However, the final argument goes, the reason why they can do that is that they are non-separable, in contrast with wavefunction realism which is the only approach of this type (that is, the only one among the approaches which take the quantum state as the ontology of matter) which is separable. To use Ney's definition: "a metaphysics is *separable* iff (i) it includes an ontology of objects or other entities instantiated at distinct regions, each possessing their own distinct states and (ii) when any such objects or entities are instantiated at distinct regions $R1$ and $R2$, all categorical facts about the composite region $R1 \cup R2$ are determined by the facts

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[2] In the pilot-wave theory the wavefunction only partially describes the system, as one also needs particles' positions, but it still evolves according to the Schrödinger equation, which is one of the two fundamental equations of the theory.

[3] In the spontaneous localization theory, the wavefunction is complete and the fundamental equation of the theory is still an equation for the evolution of the wavefunction, even if it is not exactly given by the Schrödinger equation, which is modified by adding a nonlinear stochastic term.

[4] This objection seems less sever if position is taken as a preferred basis, which however requires independent justification (thanks to David Z. Albert for this suggestion).

about objects and properties instantiated at $R1$ and $R2$ individually" (2021). Roughly, that is, all facts about a composite are captured by facts about its components. The crucial thing to notice is that if the quantum state represents the fundamental ontology of matter, and if it is thought of as living in three-dimensional space, then it has to be non-separable in order to accommodate for entangled states. For instance, in spacetime state realism, matter is represented by some spatiotemporal function of the wavefunction, and a pair of entangled particles have a property (namely being in an entangled state) which cannot be reduced to the properties of the individual particles: they fail (ii), so they are non-separable. Instead, this is not the case for wavefunction realism: this approach is separable, not in three-dimensional space but *in its own fundamental space*. In fact, matter lives in configuration space and thus the state of every system, including entangled states, is completely specified by localized assignments of amplitude and phase to each point in configuration space.

Therefore, separability sets apart wavefunction realism from the other approaches which consider the quantum state as describing matter. The only view left is the primitive ontology program, discussed in more detail in the next section. In this approach matter is described fundamentally by a spatiotemporal entity, dubbed the primitive ontology, while the wavefunction is seen as partially describing the interaction between the entities in the primitive ontology. In virtue of this, one can account for entanglement: the pair of particles in an entangled states interact with one another with a particular type of wavefunction described by an entangled state.

Ney argues that what uniquely characterizes wavefunction realism over the primitive ontology framework is that the latter is nonlocal, while wavefunction realism is not. Locality, or local causality, is the idea that interaction propagates. That is, that it takes time for an object to 'be seen' by another object at some distance from it. Or, in other words, that there is no instantaneous action at a distance. The primitive ontology approach is nonlocal: the wavefunction, which partially describes the interaction between the fundamental entities, depends on the coordinates of all of them at the same instant. So, modifying one will instantly change the others. This is not the case for wavefunction realism. Even if not in spacetime, wavefunction realism is local *in its own fundamental space*, namely the high-dimensional space in which the wavefunction lives. More precisely, one can reformulate the notion of locality independently of the space in which it is formulated: one can say that a theory is local if and only if there are no instantaneous interaction across spatial distances, where space could be configuration space. With this definition, regardless of whether the wavefunction evolves according to the Schrödinger equation or according to the GRW dynamics, in the wavefunction realist framework there is no action at a distance in configuration space.

The idea is then to claim that wavefunction realism is better than all the alternative quantum ontologies because separability and locality are desirable features for a fundamental physical theory to have, and wavefunction realism is the only approach which 'saves' them both. This is the final argument for wavefunction realism: it is the only approach to quantum ontology which is local and separable. In this way, wavefunction realism becomes normative: when facing underdetermination, it prescribes that one should follow a principle of the form: "chose the theory which has a local and separable ontology."

Two things need to be discussed: how wavefunction realism explains the three-dimensional phenomena of our everyday experience; and why we should care about locality and separability. As for the first question, there are several proposals, but here I focus on the one of Ney (2021). She argues that three-dimensional space and the objects we experience exist, even if not fundamentally. She has argued that three dimensions are singled out in terms of symmetries: they are the only number of dimensions which preserve symmetries of the dynamics like permutation symmetry. In addition, in this approach macroscopic objects are not seen as composed of microscopic entities, as the fundamental ontology (the wavefunction) lives in a larger space than the derived one (the macroscopic object). In this sense, thus, the separability of wavefunction realism is not to be understood as related to compositionality. Rather, the 'particle' we seem to see at a microscopic or mesoscopic scale (larger than the microscopic scale but smaller than the macroscopic one) when we observe a track in a detector, is partially instantiated by the wavefunction, as it is a part of the wavefunction where its amplitude is large, where there is no spreading. Instead, when we see an interference pattern, the 'particle' has indefinite location because the part of wavefunction it corresponds to is spread out. Finally, the macroscopic objects we experience like tables and chairs are understood as composed by the (partially instantiated) 'particles' as if they were fundamental. Thus, to summarize, the wavefunction realist explanation of the macroscopic phenomena proceeds in three step. Fist, three-dimensional space is recovered using symmetries, then microscopic 'particles' emerge as partially instantiated, and finally usual compositional techniques are used to account for macroscopic objects.

