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Quantum Mechanics, Fields, Black Holes, and Ontological Plurality

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Abstract: The ontology behind quantum mechanics has been the subject of endless debate since the theory was formulated some 100 years ago. It has been suggested, at one time or another, that the objects described by the theory may be individual particles, waves, fields, ensembles of particles, observers, and minds, among many other possibilities. I maintain that these disagreements are due in part to a lack of precision in the use of the theory's various semantic designators. In particular, there is some confusion about the role of representation, reference, and denotation in the theory. In this article, I first analyze the role of the semantic apparatus in physical theories in general and then discuss the corresponding ontological implications for quantum mechanics. Subsequently, I consider the extension of the theory to quantum fields and then analyze the semantic changes of the designators with their ontological consequences. In addition to the classical arguments to rule out a particle ontology in the case of non-relativistic quantum field theory, I show how the existence of black holes makes the proposal of a particle ontology in general spacetimes unfeasible. I conclude by proposing a provisional pluralistic ontology of fields and spacetime and discussing some prospects for possible future ontological economies.

Keywords: quantum mechanics; quantum field theory; interpretations; ontology; black holes; spacetime; fields; realism; materialism

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1. Introduction: Quantum Ontology and Its Discontents

Quantum mechanics (QM) is a fundamental theory of the behavior of matter at low energies. It is concerned with objects[1] such as electrons, photons, and atoms. It is not necessarily limited to the microphysical world, as it can be used to describe macroscopic systems with non-classical behavior, such as superconductors, superfluids, and neutron stars. The foundations of the theory were laid during the first three decades of the 20th century by a number of outstanding physicists, including Max Planck, Albert Einstein, Niels Bohr, Louis de Broglie, Max Born, Werner Heisenberg, Pascual Jordan, Erwin Schrödinger, Paul Dirac, Wolfgang Pauli, and many others (see [1] for a history of QM).

The mathematical structure of the theory was already established in the early 1930s and can be found in the classic books by Dirac [2] and von Neumann [3]. The formalism is quite simple: each quantum object is associated with a complex function $\psi(\bar{x})$ belonging to a Hilbert space $\mathcal{H}$. Such a function somehow represents the "state" of the system and is defined over a Euclidean three-dimensional space of spatial coordinates $\bar{x}$. This function is used to compute the values of the properties of the quantum objects. The inner product of two states is definedas

$$\langle\psi|\phi\rangle = \int \mathrm{d}\bar{x}\, \psi^*(\bar{x}) \cdot \phi(\bar{x}). \tag{1}$$

The values of the *properties* of a quantum system can be computed with self-adjoint operators defined over the Hilbert space $\hat{A}(t) : \mathcal{H} \longrightarrow \mathcal{H}$ acting on the wave functions. A first surprising fact is that, unlike classical systems, quantum objects usually do not have precise or sharp values for their properties. Instead, we can calculate the average $\langle \hat{A} \rangle$ for a given property of a system in a given state ψ:

$$\langle \hat{A} \rangle = \langle \psi | \hat{A} | \psi \rangle. \tag{2}$$

The property is spread as

$$\Delta_\psi \hat{A}^2 = \langle \hat{A} \rangle^2 - \left\langle \hat{A}^2 \right\rangle. \tag{3}$$

If the spread $\Delta_\psi \hat{A}$ of a certain property of a quantum state $\psi_k(\overline{x})$ is zero, then the property takes a sharp value λ_k. The corresponding state $\psi_k(\overline{x})$ is called an eigenstate of the operator $\hat{A}$, λ_k is its eigenvalue. In such a case:

$$\hat{A}\psi_k(\overline{x}) = \lambda_k \psi_k(\overline{x}). \tag{4}$$

Under certain conditions, the values of λ_k form a countable set, i.e., the values of the property can be quantized. This is another peculiarity of quantum objects: they have discrete values of some properties.

Since the operators evolve with time, the properties also evolve. The evolution equation is

$$\frac{d\hat{A}}{dt} = \frac{i}{\hbar}(\hat{H}\hat{A} - \hat{A}\hat{H}) + \frac{\partial \hat{A}}{\partial t}, \tag{5}$$

where $\hat{H}$ denotes a special operator called the Hamiltonian of the system and $\hbar$ is the Planck constant over 2π. The Hamiltonian represents the energy of the system. This dynamical equation is called the Heisenberg equation. Note that if the system is not interacting, $\hat{H} \neq \hat{H}(t)$, and the evolution of any property from a state given at time t_0 is

$$\hat{U}(t,\ t_0) = \exp -\frac{i}{\hbar}\hat{H}(t - t_0), \tag{6}$$

where the evolution operator is clearly unitary:

$$\hat{U}(t,\ t_0)\hat{U}(t,\ t_0)^\dagger = \hat{I}. \tag{7}$$

An alternative, equivalent formulation of the theory can be obtained by using time-independent operators to represent the properties and a time-dependent wave function $\psi(x) = \psi(\overline{x},\ t)$ that satisfies the Schrödinger's equation:

$$\hat{H}\psi(x) = \frac{i}{\hbar}\frac{\partial \psi(x)}{\partial t}. \tag{8}$$

The two pictures differ only by a change in the basis with respect to the time dependence, which corresponds to the difference between active and passive transformations. In fact, both equations can be derived from the fundamental symmetries of the invariance group of the theory, in this case, the Galilei group (see details in [4,5]).

The evolution equations are linear, and once the initial and boundary conditions are fixed, the evolution of the system is uniquely determined: each property evolves as

$$\hat{A}(t) = \hat{U}(t,\ t_0)^\dagger \hat{A}(t_0)\hat{U}(t,\ t_0), \tag{9}$$

and the state evolves as

$$\psi(x) = \hat{U}(t,\ t_0)\psi(\overline{x}_0), \tag{10}$$

where $(\overline{x}_0, t_0)$ are the initial conditions. The linearity of the evolution equation implies the validity of the superposition principle: the linear combination of solutions is a solution. This means that $\psi(x) = \Sigma_k \lambda_k \psi_k(x)$, where λ_k is a set of eigenvalues of an operator $\hat{A}$ and the ψ_k are the corresponding eigenstates that form a complete basis of the Hilbert space. As long as the system evolves unitarily, it is in a superposition of states. Then, the predictions of the theory are probabilistic: we can only say what is the probability of a quantum object to be in a certain state at a certain moment. This probability is

$$p_k = |\langle\psi|\psi_k\rangle|^2, \tag{11}$$

where $0 < p_k < 1$. This probability is always less than 1, but when an interaction occurs, the system is always found in one state or another since a sharp value of the property occurs. The original theory does not explain how this transition occurs, so the usual Copenhagen interpretation introduces an additional assumption: if a measurement of a property $\mathcal{A}$ associated with an operator $\hat{A}$ on the quantum object in a state ψ gives a real value a_n associated with the eigenstate ψ_n, then immediately after the measurement the object evolves from ψ_n according to $\hat{A}\ \psi_n = a_n\ \psi_n$ [3]. This is called the "collapse of the wave function" and is the core of the orthodox interpretation.

This opens an ontological Pandora's box, as it has been used to claim that the collapse introduces the "observer" into the theory. It has been suggested that the implications are so extreme that an independent reality of the physical world is not viable, and even the reality of the observers has been questioned [6]. Others have concluded that materialism is untenable in the light of quantum mechanics [7], or have proposed that quantum physics cannot be formulated without appealing to consciousness [8]. And that was only the beginning. Early surveys of interpretations of quantum mechanics, such as those of Margenau [9] or Bunge [10], already identified dozens of different interpretations. By the time of Max Jammer's famous book on interpretations of quantum mechanics [11], the number was approaching a hundred.

No one questions the soundness of quantum formalism, which has been tested with overwhelming precision. The controversies concern the nature of quantum objects. What is QM really about? The answers can be as varied as observers, consciousnesses, minds, infinite worlds, particles, waves, measuring devices, ensembles of particles, pilot waves, and more (see refs. [12–14]).

This ontological uncertainty extends to other aspects of the theory that differ greatly from the common sense formed by our experience with macroscopic objects. Such aspects include the so-called Heisenberg inequalities (sometimes treated as a "principle" although they are a theorem [4,15,16]) or quantum entanglement [17]. For a discussion of the various peculiarities of quantum mechanics, see ref. [18]. These peculiarities, however, always lead to ontological questions: How is it possible for a quantum object to behave sometimes as a wave and sometimes as a particle? How can the state of a system formed by entangled particles remain linked in such a way that when the state of one particle is fixed in an interaction, the state of the other is also fixed according to the initial state of the superposed pair? How can quantum objects be considered individuals if the number of them remain countable in a superposed state but are no longer identifiable? (See discussions in [19–24].)