Notice that wavefunction realism, being a form of monism, is such that the wavefunction describes both matter and the way in which various parts in it interact with one another. This is different from what is assumed classically, where matter is described by some entity, say particles positions, while the interaction is mediated by something else, for instance fields, and it is commonly described by potentials.

Being that as it may, regarding the second question, namely why we should we care about locality and separability, Ney argues that it is because these features are supported by our rational faculties, such as intuition. In this sense, they are intuitive. She writes that they are "supported by claims that are analytic and so closer to the center of my (but I think not just my) Quinean web of belief" (2024). In other terms, they are almost unquestionable because denying that they are true almost feels like denying an analytic truth. Another way of seeing this perhaps could be in Lakatos' terminology: they belong to the hard core of the theory, rather than the protective belt, and so they are the last to be questioned when facing underdetermination (or even falsification). Similarly, assuming separability and locality is compatible with Einstein's view that science should be a refinement of everyday thinking: these are pre-theoretic intuitions, and we should start questioning them only as a last resort (Allori 2013).

Ney remarks that scientists of the caliber of Einstein thought that separability is almost undeniable, as he assumed without questioning that "the basic facts about one entity don't depend on facts about any other entity" (1948). After all, separability seems at the core of atomism, and of Newton's reductive program to account for all the physical phenomena in terms of fundamental point-like particles. In fact, separability is closely connected, if not identical, to the idea that one can completely describe a macroscopic object in terms of its fundamental microscopic components, so that all properties at the macroscopic level are explained in terms of the microscopic dynamics. For instance, the solidity of a table is completely determined in terms of the way the particles composing the table are bound together.

One can make a similar reasoning for locality, which has always been considered an essential assumption since the times of Newton and Maxwell. In fact, locality seems to be based on the idea that "an object cannot act where it is not" (as Clarke put it, in discussion with Leibniz, as reported by Ney, 2024), denying which seems almost like denying an analytic truth. In classical theories, fundamental objects interact with one another in virtue of their properties of mass and charge. Notice that describing the interaction between particles in terms of forces was seen as problematic, as it is nonlocal: forces are generated by a given particle and they act on a distant particle instantaneously. Newton disliked this feature, but he could not reformulate his theory locally. The nonlocality of gravitation could only be dealt with in general relativity, where the gravitational force is eliminated and the interaction between particles is re-interpreted as free motion in a curved space-time. The case of electrodynamics, in which particles interact with one another due to their charges, is different: the interaction can be formulated in terms of instantaneous forces, but it can also be interpreted as mediated by the electromagnetic fields, which travel at the velocity of light. This action is local, in the sense that it propagates at finite velocity. To summarize, therefore, the development of classical theories was (partially) guided[5] by the need to find a local theory, because otherwise the interaction would act mysteriously. Moreover, according to Einstein, without locality and separability it seems that it would be impossible to do physics. Had separability and locality been false, an arbitrarily distant object could instantaneously influence a given system, so that one could never consider that system as isolated. Consequently, one could never find the causes of an object' behavior by looking at nearby systems. Since instead we can successfully treat objects as if they are isolated and we successfully can identify the causes of the phenomena, it seems that nonlocality and separability have to be empirically false. Finally, nonlocality also seems theoretically impossible, as it contradicts one of the principles of the special theory of relativity according to which the velocity of light is the maximum speed.[6]

3. Primitive Ontology and Intuitions

As wavefunction realism, the primitive ontology approach provides a possible quantum ontology. In this section, I draw a parallel between this approach and wavefunction realism: I show how the primitive ontology program can also be seen as a normative framework, prescribing a structure all satisfactory fundamental physical theories should have, and that one can find three arguments to support it, the last of which involves preserving intuitive notions.

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[5] In fact, it should be noted that historically one of Einstein's main motivations for special relativity was to unify classical dynamics and electromagnetism under the same space-time transformations.

[6] Even though one cannot send faster-than-light or instantaneous signals using non-local correlations.

In short, the primitive ontology approach states that the ontology of matter of a satisfactory fundamental physical theory should be spatiotemporal. Accordingly, the 'primitive ontology' of a theory is the spatiotemporal quantity which expresses what in the theory matter is made of. If a quantity is not spatiotemporal, like the wavefunction, it cannot be a candidate for the ontology of matter.

The best example of a primitive ontology is the one of particles, as in the case of classical mechanics. As we have seen, classical theories, from classical mechanics to classical electrodynamics, start from a three-dimensional fundamental space in which fundamental objects live: classical particles are point-like entities defined in three-dimensional space moving in space and evolving in time, and electromagnetic fields oscillate in space and time. Macroscopic objects are seen as composed of particles and their properties are determined by the microscopic dynamics, as discussed. In the quantum domain, this does not seem to be the case anymore, even considering realist theories, at least in the case of GRW and Everett. In fact, in these theories matter is represented by an object, the wavefunction, which does not live in spacetime, as the wavefunction realists suggest. Different is instead the pilot-wave theory, in which there are particles moving in spacetime according to an equation whose expression involves a Schrödinger evolving wavefunction. So, it is not surprising that the primitive ontology approach started being developed within this theory: it is easy to interpret the pilot-wave theory as a particle ontology, in which the wavefunction does not represent a physical field but rather it describes the interaction between the particles. This means that the wavefunction is an object which is more similar to a potential than to a material field: it is part of the ingredients necessary to write down the law of motion, rather than representing physical objects (Allori 2021a).[7]

Notice that none of the other realist quantum theories, such as GRW and Everett, is satisfactory from the primitive ontologist perspective because they are all theories with a wavefunction ontology, which is a non-spatiotemporal field. This is why primitive ontologists claim that, if one wishes to seriously consider these theories, they need to 'supplement' them with a spatiotemporal ontology. For instance, a matter density ontology has been proposed for GRW (GRWm; Benatti *et al*. 1996) as well as for many-worlds (Sm, where 'S' stands for 'Schrödinger evolving wavefunction'; in this notation the pilot-wave theory would be Sp; Allori *et al.* 2008). Otherwise, a spatiotemporal event ontology, often dubbed 'flashes', has been proposed for GRW (GRWf; Bell 1987) and for many-worlds (Sf; Bell 1987, Allori *et al.* 2008). Similarly, a particle ontology has been put forward for many-worlds (Sip, where 'i' stands for 'independent', to distinguish it from Sp, namely the pilot-wave theory; Allori *et al.* 2011) and, somewhat surprisingly, only much later for GRW (GRWp6, Allori *et al.*, Allori 2020).

The primitive ontology account provides a description of how our current theories describe and explain the phenomena: matter is composed of fundamental spatiotemporal entities. But, as in the case of wavefunction realism, it is also normative, as it prescribes, when facing

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[7] So, Bohm's original formulation of the theory, in terms of the quantum potential, is illuminating in this sense, even if it is misleading in other aspects, like suggesting that the theory is second rather than first order (see Dürr *et al*. 1992). Moreover, the analogy with the potential, should not be regarded as too strict. In fact, while a potential is always originated by some underlying physical field, the wavefunction is not associated to any such field.

underdetermination, to follow a principle of the form: “chose the theory which has a spatiotemporal ontology.”

As in the case of wavefunction realism, one can identify (at least) three, progressively better arguments for the primitive ontology approach. First, *prima facie*, one can say that we should keep using the assumptions which have worked in the past: in classical theories a spatiotemporal ontology has always been assumed, very successfully, and there seem to be no reasons to change this (Allori *et al.* 2008). Historically, as mentioned above, all fundamental physical theories before quantum mechanics have always assumed a spatiotemporal ontology. Even at the beginning of quantum theory, the idea was to keep the ontology in spacetime. In fact, when discussing Schrödinger’s wave mechanics, Lorentz and Einstein both praised the fact that the approach was, in contrast with Heisenberg’s matrix mechanics, visualizable. In fact, it had a clear ontology, waves, which could be used to have a clear picture of what was going on at the fundamental level: for instance, quantized energy levels of the hydrogen atom could be explained in terms of nodes of a standing wave. Nonetheless, Schrödinger’s wave was in configuration space, and thus it could not be imagined as something oscillating in space and time, like electromagnetic fields. Schrödinger himself was troubled by this feature (1926), and Lorenz even wrote that, hadn’t Schrödinger found a way to restore his wavefunction into ‘physical’ space, he would go back to matrix mechanics (Prizbram 1967). That is, we seem to be again in the same situation we encountered before, in which without a specific assumption (spatiotemporality, in this case) physics as we know it would be impossible. Notice that if we assume a spatiotemporal ontology, separability comes automatically, if we wish the theory to be empirically adequate. In fact, with a particle ontology, separability being the central core of atomism, comes for free: a table completely described in terms of it being a collection of suitably interacting particles. If instead we have another primitive ontology, as a matter field or a flash ontology, in order to account for experimental results like particle tracks in detectors, one needs the ontology to behave *as if* it were particles. If not at the fundamental level, at least at a given mesoscopic scale (Allori 2018).[8]