Discussions about the interpretation of quantum mechanics have been going on for almost a century. Such persistence is so stubborn that it suggests a fundamental misunderstanding about the relationship of formalism and the way it relates to the physical world it is supposed to represent. In this paper, I will discuss this issue and argue that a realist and materialist interpretation of the theory is possible if we pay more attention to the semantic connectors of the theory. These are the elements of the theory that connect mathematical symbols and elements of the language used to express the theory to objects that are supposed to exist in the world. They are rarely made explicit in the unusual formulations of the theory, and this opacity works in favor of semantic confusion. I argue that semantic confusion is at the root of much of the ontological fog that surrounds QM.

The ultimate goal of the paper is to show that an ontology of particles is incompatible with the extension of QM to relativistic quantum field theory. I demonstrate that the number of particles and their energy–momentum are not invariant in curved spacetimes, particularly in the presence of black holes. What remains invariant is the energy–momentum of the fields. I will conclude that, based on our current understanding of physics, the ultimate ontology of the world is that of material fields existing in a material spacetime.

I devote the next section to clarifying some basic issues in the semantics of physical theories.

2. Theory and Reality: Semantic Relations

We try to articulate our views of the world through systems of propositions called theories. These systems should be well formulated, coherent, and, at least for mature theories, closed under the operation of logical implication [14,15]. Each theory deals with a class of entities that are assumed to exist. Let us call this class the *reference class* of the theory. Since entities cannot just exist but should exist in one way or another, they have *properties*. A property is simply a way in which something exists [25–28][2]. Physical things can have many properties, such as mass, charge, spin, spatial location, and so on. Some of these properties are intrinsic, such as spin or charge (i.e., they depend solely on the thing), and others are relational, such as their velocity or spatial location (i.e., they depend on some other thing). In a theory, we try to represent the properties of the referents by mathematical functions (for example, the intensity of an electric field is represented by a 3-vector, the temperature of a gas by a scalar, the curvature of spacetime by a fourth-rank tensor, etc.).

The set of all functions representing the properties of a thing forms an abstract space called the *state space* of the thing. The evolution of a thing, i.e., the change of its properties over time, is described by a trajectory in this multidimensional space. Since the properties of things do not change arbitrarily but seem to be limited by their relations to the properties of other things, not the whole state space is accessible to a particular thing. These restrictions on the possibilities of change of things are known as *natural laws*, and manifest as regular patterns of occurrences observed in the world [28]. Mathematically, we formulate these laws by *statements of law*, which take the form of restrictions on the functions representing properties. Such restrictions, if local, are encoded in differential equations, although sometimes they can be expressed as integro-differential equations or algebraic equations [14,15].

For instance, electromagnetic fields are restricted by the laws expressed in the Maxwell equations:

$$\partial_\mu F^{\mu\nu} = J^\nu, \tag{12}$$

$$\partial_\mu \widetilde{F}^{\mu\nu} = 0, \tag{13}$$

$$\partial_\alpha F_{\mu\nu} + \partial_\mu F_{\nu\alpha} + \partial_\nu F_{\alpha\mu} = 0, \tag{14}$$

$$\partial_\alpha \widetilde{F}_{\mu\nu} + \mu_0 J_\nu = 0, \tag{15}$$

where $F^{\mu\nu}$ is the electromagnetic field tensor, $\widetilde{F}^{\mu\nu}$ is its dual, J^ν is the four-current, and μ_0 is the permeability of free space.

This set of equations relates changes in the field components to changes in the motion of electric charges. Note that the equations have two different referents: the electromagnetic field and the currents. In no way do the equations express that the currents are the *sources* of the field. As far as the equations are concerned, they simply state that a change in the field implies a change in the currents and vice versa. If we want to claim that the currents are the sources of the fields, an additional assumption must be introduced [15], an assumption that, while useful in some contexts, ultimately leads to problems because fields can exist independently of charges. This, and the fact that an independent equation must be postulated for the motion of charges in a given field (the Lorentz equation), suggests the existence of a deeper level of reality. Such a level is explored by quantum field theory (QFT) in general and quantum electrodynamics (QED) in particular.

This example provides a good opportunity to clarify the role of four key semantic concepts that are usually ignored in the formulation of physical theories. These concepts are related, but they play quite different roles. They are the concepts of denotation, designation, reference, and representation (see [14,32,33]).

We *denote* an object by simply assigning a symbol to it. For example, we can say that 'e' denotes an electron. In other words, denotation is a relation that assigns symbols to objects of the universe or domain of discourse (the reference class) of a theory: $D : \Sigma \rightarrow O$. Here, D is the relation of denotation, Σ is the set of primitive symbols of the language of the theory, and O is the set of extra-linguistic, putative objects with which the theory is concerned. I write "putative" because it may be the case that research will ultimately lead to the conclusion that the reference class is empty (think of the ether, taquions, ghost fields, strings, and other objects discussed in theories that are either ruled out or strongly questioned). To denote is essentially to assign a name. By such an operation, we do not gain any knowledge about the objects. But we should be careful; sometimes, naming creates a familiarity that induces the *illusion* of knowledge.

Designation is a similar operation that assigns elements of the language of the theory to *concepts*: $\mathcal{D} : \Sigma \rightarrow C$. A concept C is a conceptual *construct* usually obtained by the process of *abstraction* [14]. For example, we stipulate that $\mathcal{H}$ designates a Hilbert space and $\mathcal{L}$ a Lagrangian density. Note that with these stipulations, we are doing much more than merely introducing a name for an object that appears in a theory: we are introducing complex concepts that have rigorous formulations in some specified background knowledge.

Reference is another important relation. It associates *constructs* like functions, vectors, tensors, etc., with any kind of object, either things we think exist or might exist in the world, or other formal constructs. Formally, $R : C \rightarrow \Omega$, with $\Omega = O \cup C$. Equation (12), for example, refers to electromagnetic fields and currents. The statement "the doctor successfully operated on the patient and transplanted the liver" refers to a doctor, a patient, and a liver. In general, the reference class of a predicate is the collection of its arguments [14]. An important point is that the reference class is preserved under the operation of deduction. Thus, if a referent does not appear in the reference class of the axiomatic basis of a theory, it cannot appear later in the theorems. When a body of knowledge is presented heuristically or from a historical point of view, it is common for referents to be added without being necessary for the rigorous formulation of the corresponding theory. One such example is the "observer" in QM, which, among other things, is said to be the cause of the Heisenberg dispersion relations. In fact, these relations are derived from the non-commutativity of operators and the Schwarz inequality without any further assumptions. Another example is the invocation of mind or consciousness, which does not appear in any part of quantum formalism. Moreover, mind and consciousness are not things but processes that occur in certain things, namely, the brains of humans and other evolved animals.

Another essential semantic relation in any theory is the relation of *representation*. This relation, designated by '$\hat{=}$', applies constructs to *states* (i.e., collections of properties) of a given thing: $\hat{=} : C \rightarrow F$. For instance, we represent the velocity of a system by a vector, a metric field by a second-rank tensor, or the state of a quantum object by a ray in a Hilbert space. In general, we represent properties by functions, things by sets, events (changes) by sets of statements, and laws by equations. For example, in the case of a gas, pressure is represented by a scalar function, the gas itself by a set of particles, any change as an ordered pair of states, and the fundamental laws of the gas by are represented by its equation of state and the equations of conservation, plus the equation of motion.

Representation is not a function but a relation, which is neither symmetric (facts do not represent constructs, i.e., nature does not care what we think about it), nor reflexive (constructs do not represent themselves), nor transitive (facts do not represent anything, they just are). Moreover, representations are not unique: there are many ways we can represent nature. In the case of QM, think for example of the Heisenberg and Schrödinger pictures, which are equivalent.

Let us now turn to the referents of QM.

3. The Referents of Quantum Mechanics

In order to determine the ontological assumptions of QM, it is convenient to axiomatize the theory in order to reveal all its constitutive elements. The axiomatic basis of the theory includes a set of undefined terms, a set of definitions, and a set of axioms. An axiomatization is viable if the axioms are independent and coherent (i.e., no logical or semantic contradiction can be derived from them), and all the standard mathematical apparatuses of the theory can be obtained from them as theorems in such a way that the predictive power is not less than that of any heuristic representation. The main advantage of axiomatization is that it makes all assumptions explicit from the beginning [34]. Since reference is preserved under deduction, the reference class of the theory can be determined from the axioms, which are finite.