However, this argument is not very strong: the fact that we successfully used a spatiotemporal ontology in the past does not necessarily justify its use in a different context: further justification seems to be needed. A better argument for the primitive ontology approach provides such a justification: in parallel with what has been argued in wavefunction realism, one could maintain that we should preserve a spatiotemporal ontology because spatiotemporality is an intuitive notion. Having an ontology in spacetime is intuitive, in the sense as almost undeniable: physical objects seem to be having the fundamental property of being located somewhere in space, and they seem to be changing in time. It seems also undeniable that something like space, understood in the usual way as three-dimensional, exists, even if we might disagree about its nature, as the relationist-substantivalism debate shows. Similar reasoning for time: it exists, even if we might disagree about its nature and whether it passes. As in the case of locality and separability, these intuitions about space and time are corrigible: space might not be three-dimensional, and time as we perceive it might not exist. But a view which denies these notions

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[8] One could have a particle ontology which is non-separable if one allows for ‘shared’ properties, like for instance the total spin in the case of an entangled pair (see also the last section).

certainly faces the charge that it is counterintuitive: they are contrary to our direct experience and thus, they require further justification. This argument based on intuition does not explain why these intuitions are better than others. After all, wavefunction realists, as we have seen, also wish to keep intuitions, even if they disagree with the primitive ontologists about which ones we should keep: primitive ontologists require spatiotemporality, while wavefunction realists advocate for locality and separability. Primitive ontologists thus need to provide a reason why we should favor spatiotemporality (and thus separability) over locality and separability.

This is, in my opinion, where the best argument for the primitive ontology framework comes in: one should favor spatiotemporality because it allows the theory to produce a *constructive explanation* of the phenomena, which is the most satisfactory type of explanation (Allori 2024). In fact, arguably, the reason why spatiotemporality (from which separability follows) was so important in the development of physics is that without a spatiotemporal ontology one could not have what Einstein called a constructive theory (1949). He distinguished between principle and constructive theories. A principle theory is one which explains the phenomena 'top-down,' in terms of principles stating what can or cannot happen. For instance, the thermodynamic principle that 'energy is conserved' tells us that a phenomenon in which energy is not conserved will never be observed because it violates the principle, and thus cannot happen. In contrast, a constructive theory is one in which the phenomena are explained 'bottom-up,' in terms of an ontology of fundamental entities composing macroscopic objects, and whose dynamics explains the principles restricting the possible behavior of macroscopic phenomena. For instance, kinetic theory explains why the principle that 'energy is conserved' holds in terms of the energy of the fundamental particles. Constructive theories, in other words, explain the phenomena Lego-style: the fundamental entities are like Lego bricks which together constitute macroscopic objects, whose properties are determined compositionally in terms of the property of the fundamental ontology. That is, constructive theories are based on a spatiotemporal, separable, fundamental ontology. From what we have seen, classical mechanics is a constructive theory: it assumes that there are fundamental microscopic components in space evolving in time (spatiotemporality) which compose macroscopic objects determining their behavior (separability).[9]

According to Einstein, constructive theories are explanatorily superior, as they justify why principles hold. Physics aims at providing constructive theories, even if principle theories will be provisionally accepted, in absence of constructive alternatives. Moreover, there is a close relation between constructive explanation of a phenomenon and its visualizability: when one provides a constructive understanding of a given phenomenon, one also provides a picture of what happens at the microscopic level. This is the reason why scientific realists (at least in the past, see Einstein, Schrödinger, Lorenz) seem to favor constructive theories. So, if one thinks that one should pursue a constructive explanation of the phenomena, one should require a

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[9] Different is the story of constructive explanations with a wave ontology. They cannot be thought as Lego bricks or as microscopic entities because waves are extended objects. However, waves combine with one another according to the superposition principle. This is how for instance Schrödinger thought about particles: wave-packets of superimposed waves with different wavelength. Arguably, this is what a constructive type of explanation with waves looks like.

spatiotemporal (and thus separable) fundamental ontology. Thus, while in the literature usually one discusses the primitive ontology approach as requiring a spatiotemporal ontology, I think the best way of characterizing this perspective is as providing a criterion, or a principle, for theory selection: *choose the theory which gives you a constructive explanation*.[10]

If one rejects spatiotemporality of the ontology, as in the case of wavefunction realism, as we have seen, the explanation of the phenomena is not entirely constructive. Given three-dimensional space, the 'particle' is thought of as partially instantiated by the wavefunction when it is not spread out.[11] Moreover, once we have the partially instantiated 'particles,' then we can use them as building blocks to construct macroscopic objects. In contrast, however, the explanation of where three-dimensional space comes from is not constructive. In fact, to explain three-dimensionality, wavefunction realism uses the principle that: "the symmetry of the dynamics are the same as the symmetry of the space." This is an explanation that is typical of principle theories: the principle above systematizes the phenomena in terms of what can and cannot happen without explaining the reason why it happens.

To conclude the parallel with wavefunction realism, which is the only local and separable approach, the primitive ontology framework is the only spatiotemporal and separable approach. In virtue of this, as wavefunction realists reject all alternatives approaches because they are non-separable and the primitive ontology approach because it is nonlocal, primitive ontologists reject all their competitors because they do not provide a constructive framework. While the challenge for wavefunction realism is to explain the three-dimensionality of our experience, the cost of the primitive ontology framework is to explain what it means that the interaction is not local.

4. Three Fundamental Intuitions in Physics and the Challenge from Quantum Theory

From a scientific realist perspective, a fundamental physical theory explains the phenomena providing an approximately true description of reality. As we have seen, classical theories

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[10] Notice that while some primitive ontologists talk about GRW and many-worlds theories with a spatiotemporal ontology (GRWm,f,p; Sm,Sf,Sip) as if they are on the same footing as the pilot-wave theory (see e.g. Dürr and Lazarovici 2020, Tumulka 2023), this does not seem to make much sense if the spatiotemporality of the primitive ontology comes from the requirement of having a constructive theory. In fact, a constructive explanation is straightforward with a particle primitive ontology, so why care about another type of ontology, given that these ontologies require some adjustment to obtain a constructive explanation? For instance, with a flash ontology, there are no longer trajectories at the fundamental level, even if one can imagine them to emerge at a mesoscopic level (a similar thing can be said for the matter field; Allori 2018). It would make sense to entertain these theories if they gave us some advantage elsewhere, like for instance helping us reconciling quantum theory with relativity. Nonetheless, in this case what seems to matter is not the type of ontology (particle or not) but rather the type of spatiotemporal structure used to implement relativistic invariance, which seems to privilege a stochastic evolution. So, one might be justified in looking at relativistic extensions of stochastic theories with a particle ontology. However, no such theory currently exists, and in general it has been argued that a stochastic evolution would be more nonlocal than needed (Allori 2022), and thus it would be undesirable when compared to their pilot-wave counterparts.

[11] This is similar to Schrödinger's thinking of particles as wave-packets, so it provides a constructive understanding in terms of waves.

describe physical objects as composed of fundamental entities moving in spacetime. They take time to interact with one another, in the sense that there is no instantaneous action at a distance. So, to summarize, (*modulo* what we have said so far) the following three notions seem to play an important role in the explanation of the phenomena, at least classically:

1- Spatiotemporality: physical objects are thought of as living in three-dimensional space or four-dimensional spacetime;
2- Locality: the interaction between objects is not instantaneous but travels at finite velocity;
3- Separability: physical objects are composed of smaller parts, and their behavior is completely described by the behavior of their parts.

We have already seen why they have been considered so fundamental: they are intuitive notions, almost undeniable. The primitive ontology approach and wavefunction realism have a common strategy: trust our intuitions and keep as many as possible. As we have seen, in virtue of this, they reject their competitors, even if they disagree about which intuitions are more basic.

Two questions come to mind at this point. First, one wonders whether in the quantum domain it is possible to have a theory in which all three intuitions are respected, as it happened classically. I will show next that this is unfortunately not the case. Then, given this, how should we proceed? That is, given the disagreement between the two approaches, which one should one choose? I get back to this question in the next section. Let's address the first question now.

Even if it would be desirable for all three of these notions to be the case also in the quantum domain, let me discuss why they are incompatible. Arguably, one can think of the Einstein, Podolsky and Rosen argument (EPR 1935) as further evidence that Einstein would have wanted them all. Einstein observed that quantum theory with von Neumann's collapse rule is nonlocal: the collapse instantaneously transforms the state from a superposition into one of its terms. He however thought that such nonlocality was just apparent, merely evidence of the incompleteness of the description provided by quantum theory. He thought that by providing a complete description this nonlocality would evaporate. Together with Podolsky and Rosen, he provided an argument for this conclusion. In Bohm's 1951 version of the argument, consider a pair of particles in a spin singlet state traveling in opposite directions. The values of the spin properties of each particle are empirically found to be perfectly anti-correlated: when one is found 'up', the other is found 'down,' and the other way around. Quantum theory prescribes that since initially the pair was in a singlet state, both spin properties are created during measurement. This is a non-local action: what happens in one location, for instance measuring the spin of the first particle and finding 'up,' determines instantaneously something arbitrarily distant from it, namely the spin of the second particle being 'down.' Instead, assuming locality, which can be generally characterized assuming that the probability of some event only depends on what happens in its past light-cone (Bell 1964, 1966), the only explanation available for the anti-correlations is that each particle had a given spin property all along, which was later revealed by the measurement. This is true for all directions of spin. So, schematically, the EPR argument looks like this:
$EPR: (locality) \longrightarrow (properites\ for\ all\ spin\ directions)$.