There are several axiomatic formulations of QM with different sets of axioms (e.g., refs. [3–5,15]). The system presented by Perez Bergliaffa et al. has the advantage of making all semantic designations explicit, and also of adopting as a central physical statement the group of symmetries of the theory (the Galilei group in the case of non-relativistic QM), in such a way that all important equations such as Heisenberg's, Schrödinger's, and Heisenberg's inequalities are obtained as theorems. So I will take this axiomatic as an example here (see ref. [4] for single quantum objects, and ref. [5] for systems of them).

One thing to note from the outset is that not all terms in a theory necessarily have ontological significance, even in a realist interpretation. Various terms may be instrumental in computing values of properties, without directly representing any feature of reality. Other terms may be purely mathematical, with no physical counterpart. In general, axioms are divided into semantic ones (those that are connected to the factual domain of the theory by semantic relations), those that are purely mathematical, and those that have physical content in the sense that they express relations that are expected to be valid between the referents of the theory (physical laws).

In the case of the axiomatization of QM given by Bergliaffa et al. [4], the first important axiom is the postulation of quantum objects (σ). Each σ is supposed to have an environment ($\bar{\sigma}$) made up of other things, some of which may interact with σ. If nothing interacts with the quantum object, σ is said to be a closed microsystem. If the environment is an empty collection represented by the empty set, it is denoted by $\bar{\sigma}_0$. Note that so far, nothing has been said about the nature of the class formed by all σ. It is just established that the theory is about *something* that actually exists, and such a something can interact with its environment.

Then, a formal axiom establishes that for any pair $\langle \sigma, \bar{\sigma} \rangle$, we can define a rigged Hilbert space $\mathcal{H}_r$. The use of such a space (actually a triplet of spaces) allows to accommodate the use of eigenfunctions of infinite norm within the formal structure of the theory [35–40]. Then, a crucial semantic axiom is introduced: there is a one-to-one correspondence between the physical states of each σ and rays Ψ in $\mathcal{H}_r$. Note that only a correspondence is claimed, not a direct representation. So, strictly speaking, ψ is not what classical physics calls a state function, i.e., an element of a functional space where each function *represents* a property of the system.

Properties are introduced in another set of axioms, which states that for every property of σ, there exists an operator (which satisfies hermiticity and linearity) defined on $\mathcal{H}_r$ which represents such a property. And then follows a crucial semantic axiom: for every pair $\langle \sigma, \bar{\sigma} \rangle$ to which a function $\psi \in \Psi \subset \mathcal{H}_r$ corresponds, and for every property $\mathcal{A}$ represented by an operator $\hat{A}$ such that $\hat{A}|a\rangle = a|a\rangle$, where $|a\rangle$ is an eigenvector associated with the spectrum of $\hat{A}$, then $\langle \psi|a\rangle\langle a|\psi\rangle$ is the probability density for the property $\mathcal{A}$ when the quantum object σ is affected by the environment $\bar{\sigma}$. This means that $\int_{a_1}^{a_2} \langle \psi|a\rangle\langle a|\psi\rangle da$ gives the probability of σ having a value of the property represented by $\hat{A}$ in the interval $[a_1, a_2]$ when it is in the environment $\bar{\sigma}$.

The main physical axiom of the formulation of the theory consists in the introduction of the symmetry group, which is the Galilei group extended by a one-dimensional Abelian subgroup plus the unitary group of gauge transformations related to the electric charge. More technically, the symmetry group S of QM consists of two ideals: an 11-dimensional ideal corresponding to the central extension of the algebra of the universal covering group of the extended Galilei group times a 1-dimensional Abelian ideal corresponding to the algebra $U(1)$, whose generator is the charge operator $\hat{Q}$. Mathematically speaking, $S = \tilde{G} \otimes U(1)$.

The explicit structure of the Lie algebra of S must be postulated, with all the relations of commutation among its generators (see [4,41]). These generators are the operators that represent all physical properties of the system.

This axiomatic formulation is quite powerful since it allows to obtain as theorems the probability amplitudes of any system in a given environment, the standard Heisenberg and Schrödinger dynamical equations, the deterministic evolution of non-interacting systems, the Heisenberg inequalities, and all other standard expressions of the theory. There is no projection postulate (the so-called 'collapse of the wave function'). Firstly, this is because the wave function cannot collapse: only physical things from buildings to human beings can collapse, not mathematical functions. The transition of the description of the state from a general function to a particular one occurs only for systems that are not isolated and with a given environment $\bar{\sigma} \neq \bar{\sigma}_0$. The details of each interaction will depend on the specific form of $\bar{\sigma}$ and must be formulated in a different theory: a quantum theory of measurement. There are reasons to believe that even in this theory, the postulate in question can be eliminated and replaced by a dynamical evolution that does not follow the linear equations of QM [42–45].

The axiomatic formulation can be easily extended to systems of many quantum objects (see [5]), which allows to discuss the EPR paradox [17] and entanglement from a realistic point of view, the implications of the Bell inequalities and related experiments, as well as decoherence on the matrix density (see also [46]). In particular, it is worth noting that if Bell's inequalities are disproved by experiment, then (1) hidden variable theories are false (i.e., QM is complete), or (2) the theory is non-local, or (3) both (1) and (2) are true. The axiomatization of Perez Bergliaffa et al. *assumes* non-locality and completeness from the beginning [5], so it *predicts* that Bell's inequalities are false.

What can we say about the referent class of the theory in the light of this axiomatization? First, the observers, minds, and consciousness play no role in the theory: none of them are included in the reference class, and thus they cannot appear in the theorems. In particular, as noted by Messiah, Bunge, and others [4,16,47,48], the observer or the measuring device are not responsible for the Heisenberg inequalities. These relations reflect a peculiar feature of quantum objects: they do not have sharp simultaneous values of properties represented by non-commuting operators, such as position and momentum. Second, the theory does not refer to ensembles of particles but to single systems. Third, the postulated ontology is realistic in the sense that quantum objects are assumed to exist in space and time and can interact with each other and with the environment. Fourth, Bohm's theory is not an interpretation of QM: it is a different theory because it postulates a different ontology that includes a pilot wave that is also realistically interpreted. Which theory better represents reality must be decided by experiment. Fifth, quantum objects are neither waves nor particles, although in some environments they can behave like classical particles or classical waves. But they are *sui generis* objects defined in theory. Sixth, superposition creates problems of indiscernibility: if we have two electrons in the He atom, we can count them, but we cannot label them. If an ionized He atom captures an electron and later emits an electron, it is impossible to say whether it is the same electron that was captured or not. Quantum objects appear to be fungible, like money in the bank. If you deposit a bill of ARS10 in your account and then transfer from there ARS 10 to mine, there is no point in asking whether it was the same bill. The question simply makes no sense in that context. Seventh, entanglement implies correlation at a distance but not action at a distance. Action requires a transfer of energy and a change of state as a consequence of the action: a component of the system goes from state e_1 to state e_2. What we have is a *determination* of a state according to the original preparation of the system. Before the state of the first component was not fixed, the second was not either. This is a non-local correlation but not a non-local action. There is no mechanism for such a determination: as the theory is formulated, it seems to be a brute fact. Finally, the transition from a quantum to a classical regime and the interactions of quantum systems with the macroscopic environment must be studied by different but closely related theories, such as decoherence and quantum measurement theory.

Still, quantum systems remain somehow perplexing. Brute facts are repugnant to most of us because they do not allow for mechanisms. And mechanisms are essential for understanding. Perhaps we can shed some light on these questions of the ultimate nature of quantum objects by looking at a field formulation of QM. I will do this in the next section.

4. Quantum Field Theory: A Semantic Shift

The program of quantum field theory was originally outlined in the classic paper by Born et al., in a section written by Pascual Jordan [49], and then initially explored in papers by Dirac, Jordan, and Klein [50–52]. The theory was then developed in the late 1940s and 1950s in the context of quantum electrodynamics.The development of gauge theory and the completion of the Standard Model in the 1970s led to a renaissance of quantum field theory (QFT). The basic idea of QFT is that the fundamental quantum objects are fields extending over spacetime. The referents of QM discussed in the previous section are treated as excited states (also called quantum levels) of the underlying quantum fields. The axiomatization of QM presented above can be easily generalized to a Galilean QFT (GQFT) [53]. However, the Galilei group is not the symmetry group at high energies, and the resulting theory does not allow to correctly describe relativistic interactions, antiparticles, and other important features. Therefore, the theory has to be constructed with the Poincaré group as the fundamental symmetry group. In the Appendix A, I will just outline some basic features of relativistic quantum field theory (RQFT) in order to discuss the important semantic shift it implies for the reference class of the theory. For further details, the reader can check the paper by Puccini and Vucetich [54] or the classical book by Weinberg [55].