Bell started from the EPR result and then showed that a theory like the one needed by EPR (which completed quantum theory with the values of the spin properties) would obey a given inequality, which is instead not valid in quantum mechanics:
$Bell\colon (properites\ for\ all\ spin\ directions) \longrightarrow (inequality)$.
Later, a version of this inequality was tested by Aspect and collaborators (1981), and it was found to be falsified:
$Aspect\colon (inequality) \longrightarrow (falsification)$.
Notice that these three steps combine as:
$(locality) \longrightarrow (properites\ for\ all\ spin\ directions) \longrightarrow (inequality) \longrightarrow (falsification)$,
That is: $(locality) \longrightarrow (falsification)$.
The only way to avoid empirical falsification is to reject the assumption of locality (rejecting spin properties will not help, as they are what logically follows from assuming locality).[12] Therefore, Bell's theorem has proven that quantum objects, thought as spatiotemporal objects, may interact non-locally: very succinctly, assuming locality, the observed correlations in measurements of entangled states imply the existence of properties of the system not specified by quantum theory, which however produce empirically falsified results, thereby disproving that the interaction is local.[13] Notice that this is true for all quantum theories, even those which do not have von Neumann's collapse rule. The GRW theory is nonlocal because the quantum state still collapses, even if it is a matter of law rather than observation. Instead, a theory like the pilot-wave theory is manifestly nonlocal because the interaction between the particles in mediated by the wavefunction, which is a function of the positions of the particles at the same instant. So, modifying one of them would instantly affect all the others, regardless of their distance. More difficult is assessing the situation for the many-worlds theory because, to start with, it is unclear how Bell's theorem applies to it: in fact, Bell's theorem assumes unique outcomes, while this is denied in the many-worlds theory.

Notice that the nonlocality conclusion follows only if one assumes a spatiotemporal ontology. In fact, in Norsen's reconstruction of Bell's theorem (2017), the definition of locality used in Bell's proof is the requirement that the probability of an event happening only depends on what is in its past light-cone in spacetime.[14] Therefore, *insisting on a spatiotemporal ontology, even if separable, implies nonlocality of the interaction*:
$(spatiotemporality)\ \&\ (separability) \longrightarrow \sim(locality)$.
This is what happens within the primitive ontology framework: physical objects are composed of the entities in the primitive ontology, which interact nonlocally in terms of the wavefunction. In any case, formulating Bell's theorem in this way one can see how one can 'save' locality by suitably thinking of the theory as not spatiotemporal. In a local theory, one thinks of the

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[12] However, see the next paragraph.

[13] In this presentation, I have followed Bricmont (2016) and Norsen (2017). See also Goldstein *et al*. (2011).

[14] As a side remark let me notice, for completeness, that there is also another way of resisting the nonlocality conclusion, which is denying another 'undeniable' assumption in Bell's theorem, dubbed 'statistical independence.' Theories of this sort are called superdeterministic because they arguably require an incredible amount of fine tuning and coincidences, and which seem borderline scientific (see Chen 2021, Baas and LeBihan 2021, Allori 2024b). Otherwise, one can deny that influences can go only towards the future and introduce retrocausal theories in with backward causation (see Adlam 2022 for an assessment).

interaction between spatiotemporal objects as mediated by a field, like in the case of electromagnetism. In this case, the fields are spatiotemporal: they oscillate in space and time. Instead, as we just saw, quantum theory is nonlocal because the wavefunction is in configuration space. Now, if locality amounts to the absence of instantaneous action at a distance between different spatial locations, one can have a local quantum theory by postulating that the fundamental space is configuration space, and the fundamental ontology is the wavefunction in that space. That is, *assuming the wavefunction in configuration space is the fundamental ontology, it follows that all interaction is local in that space*. However, this implies that one has to *renounce to a fundamental ontology is in spacetime*, even if it were separable:
$(locality)\ \&\ (separability) \longrightarrow \sim(spatiotemporality)$.
This is what wavefunction realism does: physical objects are suitably extracted from the wavefunction in configuration space, which also describes their mutual interaction locally in that space.

5. Ranking Intuitions

The question about which perspective is more compelling boils down to which intuition is the more basic. One might think this is just arbitrary, as sometimes having a given basic intuition is like having a favorite ice cream flavor. Even Ney (2024) does not try to show that wavefunction realism is ‘the’ true metaphysics. Rather, she seems content with claiming that wavefunction realism is worth considering, perhaps on the same footing of the other approaches, and that the decision about which framework to endorse depends on one’s personal attitudes. That is, one could think that intuitions can be ranked differently, and that choosing one ranking or another is a matter of preference. Instead, I wish to argue in the rest of this section that some rankings are more justified than others because spatiotemporality, separability and locality are not mutually independent. Rather, they come in a hierarchical sequence: requiring separability and locality makes sense only if we first require spatiotemporality. Since only the primitive ontology approach respects that sequence, this framework is more justified.

Wavefunction realism tells us we should save locality and separability because they are intuitive, even if they cost us a spatiotemporal ontology. The meaning of spatiotemporality and locality change, given that now they are not in spacetime, but they are in high-dimensional configuration space. Ney of course is aware of this, but nonetheless states which they are intuitive, if properly re-defined. As we have seen, locality has to be understood as the requirement that interaction travels at finite velocity in the fundamental space; while separability is the idea that “all facts about regions that are determined by facts about their subregions” (Ney 2024).
Nonetheless, these definitions seem still underdetermined. Both these definitions are about regions, objects, interaction. In wavefunction realism, regions are regions of configuration space. However, how should we understand the notion of object or interaction, given that in configuration space there is only the wavefunction? It seems that the definition of both separability and locality requires the presence of more than one object in the world: the world is separable if the objects in it can be thought of suitably independent, and the objects in the world

interact locally if their mutual action on one another is not instantaneous. However, if we have only one object, regardless of the dimension of the space it lives is, it is not obvious what it really means that the ontology is separable and local.

In addition, aside from this, the reasons we have provided in section 2 to support that these notions are intuitive are compelling only if locality and separability are understood in three-dimensional space. In fact, a wavefunction realist cannot appeal to the fact that historically locality and separability in configuration space were requirements for a satisfactory theory, because what was required was their spatiotemporal counterparts. In particular, she cannot claim that separability in configuration space is at the core requirement of atomism, because only separability in three dimensions translates as compositionality: the properties of macroscopic objects are completely determined by the microscopic entities composing them. Instead, as discussed, in the case of wavefunction realism compositionality does not hold, at least not at all steps of the explanation.

Ney agrees, but she claims that separability (in whatever space) is an intuitive notion nonetheless: a fact about an entity should not be influenced by the facts about another entity. Similarly, locality (independently on the space in which it is defined) is intuitive: an object does not act where it is not. Ney argues that being intuitive is a virtue and that denying intuitions like this is almost like denying an analytic truth. However, is it enough to say that a notion being intuitive is worth keeping if we do not know why denying it seems so wrong? In other words, we should be able to explain why these notions are so entrenched. Why are they in our Quinean web of belief? Why are they at the hard core of our theory? Ney does not seem to have an answer for configuration-space locality. However, she argues that separability in configuration space is valuable because it allows the thesis of Humean supervenience to be true, which is important to preserve because it is simple. However, why should we care about simplicity given that the explanation of the phenomena we provide is so complex?

Our intuition that separability is important is connected to the fact that the *objects of our experience*, which we see in three-dimensional space evolving in time, are separable. But if these objects are actually derived from a more fundamental ontology in a high-dimensional space, why should we care about separability in that space? Indeed, why should it be almost an analytic truth that facts about an entity in configuration space should not depend on facts about another entity in configuration space, given that this is intuitively the case for three-dimensional space? After all, the opposite seems to be the case in classical mechanics: this theory, which is separable in three-dimensions, thought as reformulated in configuration space becomes non-separable. In fact, a set of classical particles of three-dimensional coordinates $r_1, \dots, r_N$ in configuration space identifies an object in terms of a point given by their configuration $q = (r_1, \dots, r_N)$. So, while the set is composed of separable particles, the point in configuration space is not.[15]

A similar reasoning can be done for locality: we have always thought, classically, that interaction had to be local because we had in mind what we observe every day, namely that objects do not act where they are not. Here instead we are talking about locality in configuration

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[15] One might object that a point in configuration space is merely a point, so the notion of separability no longer applies. Nonetheless, it is supposed to represent a composed object, and this is a non-separable representation.

space. It is unclear why it should be almost undeniable that in that space the interaction is local, as the notion of locality is connected to the one of interaction, which requires the presence of more than one object. Classical systems interact locally in three-dimensions: a set of particles interacting locally are represented by their three-dimensional coordinates $r_1, \ldots, r_N$ and the fields mediating the interaction. However, it is not obvious how to think of their interaction in configuration space, because there is just one configuration q and the field written in terms of q. Since we have just one object, it is difficult to make sense of the notion of locality, which needs at least two objects to be defined.

I think that this difficulty for wavefunction realism comes from the fact that in order to define properly separability and locality as intuitive notion, we need to first require that the fundamental space is three-dimensional. If we assume, like the primitive ontologists do, that matter is in spacetime, then, as we have seen, separability comes for free. Locality is instead about the interaction between separable objects. Only then we can check whether we can have locality of the interaction. Indeed, this is arguably what Bell tried to do. When he learned about the pilot-wave theory, he claimed that he saw 'the impossible done:' in fact, von Neumann has argued that it was impossible to complete quantum theory, while this is exactly what the pilot-wave theory seems to be doing. That is what prompted Bell to look for a mistake in von Neumann's proof, which he later found (1982). Then he noticed that the pilot-wave theory, which was in spacetime and separable, was however non-local. So, he started wondering whether it was possible to find a theory which was spatiotemporal, separable and local. He showed that such a theory would have to obey his famous inequality which however was later empirically falsified, as we have seen earlier. The reason I mention this again here is to emphasize that he started assuming spatiotemporality and then checked whether one could keep also the other notions, separability and locality. Of course, the conclusion is that, since quantum theory in spacetime is nonlocal, we have to reject locality.