In the transition from QM to QFT, the reference class of the theory changed from quantum objects with properties such as mass, charge, or spin to fields. A field is an entity extended over spacetime. Technically, a field is generally defined as a material system with an infinite number of degrees of freedom for which certain dynamical equations hold. The field is represented by the specification of a field value for each point $\mathbf{x}$ in space, where this specification can change with time t. A scalar field can thus be specified by a function $\phi(\mathbf{x};t)$, i.e., by a (time-dependent) mapping from each point in space to a field value. In QFT, the field values are replaced by a *field operator*: $\phi(\mathbf{x};t) \rightarrow \hat{\phi}(\mathbf{x};t)$. These operators in turn are used to determine the state of the field at each point and to make probabilistic predictions (see the Appendix A for details). Equations of motion are obtained from the corresponding Lagrangian density.

The objects of QM in this context are no longer things in themselves but *excitations* of the field. For each type of microsystem referenced in QM, we now have a field that can be excited, forming a discrete spectrum of excitations. The situation is somewhat similar to the semantic shift from Newton's theory of gravity, where gravity is a force acting at a distance, to general relativity, where gravity is now a manifestation of a property (curvature) of a new entity: spacetime. Similarly, the referents of QM are incorporated into QFT as a kind of property of the fields, not as things in themselves. This allows for great explanatory power, in addition to the much greater predictive power of the theory.

For example, the two-slit experiment, which gives such counterintuitive results in QM, can easily be accommodated in the context of QFT (see ref. [56] for details). Or, quantum entanglement need not be accepted as a brute fact if we consider the possibility of non-local fields (see refs. [57–59,59,60]). Moreover, QFT allows us to understand why all electrons are identical: they are excitations of the same field. The same is true for the other elementary particles. There is also an argument based on ontological economy: from a myriad of the individuals of QM, we now have only 25 entities associated with the 25 fields for the Standard Model.

However, the field interpretation of QFT is not without its critics. Teller [61], for example, argues that quantum fields lack an essential feature of all classical field theories so that the term 'quantum field' is not justified. His reasoning is that in the case of quantum fields, unlike all classical fields, there are no definite physical values assigned to spacetime points. Instead, the assigned quantum field operators represent the entire spectrum of possible values. He seems to think that what defines a field is the direct assignment of a physically observable or "determinable" quantity to each point in spacetime. In the case of quantum fields, something physical emerges only when the state of the system along with the initial and boundary conditions are provided. I think this criticism is based on a semantic mistake. It is true that in the case of a classical electromagnetic field, for example, the intensity of the electric and magnetic fields is associated with each point in spacetime, and that these quantities can be measured fairly easily. But this is not necessarily the case. The field should not be confused with the mathematical apparatus we use to represent its properties and the way we use it in our theory to determine quantities experimentally. In QFT, the properties are represented by operators that act on any point of the field. To obtain an experimentally determinable property, however, you should also know the state of the field at that point, plus, as Teller mentions, the boundary conditions. Only then do you obtain a physical property. This is because in QFT, the representation of the properties is actually not only given by an operator but by an operator *acting on a state* in a given circumstance. If we confuse the field with the way we represent its properties, and then compare that with the way we represent them in classical theories designed to describe the world at a different scale, we can obtain a false picture. Teller's own proposal is an ontology of QFT in terms of quanta, as given in the Fock representation. But, as I will discuss in the next section, such an ontology becomes untenable when spacetime has non-zero curvature.

To summarize the ontological conclusions of this section, the reference class (or ontology) of QFT are fields extended over spacetime. Such fields are not like classical fields, but they have their own special properties. The fact that the fields are real can be seen from their energy–momentum, which cannot be set to zero over the whole spacetime. Only what actually exists can exist independently of our way of representing reality. And only existing entities can have energy, because without energy, no change is possible. All entities that exist can change, as far as we know.

5. Quantum Field Theory in Curved Spacetime: Particles Are Modes

Teller is not the only critic of a field interpretation of QFT. Baker [62], for example, argues against the idea of conceiving fields on the basis of the notion of wave functional space, which represents the states of QFT as superpositions of classical fields (which is not our case here), and advocates an ontology for QFT in terms of an algebra of observables. There are other criticisms, but I think that if we make another shift in the domain of QFT from flat to curved spacetime, it becomes clear that an ontology based on quanta, particles, or any other localizable putative entity becomes unattainable. The reason lies in the shift of the symmetries of spacetime: Minkowski spacetime has the symmetries of the Poincaré group. This allows to formulate the theory in the framework of a class of reference systems (inertial reference systems) that are physically equivalent, and then allows to have a unique state vacuum. In curved spacetime, the situation changes dramatically: a generic curved spacetime will have no symmetries at all, so it is not possible to require "Poincare invariance/covariance" or invariance under any other type of spacetime symmetry. Thus, there is no "preferred" choice of vacuum state. As we will see, this translates into the fact that the number of excitations of the field ("particles") becomes dependent on the choice of the reference system in which the particle detector is located. Since objective existence cannot depend on the reference system used to describe the world, the ontological implications are profound.

Let us start reminding that in a general spacetime, the line element is written as:

$$d^2s = g_{\mu\nu}(x)dx^\mu dx^\nu, \quad \mu, \nu = 0, 1, ...3. \tag{16}$$

The determinant of the metric tensor $g_{\mu\nu}(x)$ is denoted by g. The metric is determined for the matter fields with energy–momentum tensor $T_{\mu\nu}$ by Einstein field equations:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}. \tag{17}$$

Here, $R_{\mu\nu}$ is the Ricci tensor formed with the second derivatives of the metric, R is the Ricci scalar, Λ is the cosmological constant, G is the gravitational constant, and c, as usual, is the speed of light.

The solutions of these equations, once fixed $T_{\mu\nu}$, fully describe a spacetime of metric $g_{\mu\nu}(x)$. In order to formulate a QFT (for a scalar field, for simplicity) we can proceed as before, starting from the Lagrangian density:

$$\mathcal{L} = -\frac{1}{2}g^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - \frac{1}{2}m^2\phi^2\sqrt{-g}, \tag{18}$$

where ∇_μ is the covariant derivative, and we have assumed a minimally coupled case. Then, varying the action, we obtain the dynamical equation for the field:

$$\nabla_\mu(\sqrt{-g}g^{\mu\nu}\nabla_\nu\phi) + m^2\phi\sqrt{-g} = 0. \tag{19}$$

This is the general relativistic analog of Equation (A3). Again, the general solution of this equation for a scalar field can be written as a superposition of plane waves. However, since in general spacetimes there are different complete sets of modes for the decomposition of the field, we can use different Fock spaces defined from different vacuum states:

$$\hat{a}_k|0\rangle = |0\rangle, \quad \forall k. \tag{20}$$

$$\hat{\bar{a}}_j|\bar{0}\rangle = |\bar{0}\rangle, \quad \forall j, \tag{21}$$

The field $\hat{\phi}(x)$ can be expanded in any of the two bases:

$$\hat{\phi}(x) = \sum_i[\hat{a}_i u_i(x) + \hat{a}_i^\dagger u_i^*(x)], \tag{22}$$

and

$$\hat{\phi}(x) = \sum_j[\hat{\bar{a}}_j \bar{u}_j(x) + \hat{\bar{a}}_j^\dagger \bar{u}_j^*(x)]. \tag{23}$$

Since both expansions are complete, we can express the modes $\bar{u}_j$ in terms of the modes u_i as

$$\bar{u}_j = \sum_i(\alpha_{ji}u_i + \beta_{ji}u_i^*), \tag{24}$$

and conversely,

$$u_i = \sum_j(\alpha_{ji}^*\bar{u}_j - \beta_{ji}\bar{u}_j^*). \tag{25}$$

The matrices α_{ij} and β_{ij}, known as Bogolyubov coefficients, can be calculated as

$$\alpha_{ij} = (\bar{u}_i, u_j), \tag{26}$$

$$\beta_{ij} = -(\bar{u}_i, u_j^*), \tag{27}$$

and satisfy the relations

$$\sum_k(\alpha_{ik}\alpha_{jk}^* - \beta_{ik}\beta_{jk}^*) = \delta_{ij}, \tag{28}$$

$$\sum_k(\alpha_{ik}\beta_{jk} - \beta_{ik}\alpha_{jk}) = 0. \tag{29}$$

The operators on the Fock space can then be represented by

$$\hat{a}_i = \sum_j(\alpha_{ji}\hat{\bar{a}}_j + \beta_{ji}^*\hat{\bar{a}}_j^\dagger), \tag{30}$$

and

$$\hat{\bar{a}}_i = \sum_i (\alpha^*_{ji}\hat{a}_i - \beta^*_{ji}\hat{a}^\dagger_i). \tag{31}$$

An immediate consequence is that

$$\hat{a}_i|\bar{0}\rangle = \sum_j \beta^*_{ji}|\bar{1}_j\rangle. \tag{32}$$

Since in general $\beta_{ij} \neq 0$, the expectation value of the operator $\hat{N}_i$ is:

$$\langle\bar{0}|\hat{N}_i|\bar{0}\rangle = \sum_j |\beta_{ij}|^2 \neq 0. \tag{33}$$

This is a surprising result. It means that the number of quanta (particles) of the field is different for different decompositions. Since different decompositions correspond to different choices of reference frames, we must conclude that different detectors measure a different number of quanta. These particles activate detectors in some reference systems and not in others. They are essentially a frame-dependent property of the field. Something similar happens at the classical level with many relational properties. If you measure the speed of your car with a radar on the highway, you will find that it is moving at a certain speed. But if the radar is in a car moving at the same speed as yours, your car will be at rest. If we accept the extended idea that whatever exists objectively cannot depend on our choice of a particular reference system, then the assumption that particles are self-subsistent individuals falls apart.

You might argue that in the car example, speed is relative but real: if you crash, you will find that your car was moving relative to the highway. This is true. In the same way, particles hit some detectors, but not all. You cannot crash into another car that is moving at exactly the same speed as you. In the case of the car, speed is not a thing, it is a relational property of your car and the surroundings. Similarly, quanta are properties of the field with respect to a reference system, not things. The ontological import is in the field, not in the quanta.

In quantum field theory, particles are not treated as individuals but as properties of quantum fields and relative to a particular choice of mode decomposition of the field, which is frame dependent. Questions of existence should not be solved by simply counting or individuating with respect to some reference system but by considering true invariant properties and their referents. In this sense, it is the energy–momentum complex and its mathematical representation by a second-order tensor field $T_{\mu\nu}$ that provides an objective indicator of independent existence. In contrast to the excitations of the field, which depend on global modes defined over the whole spacetime, the energy–momentum of the field is locally defined by a tensor quantity. For a fixed state $|\psi\rangle$, the results of different detectors when measuring the expectation value $\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle$ can be related by the usual transformation laws of tensors. In particular, if $\langle\psi|\hat{T}_{\mu\nu}|\psi\rangle = 0$ in a reference system, the energy density of the quantum field will be zero for any reference frame. This situation is quite different for particles, which may or may not be detectable in the same region of space by different observers in different states. This clearly indicates that the ontological meaning is in the quantum field, not in the particles. And it is not in the structure either since the structure emerges from the relations of the fields[3].

One might object that in the case of Minkowski spacetime, all fields are in the same vacuum state, and then $\langle 0_{\mathrm{M}}|\hat{T}_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$. But an accelerated observer in this spacetime should actually detect thermal radiation [65]. In the accelerated frame, it is also $\langle 0_{\mathrm{M}}|\hat{T}^{\mathrm{acc}}_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$, so thermal radiation seems to violate the conservation of energy. But this is a false conclusion based on considering only one part of the system. The whole system is the accelerated detector plus the field in the vacuum state. The field couples to the accelerated system, creating a resistance to the accelerating force. It is the work of the external force that produces the thermal bath measured by the detector in the co-moving system. The same radiation is not measured by a detector at rest because it is not coupled to the field. I recall here that a vacuum state of the field does not correspond to the absence of the field but to the absence of discrete excitations of the field. The example only shows the reality of the field even when there are no excitations. The excitations themselves, the quanta, can be present in one system and not in another, depending on the state of the system with respect to the field.

When there is curvature in spacetime, inertial frames are associated with free-falling systems, and in general no unique choice of vacuum state can be made to express the field, as we saw above. Thus, different detectors located in different reference systems will detect different numbers of particles. The polarization of the vacuum by event horizons leads to Hawking radiation, which is detectable in the asymptotically flat region of spacetime. In general, there is no simple relationship between $\langle \hat{N}_i \rangle$ and the number of particles measured by different detectors [66].

Perhaps it is worth taking a closer look at black holes. A black hole is essentially a region of spacetime that, because of its curvature, is causally disconnected from the rest of spacetime: nothing that happens inside the black hole can affect what happens outside. The surface that divides spacetime into the two regions, the black hole interior and the rest of the universe, is called the *event horizon*. The Schwarzschild metric corresponding to the simplest spherically symmetric black hole is

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right)dt^2 + \frac{dr^2}{\left(1 - \frac{2GM}{c^2 r}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2), \tag{34}$$

where t is the time coordinate, r is the radial coordinate, θ and ϕ are the angular coordinates, and M is the mass of the black hole. The horizon is located where the radial term diverges:

$$1 - \frac{2GM}{c^2 r} = 0 \quad \Rightarrow \quad r_{\mathrm{H}} = \frac{2GM}{c^2}. \tag{35}$$

The metric becomes singular at $r = 0$. Because of the symmetries, the relevant coordinates are t and r. We can simplify adopting a two dimensional metric of the form (see [66]):

$$d^2 s = C(r) du dv, \tag{36}$$

where

$$\begin{aligned} C(r) &= 1 - \frac{2GM}{c^2 r}, && (37)\\ u &= t - r^*, && (38)\\ v &= t + r^*, && (39)\\ r^* &= \int C^{-1} dr. && (40) \end{aligned}$$

Here, u are called "outgoing" coordinates, while v are "ingoing". We can now proceed to estimate the expectation value of the energy–momentum tensor of the vacuum state of a massless scalar field near the event horizon. For details of the calculation, see [66,67]. The result is

$$\langle 0 | T^{uu} | 0 \rangle = \frac{\hbar c^4}{48\pi^2 r_H^2}$$

$$\langle 0 | T^{vv} | 0 \rangle = -\frac{\hbar c^4}{48\pi^2 r_H^2}$$

Note that the same flux occurs in both directions but with opposite signs. The flux towards the BH has negative energy, and then it decreases its mass M, eventually causing its evaporation on a timescale of

$$\tau_{\text{evap}} \approx \frac{5120\pi G^2 M^3}{\hbar c^4} \approx 2.14 \times 10^{67}\ \text{years} \left(\frac{M}{M_\odot}\right)^3.$$

Asymptotically, when $r \to \infty$, we have:

$$\langle 0|T^{uu}|0\rangle = \frac{\kappa^2}{48\pi}, \quad \langle 0|T^{vv}|0\rangle = \langle 0|T^{uv}|0\rangle = 0, \tag{41}$$

where

$$\kappa = \frac{c^3}{4GM} \tag{42}$$

is the surface gravity of the BH. The outgoing radiation measured by a detector far from the BH is exactly that corresponding to a blackbody of temperature $T = \kappa/2\pi k_{\rm B}$, where $k_{\rm B}$ is the Boltzmann constant as predicted by Bekenstein [68] on the basis of purely heuristic and thermodynamic considerations.

Some final thoughts on the behavior of the quantum field near the event horizon of a black hole are given:

- The Hawking radiation is not emitted by the BH but by the quantum field in the vicinity of the black hole. The evaporation of the BH is the result of the negative energy input it receives from the polarized vacuum field.
- Different detectors will measure different Hawking fluxes. For example, a free-falling detector will measure no radiation far from the horizon, but as it approaches the BH, the horizon will behave like a Rindler horizon. The classic Hawking argument that the free-falling observer will measure nothing near the BH because the wavelength of the radiation is $\lambda \sim r_H$ fails since there will also be a Doppler blueshift of the outgoing photons [69].
- Since the wavelength of the radiation is on the order of the Schwarzschild radius r_H, the black hole heats up as it evaporates.
- Similar effects are produced by cosmological horizons [66]. Again, the radiation depends on the location of the detector since each observer sees different horizons at different cosmological times.

The ontological status of quanta (or "particles") in quantum field theory in curved spacetime is that of a complex relational property between fields and detectors (reference frames). But the ontological substrate is provided by the fields. Remove them, and nothing is left: no energy–momentum, no excitations, no expectations, no structure. I conclude that quantum objects are quantum fields over spacetime, and quanta or particles are mere *modes* of the fields. There is a subtle difference between a mode and a property. While a property is the way an entity is, a mode is a way of manifesting and behaving. A mode is better identified with a state or process than with a property.