However, we can still have a constructive explanation: fundamental entities compose, Lego-style, larger objects and their dynamics explains their properties, even if the interaction can be nonlocal. In fact, quantum nonlocality is not eliminable as in the classical case: there is no local mediating field (as in the case of electromagnetism), and there seems to be no way of eliminating the interaction by changing the geometry (as in the case of gravity). Classically, the strength of the interaction, even when understood nonlocally in terms of forces, decreases as the inverse of the square of the relative distance between the objects. Thus, the classical interaction is negligible at large distances, while quantum mechanically its strength is unaffected by distance. Nonetheless, in order to see nonlocality macroscopically, in everyday life, one would need to keep the state coherent (i.e. the various components of the state would still be able to interfere with one another) while for all practical purposes this is never the case. This is because the interaction of the system with its environment destroys the coherence and thus the possibility of detecting a nonlocal action. This observation explains why we seem to live in a local world: because, for all practical purses, we do. In turn, we can explain why objects can be thought of as isolated: because, for all practical purposes, they are. And finally, it explains why we can identify causes of events nearby: because, for all practical purposes, distant causes can never be realized. Consequently, since the nonlocality of the interaction between two systems is almost immediately suppressed by the presence of an environment, we can say that the theory is 'effectively' local, and therefore the schema used by constructive explanation still holds.

To summarize, then, spatiotemporality, separability and locality are notions that appear in physical theorizing in sequence: if we assume a spatiotemporal ontology, like in the primitive ontology approach, because it is intuitive and almost undeniable, then it follows that it is separable, and then we may check whether the interaction is local. In classical electromagnetism the interaction is local, here instead we have something which we can dub 'effective' locality at the macroscopic regime, which is enough to grant constructive explanation. The alternative provided by wavefunction realism is instead to assume separability and locality in configuration space. However, it remains unclear whether the definitions make sense, and why the fact that they are intuitive notions in three-dimensional space implies that they are also intuitive in configuration space.

6. Conclusions

I think that Ney is correct that the best way of thinking of wavefunction realism is as a framework which helps breaking cases of underdetermination by asking us to choose the local and separable ontology. This means in non-relativistic quantum mechanics to choose the wavefunction in configuration space, while in other cases, like relativistic quantum theories, this may lead to different choices. Similarly, the best argument for the primitive ontology framework is that one should require a spatiotemporal ontology because it grounds constructive explanation.

In this way, both frameworks can be claimed to be intuitive, even if they disagree about which intuitions are more important, given that in quantum mechanics one cannot have them all. However, while in the primitive ontology approach assuming spatiotemporality gives us separability for free, and we can explain why for all practical purposes the theory is local, the situation is more convoluted in wavefunction realism: assuming locality and separability while rejecting spatiotemporality requires a better story to redefine these notions, and in any case demands to give up on constructive explanation. But why should we do that, if we have the much more straightforward path given by the primitive ontology framework? Moreover, I have argued, the notion of separability and locality require the notion of spatiotemporality, and this hierarchy is respected in the primitive ontology approach and not in wavefunction realism.

Clearly now the problem for the primitive ontology approach becomes to make sense of nonlocal action.

The first possibility is to completely give up on the notion of separability: a pair of entangled states is seen as an entangled entity which is not separable. That is, it is not that the pair interacts non-locally, rather it is matter which is non-separable. This would amount to 'saving' spatiotemporality and locality, abandoning separability. However, this would cost us constructive explanation, Thus, it does not seem to be a living option for the primitive ontologists.

Otherwise, if we think of the wavefunction as a mediating field, we cannot think of it as real as electromagnetic fields were thought to be real, because it is in configuration space. So, at best we can think of it as being as real as a potential. However, since the potential classically was seen as another way of expressing the effect of the fields, this response is not satisfactory in this framework: if there is no corresponding physical field, what does this 'nonlocal potential' actually represent?

In response to questions like this, Norsen (2010), in the framework of the pilot-wave theory, has attempted to rewrite the wavefunction in terms of fields in three-dimensional space. However, aside from other considerations (based on symmetries against the idea of thinking of the interaction as a mediating field, Allori 2021b), one would need an infinite amount of fields to substitute the wavefunction, so it does not seem viable.

In any case, even if we do not have an answer right now, these are the questions one should focus on if they care about being the least revisionary (in the sense we have discussed in this paper) in doing quantum ontology.

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