6. Materialist Ontological Plurality

If we accept the ontological principle that what is there cannot depend on our way of describing it, we are led to reject particles (quantum excitations of the field) as basic ontological entities. This point has already been emphasized by Davies [70] and Hobson [56], among others. The absence of particles corresponding to a vacuum state defined by Equation (A12) is not universal. Even in Minkowski (flat) spacetime, this relation does not define a global vacuum since excitations are seen by accelerated observers [65]. The vacuum in Minkowski spacetime is shared by all observers in *inertial frames* because this spacetime is symmetric under the group of Poincaré transformations. But detectors in accelerated frames, as already mentioned, measure a thermal flux of particles, and for them, the vacuum will be a different state. Particles, as excitations of the field, are frame dependent. Therefore, they cannot be part of the ontological substratum of the world. Rather, they are modes of that substratum.

The energy density of any field at any point in spacetime is well defined by $\langle|\hat{T}_{\mu\nu}|\rangle$[4]. If we take material entities to be those capable of change, this implies that quantum fields are material, not just conceptual, devices for introducing quanta. Fields are the real material constituents of the world. Every field can change and perform work, i.e., induce changes in any potential detector. They do this by exchanging quanta, which is the mode in which they interact.

I conclude that quantum ontology is an ontology of fields, not of particles or waves, and much less of minds, infinite worlds, or observers. We live in a world of fields, and we, along with whatever else we have encountered through experimentation, are nothing more than a complex system of excitations of such fields. How many fields are there? So far, we only know the fields of the Standard Model of quantum field theory. These are 12 fundamental fields for fermions (6 quarks and 6 leptons) and 13 fundamental fields for bosons (8 gluons; 3 for the W_+, W_- and Z_0 bosons; 1 for the photon and 1 for the recently discovered Higgs field). Antiparticles do not belong to different fields as their associated quanta, but they are different excitations of the same field. All these fields exist on a background spacetime. Each field in the Standard Model is considered to be a different substance[5]. Supersymmetry (a symmetry between fermions and bosons) has never been discovered, and if it exists, it does not manifest itself at the energies we can reach on Earth. Electroweak symmetry is broken at the temperatures at which we exist. Thus, as far as our best knowledge of physics goes, the ontology of fields is an ontology of many substances, i.e., a pluralistic ontology.

Let us recall that Einstein's field Equation (17) relates the metric structure of spacetime to the energy content of the fields defined on it. But now the energy–momentum tensor should be expressed as an expectation value:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}\langle\hat{T}_{\mu\nu}\rangle. \tag{43}$$

As we have seen, the fields represented on the right side of these equations are material since $\langle\hat{T}_{\mu\nu}\rangle$ is well defined, or can be renormalized to a well-defined quantity. But what about the left side of the equations? Is spacetime material? The answer seems to be 'yes, it is'. An equation can only establish a relation (*biunivocal* in this case) between entities of the same class. Otherwise, it would be ontologically, semantically, and dimensionally inconsistent.

Equation (43) should not be interpreted (as is routinely done in textbooks) to mean that the field is the "source" of spacetime. It is true that any perturbation of the fields produces a perturbation of spacetime. But changes in spacetime also affect the matter fields. The relation is reciprocal. Moreover, perturbations in spacetime can travel at the speed of light even in the absence of any other field. They are changes in the curvature of spacetime. Such curvature should be interpreted as a physical property, not a purely geometrical one. This becomes clear when we realize that changes in curvature produce changing tidal forces that can perform work and transfer energy to other material things, such as detectors. I have presented arguments for the materiality of spacetime elsewhere. The reader is referred to, for example, refs. [14,71–74] for details.

We can cast the above reasoning in the following way. Perturbations of empty spacetime create waves. These waves carry energy, and when they act on a detector, they produce physical changes. Only material things can act on a detector. Thus, gravitational waves are material. Since gravitational waves are just traveling perturbations of the curvature of spacetime, spacetime is also material [72].

Another argument concerns the expansion of the universe. If spacetime is expanding, then there is a cosmological force acting on material objects. Such a force acts on orbiting particles around a mass in such a way that there is a maximum radius possible for any orbit in an expanding universe [75]. Such a limit is consistent with observations of the size of galaxies. Thus, dynamic spacetime acts on material systems. Therefore, spacetime is material [74].

A simpler form of the latter argument was outlined by de Sitter: if empty spacetime is dynamical, it must be material since only material objects can be dynamical. This argument convinced Einstein himself of the materiality of spacetime [76,77].

We conclude that spacetime is as material as any quantum field.

If spacetime is material, we can ask whether it is another quantum field. Certainly, it is not the same kind of field as the quantum fields we have discussed so far. All known fields are defined on spacetime and cannot exist without it [78]. Without spacetime, the energy–momentum of any field cannot be formulated because the metric is essential to it:

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta \mathcal{L}_{\mathrm{M}}}{\delta g^{\mu\nu}}, \tag{44}$$

where $g = ||g^{\mu\nu}||$ is the determinant of the metric tensor, and $\mathcal{L}_{\mathrm{M}}$ is the effective Lagrangian density of the non-gravitational material fields. Obviously, without $g_{\mu\nu}$, there is no $T_{\mu\nu}$. The converse is not true: we can have spacetime without any quantum field as shown by the vacuum solutions of (43). The first to note this was de Sitter [79]. We express this fact by saying that spacetime is background independent.

Another important difference is that while the energy of a quantum field can be localized at a single point in spacetime, this is not the case for spacetime itself, where energy is a property that is always non-local. Every attempt so far to treat spacetime as a field in order to quantize it has failed. And the obstacles seem insurmountable.

There is yet another interesting property of spacetime. As we have mentioned, black holes can be understood as regions of spacetime with a particular curvature that divides the spacetime in the region inside the BH and the region outside. We are used to thinking that black holes are the result of the collapse of astrophysical objects such as massive stars. However, this is not necessarily the case. A black hole will form whenever the energy density is high enough to induce the necessary curvature. The concentration of energy density can come from spacetime itself, for example, fluctuations in the very early universe, or the collision of gravitational waves (e.g., ref. [80]). Whether or not this happens in the universe, it is certainly plausible. This suggests another exciting ontological possibility: black holes can be thought of not as objects but as *modes* of the existence of spacetime itself [72].

At this point, we arrive at an ontological view in which the stuff of the world seems to consist of material spacetime and 25 kinds of material quantum fields. Matter[6], then, seems to come in two flavors: spacetime and quantum fields. Each is material because each has energy and can act upon the other. But they seem to be different in the sense that spacetime seems more independent and fundamental than quantum fields. The latter, we might say, are parasitic on the former. I call this view of the content of the world *Materialist Pluralism*.

Materialism and pluralism have, of course, been linked in the past. The pre-Socratic philosophers Empedocles (494–434 B.C.) and Anaxagoras (c. 500–428 B.C.) were pluralists: they believed that there was more than one substance in the world. For Empedocles, there were four material substances: air, fire, water, and earth (a view to which Aristotle later added a fifth—quintessence). Anaxagoras believed there was a basic substance for every kind of thing we observe. Everything is in everything, according to Anaxagoras. The nature of a particular object is determined by which substance predominates in its composition. Anaxagoras did not accept atoms: basic substances are infinitely divisible. Empedocles and Anaxagoras developed a new theory of change [81,82]: the Theory of Elementary Substances (TES). The gist of this theory can be summarized as follows (see ref. [83]).

Theory of elementary substances (TES):

- There is a set of elementary substances.
- The basic substances do not change.
- The basic substances combine to form derivatives (compounds).

- There is a mechanism that controls the production of derivatives of the basic substances.
- This mechanism is governed by a set of legal forces that operate between the basic substances.

We can translate this into modern notation as follows:

1. $\exists S / S = \{S_1, \ldots, S_n\}$. Def. S_i = basic substance.
2. $\forall S_i \in S, S_i(t) = S_i(t') \quad \forall t, t'$.
3. $\forall S^D \exists D = \{S_1, \ldots, S_h\} \subset S \quad \wedge \quad \exists C / S^D = C(S_1, \ldots, S_h)$. Def. S^D is a composite thing and C means the operation of composition.
4. $\exists M / M$ is a material mechanism by which C is produced.
5. $\exists F / F$ is a set of forces (processes) constituting M.
6. The world exists according to the ordered (legal) transformations of S into S^D.

If we interpret the basic substance as a quantum field and remove point 2, we are not very far from a very basic scheme of the ontological view I have outlined in this section.

7. Prospects

Materialist pluralism presents two flavors of basic material substances: spacetime and quantum fields. However, the description of spacetime given by general relativity is far from satisfactory: many physically realistic models are singular, i.e., they give an incomplete description of spacetime (see ref. [72]). Simple examples are the hot big bang model and black hole models. This fact has led to many different approaches to formulate a quantum theory of spacetime (and hence of gravity, which is a consequence of spacetime curvature). The direct attempt to consider the metric field as a classical field and to apply standard quantization methods leads to non-renormalizable theories. A variety of different ways to get around this have been tried (see ref. [84]). The crucial questions are about the nature of spacetime itself: Does spacetime have quantum properties? How should such properties be understood if they are not expressed in terms of spacetime itself? Or should they be understood in terms of matter fields? The attempt to answer such questions can be seen as a search for a conceptual unification of all forms of matter. In mathematical terms, this program implies defining the left part of Equation (43) on the basis of the right part. Spacetime would somehow emerge from matter fields. This is a reloaded Leibniz program.

A different path, followed by Einstein and Wheeler (see ref. [85,86]), was to consider spacetime as the basic entity, and then proceed to derive all other physical entities from it. Again, this is an attempt at the unification of the different types of matter. From a philosophical point of view, this is also an old tradition, elements of which can be traced back to Parmenides [87], and can be found in Descartes, W. K. Clifford, and up to the recent work of Schaffer [88]. The idea, of course, is reminiscent of that of Spinoza: one material substance with infinite modes [89].

Both paths have problems, and it is not even clear that they can be formulated consistently. An intermediate approach is to look for a prior substratum from which *both* spacetime and fields would emerge in the appropriate limits. What such a material substratum is remains open to discussion (see refs. [90,91] for some possibilities discussed from both philosophical and physical points of view). The idea of a basic material substratum from which everything else emerges through some kind of compositional mechanism is even older than the TES. It can be traced back to Anaximander and his theory of the generating substance. He called this substance the $\alpha\pi\varepsilon\iota\rho o\nu$ and thought that all other substances that seem basic to us are actually derived from it. We can summarize his ideas in the following axioms [81,83].

Theory of the generating substance (TGS):

- There is an original generating substance.
- The generating substance gives rise to derived substances or elements through certain mechanism.
- The mechanism consists of legal processes.

- When the generating substance changes, it ceases to exist.
- The things we see in the world are produced by interactions of the derived elements.

In modern nomenclature, we can express this as follows:

1. There exists a set of substances $S = \{S_1, \ldots, S_n\}$ that compose the world. Def. $S_i =$ basic substance.
2. $\exists S_g$ such that before a time t_0, only S_g existed. Def. $S_g =$ generating substance.
3. $\forall S_i \in S \quad \exists T$ such that S_i is generated from S_g by the transformation T.
4. $\exists M/M$ is a material mechanism by which T operates.
5. The world exists according to the ordered (legal) transformations of S_g.

This is a primitive scheme of a unified field theory. If spacetime must be included, the reference to time in connection with the "generating" substance should disappear. Spacetime, if not fundamental, should emerge from timeless and spaceless entities. Several research projects are going in this direction, including quantum loop gravity, emerging gravity, causal sets, etc. (see refs. [90–98] and references therein).

8. Conclusions

We started by examining the formalism of QM, which is presented in such a way that all semantic relations are explicit. We find that the reference class of the theory is formed by *sui generis* entities, quantum objects that lack most classical properties. Their actual properties are fully characterized by the formalism. Such properties include the absence of well-determined spacetime trajectories, a probabilistic character of most properties, the existence of superposition of states, entanglement, and non-locality, among others. The validity of the formalism and its semantic connections can be tested experimentally by the predictions that can be obtained from the various theorems of the theory when initial and boundary conditions are imposed. We have seen that these quantum objects do not correspond to the classical concepts of particle or wave, although in some situations, they can behave in a way that has similarities to classical waves or particles. We have also seen that the reference class of the theory does not include observers, minds, many worlds, particle ensembles, or measuring devices. The evolution of systems described by mixed states to eigenstates can only occur through interaction with the system's environment, which can be either artificial (as in an experimental setup) or natural. The theory can be interpreted in a completely realistic and materialist way, without any further additives such as pilot waves, as in Bohm's theory.

When QM is extended to include relativistic and electromagnetic phenomena, a new theory emerges, quantum field theory. And with it, a semantic shift occurs. The previous reference class is now better understood as the low-energy limit of excitations of quantum fields. These fields are extended over spacetime but should not be confused with the mathematical apparatus we use to represent their properties: operators and rays in rigged Hilbert spaces. The quantum objects of QM now appear to be *modes* of the fields. The fields, which have energy and momentum that can be well defined in all reference systems, are material entities. When we move to curved spacetime, we find that the same is not true for the excitations of the fields. They are frame dependent. One detector[7] can measure a particle flux while another remains untriggered. This shows that when the original theory is extended, there is a change in the category of the referents. They are shifted from the level of substances (to use Aristotelian terms) to modes. I have argued that the ontological view that emerges from QFT on curved spacetime is that of a number of substances (fields) interacting in spacetime (materialist ontological pluralism). So far, we know of 25 such fields (those of the Standard Model), although there seems to be a significant unification at high energies.

I also argued that spacetime is not to be understood as just another field but has a kind of ontological primacy. Spacetime can exist without anything else, but fields cannot exist without spacetime. Can fields and spacetime somehow be unified? Can ontological pluralism give way to some kind of substance monism? The question is open. There are at least three different ways to approach this problem. First, we can explain spacetime as a consequence of a more fundamental field theory. This seems to have failed so far (think of string theory). Then, we can explain fields in terms of spacetime [99]. This was Einstein's program, but no one has yet taken on this project to produce comprehensive results. Finally, we have the possibility that both spacetime and fields emerge from a more fundamental substratum. Of course, such a substratum should be spaceless and timeless. There are several research programs pointing in this direction. I think this is perhaps the most promising path, given the failures to date. Somehow, this view is a realization of Spinoza's grandiose intuition of just one substance with infinite modes.

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Abbreviations

The following abbreviations are used in this manuscript:

BH	Black Hole
GQFT	Galilean Quantum Field Theory
MDPI	Multidisciplinary Digital Publishing Institute
QED	Quantum Electro Dynamics
QFT	Quantum Field Theory
QM	Quantum Mechanics
RQFT	Relativistic Quantum Field Theory

Appendix A. A Short Introduction to Quantum Field Theory in Flat Spacetime

Let us first recall the classical concept of a field, originally introduced by Faraday. A field is a spacetime extended entity that we call σ represented by the specification of a field value ϕ (for simplicity, I consider a scalar field) for each point $\mathbf{x}$ in space, where this specification can change with time t. A field is thus specified by a function $\phi(\mathbf{x},\, t)$ which is not null over a region of spacetime. The mathematical representation is a time-dependent mapping from each point in space to a field value. The formal specification of $\phi(\mathbf{x},\, t)$ is not sufficient for something to be a field. Certain field equations must be satisfied. In the case of the electromagnetic field, these equations are Maxwell's Equations (12)–(15).

The Lagrangian density associated with a scalar field σ, whose properties are represented by ϕ is

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2, \tag{A1}$$

where ∂_μ denotes the partial derivative with respect to the spacetime coordinate, and m is the mass of the scalar field. The corresponding action is

$$S = \int \mathcal{L}(x)d^4x. \tag{A2}$$

The variation of this action leads to the Klein–Gordon equation:

$$\Box\phi + m^2\phi = 0, \tag{A3}$$

where $\Box = \partial_\mu \partial^\mu$ is the D'Alembertian operator. The general solution to the Klein–Gordon equation for a scalar field can be written as a superposition of plane waves:

$$\phi(t,x) = \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_p}} \left(a_p e^{-i(p\cdot x - E_p t)} + a_p^\dagger e^{i(p\cdot x - E_p t)} \right), \tag{A4}$$

where a_p and $a_p^\dagger$ are the amplitude of the waves, and $E_p = \sqrt{|\mathbf{p}|^2 + m^2}$ is the energy–momentum relation.

The field representation is quantized promoting ϕ to the status of an operator $\hat{\phi}$ acting upon a rigged Hilbert space $\mathcal{H}_r$, and it is assumed that there is a one-to-one correspondence between states of quantum field and and rays $\Psi \subset \mathcal{H}_r$. Then, the following commutation relations are imposed:

$$[\hat{a}_p, \hat{a}_q] = 0, \tag{A5}$$

$$[\hat{a}_p^\dagger, \hat{a}_q^\dagger] = 0, \tag{A6}$$

$$[\hat{a}_p, \hat{a}_q^\dagger] = (2\pi)^3 \delta^{(3)}(\mathbf{p} - \mathbf{q}), \tag{A7}$$

where $\delta^{(3)}(\mathbf{p} - \mathbf{q})$ is the Dirac delta function in three dimensions. This commutation relation expresses the fundamental non-commutativity of the creation and annihilation operators in the context of quantum field theory.

Now, the operator $\hat{\phi}(t, \mathbf{x})$ associated with the quantum field σ_q can be written as an expansion of the form

$$\hat{\phi}(t,\mathbf{x}) = \sum_k [\hat{a}_k u_k(t,\mathbf{x}) + \hat{a}_k^\dagger u_k^*(t,\mathbf{x})] \tag{A8}$$

where k is the wave number associated with the momentum ($p = \hbar k$) and $u_k \propto e^{i\mathbf{k}.\mathbf{x} - iwt}$.

The vacuum state $|0\rangle$ can be excited to form a so-called Fock basis of the quantized field:

$$|1_k\rangle = \hat{a}_k^\dagger |0\rangle. \tag{A9}$$

Each application of the operator $\hat{a}_k^\dagger$ adds one quantum excitation to the state k. It represents any physical process that produces such excitations. Successive applications of the operator $\hat{a}_k^\dagger$ yield:

$$\hat{a}_k^\dagger |n_k\rangle = (n+1)^{1/2} |(n+1)_k\rangle. \tag{A10}$$

Similarly, the operator $\hat{a}_k$ removes quanta:

$$\hat{a}_k |n_k\rangle = n^{1/2} |(n-1)_k\rangle. \tag{A11}$$

The operator $\hat{a}_k$ can be used to define the vacuum state as the state for which

$$\hat{a}_k |0\rangle = |0_k\rangle, \quad \forall k. \tag{A12}$$

In this way, any system of n particles is understood as a fundamental quantum field with n excitations of the vacuum. The vectors $|n_1, n_2, ..., n_k\rangle$, where n_i is the number of quanta in the state i, belong to the separable rigged Hilbert space which is the tensor sum of a countable number of Hilbert spaces $\mathcal{H}_j$, where the subscript j also corresponds to the number of (non-interacting[8]) particles present, namely, $\mathcal{H}_1 \bigoplus \mathcal{H}_2 \bigoplus ... \bigoplus \mathcal{H}_n$. Here, $\bigoplus$ indicates the direct sum. The operators $\hat{a}_i^\dagger$ and $\hat{a}_j$ obey the operator algebra given by:

$$[\hat{a}_i,\ \hat{a}_j^\dagger] = \delta_{ij}, \tag{A13}$$

$$[\hat{a}_i^\dagger,\ \hat{a}_j^\dagger] = 0, \tag{A14}$$

$$[\hat{a}_i,\ \hat{a}_j] = 0. \tag{A15}$$

In the case of fermions, where only one excitation is possible in each state, the operator algebra becomes:

$$[\hat{a}_i,\ \hat{a}_j^\dagger]_+ = \delta_{ij}, \tag{A16}$$

$$[\hat{a}_i^\dagger,\ \hat{a}_j^\dagger]_+ = 0, \tag{A17}$$

$$[\hat{a}_i,\ \hat{a}_j]_+ = 0, \tag{A18}$$

where the subscript $+$ stands for anticommutation: $[\hat{A},\ \hat{B}]_+ = \hat{A}\hat{B} + \hat{B}\hat{A}$.

In Minkowski space, a preferred basis can be constructed using the specific symmetries of this space (the Poincaré group). Then, if $\hat{N}_k = \hat{a}_k^\dagger \hat{a}_k$ is the operator number of particles, we obtain

$$\langle 0|\hat{N}_k|0\rangle = 0, \qquad \text{for all } k. \tag{A19}$$

This means that the expectation value for all quantum modes of the vacuum is zero: if there are no particles associated with the vacuum state in one (non-accelerated) reference system, then the same is valid in all of them.

Similarly, the number of quanta with frequency ω_i and momentum k_i of the field σ_{q} is:

$$\langle {}^1n_{k1},\ {}^2n_{k2},\ \ldots {}^jn_{kj}|\hat{N}_{k1}|{}^1n_{k1},\ {}^2n_{k2},\ \ldots {}^jn_{kj}\rangle = {}^in, \tag{A20}$$

and the total number of quanta is:

$$\langle|\hat{N}|\rangle = \sum_i {}^in = N. \tag{A21}$$

Here, N is the total number of excitations of the field.

It is worthy to analyze the behavior of the energy momentum of the field. The energy momentum tensor is:

$$T^{\mu\nu} = \partial^\mu\phi\partial^\nu\phi - \eta^{\mu\nu}\mathcal{L}, \tag{A22}$$

where $\eta^{\mu\nu}$ is the Minkowski metric tensor. Using Equation (A1), we obtain for the Hamiltonian density:

$$T_{tt} = \frac{1}{2}[(\partial_t\phi)^2 + \sum_{i=1}^{3}(\partial_i\phi)^2 + m^2\phi^2]. \tag{A23}$$

Using the expression for ϕ, we obtain the Hamiltonian operator integrating over the entire space:

$$\hat{H} = \int T_{tt}d^3x = \frac{1}{2}\sum_k(\hat{a}_k^\dagger\hat{a}_k + \hat{a}_k\hat{a}_k^\dagger)\omega_k \tag{A24}$$

$$= \sum_k(\hat{a}_k^\dagger\hat{a}_k + \frac{1}{2})\omega_k. \tag{A25}$$

Clearly, there is a problem with the expression (A25): the expectation value for the energy of the vacuum state is not zero as expected, as no field quanta are present. Moreover,

$$\langle 0|\hat{H}|0\rangle = \langle 0|\sum_k(\hat{a}_k^\dagger\hat{a}_k + \frac{1}{2})\omega_k|0\rangle \tag{A26}$$

$$= \langle 0|0\rangle\sum_k\frac{1}{2}\omega_k \tag{A27}$$

$$= \infty. \tag{A28}$$

Since the sum on the right side of the equation adds infinite quanta of energy ω_k, the energy of the vacuum states is infinite! Fortunately, this problem is easy to solve in Minkowski spacetime since only energy differences have physical meaning and all reference systems are equivalent. Therefore, we can *renormalize* the energy of the vacuum simply by introducing a *normal ordering* operation, which requires that the product of the creation and annihilation operators satisfy:

$$\hat{a}_k \hat{a}_k^\dagger :=: \hat{a}_k^\dagger \hat{a}_k, \tag{A29}$$

where the symbol :=: stands for the normal ordering operation. Then, the renormalized Hamiltonian operator reads $\hat{H} = \sum_k (\hat{a}_k^\dagger \hat{a}_k \omega_k)$, whose vacuum expectation value is zero.

The above quantization scheme can be easily generalized for the Dirac spinor field and the electromagnetic field (see refs. [54,55,66]), and if several fields are involved, $\sigma_{q1}, \sigma_{q2}, \ldots, \sigma_{qn}$ interactions can be included through the scattering operator and the S matrix (see ref. [53], for the basic definitions, or ref. [66], Chapter 9, for a more detailed treatment). This formalism makes QED the most powerful theory in physics in terms of the precision of its predictions and its agreement with experimental tests.

Notes

1 I define an "object" as any concrete individual.

2 For a broad introduction to the ontology of properties see the book by Edwards [29]. The general problem of properties in quantum mechanics is discussed, for instance, by Jeffrey Bub [30] and Mauro Dorato [31].

3 The view that the ontological substratum of the world is formed by structures and not by entities is called "ontic structural realism". For a reference, see, for example, Ladyman and Ross book [63]). This is not the place to make a fair and detailed criticism of this view. For more on this, see [64]).

4 All the theories discussed here are renormalizable. Renormalization in curved spacetime is notoriously more difficult than in flat spacetime, but it can be performed; see [66].

5 I define "substance" as any simple existent entity—that is, an entity that has no composition. The ways of being of such a substance are what I call "fundamental properties".

6 I note that the term "matter" is a concept, not a substance per se: it is defined as the class of all material objects [28,47]. Objects are made up of different kinds of material substances. So, the view I present is a form of *pluralism* because it admits the existence of many different kinds of material substances, twenty-six to be exact: the fields of the Standard Model plus spacetime. Even if you consider the behavior of the fields at high energies and accept the Grand Unified Theories as correct, fermions and bosons remain separate as intrinsically different kinds of material stuff. Only if supersymmetry is someday proved to exist would ontological pluralism be reduced to materialistic dualism at the temperatures where unification can be achieved.

7 It should be noted that the use of the word "detector" in what follows does not imply any commitment to a particular theory of measurement. It is simply a way to express the presence of particles in a given system of reference.

8 For interacting particles the tensor product should be considered.

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