***Particles in a Quantum Ontology of Properties***

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**Abstract**

We propose a new quantum ontology, in which *properties* are the fundamental building blocks. In this property ontology physical systems are defined as *bundles of* *type-properties* (specified by algebras of observables in a Hilbert space). Not all elements of such bundles are associated with definite *case-properties*, and this accommodates the Kochen and Specker theorem and contextuality. Moreover, we do not attribute an *identity* to the type-properties, which gives rise to a novel form of the bundle theory. There are no “particles” in the sense of classical individuals in this ontology, although the behavior of such individuals is mimicked in some circumstances. This picture leads in a natural way to the symmetrization postulates for systems of many “identical particles”.

*1. Introduction*

Although talk of particles is part and parcel of everyday practice in quantum physics, it is generally recognized that it is less than clear what quantum particles *are*: quantum mechanics makes it difficult to think of them as independent and localized entities, in the way of classical physics. Typical non-classical features that are responsible for this problematic status of particles in quantum theory are contextuality, indistinguishability and non-separability. These are recognized novel characteristics of quantum theory, but most of the philosophy of physics literature treats them as more or less independent of each other and no unifying ontological picture has been proposed in which they all find a natural place. The present paper is part of a project that aims at filling this lacuna: we propose to develop a new quantum ontology in terms of which a general characterization of quantum systems can be given.

The perspective that guides our work is that *properties* constitute the fundamental ontological building blocks that form physical systems. As we will argue, in a *quantum property ontology* the notorious quantum peculiarities emerge as natural aspects of physical systems. In this article we will focus on contextuality and indistinguishability and explain how these features naturally fit into our properties perspective, and why this has the consequence that the concept of a “particle”, with its classical connotations, cannot be taken as fundamental. We will also explain under what circumstances and with what limitations talk of particles can nevertheless be retained.

*2. Quantum systems as bundles of properties*

What is an individual? The classical philosophical concept of an individual is inspired by the ‘things’ or ‘objects’ of everyday experience. An individual object is something that can be identified here and now, is different from other individuals, and continues to be what it is as time goes on.

A classical individual is an indivisible unity in the sense that it either cannot be divided at all or, if it can be divided, that the results of the division are different from the original. Moreover, an individual is subject to the Kantian category of quantity (unity-plurality): individuals are either one or many. In the latter case, they may form aggregates, in which they can be counted individually. These features distinguish the category of individual from the category of “stuff”, which can be divided into portions without losing the stuff identity, and whose portions, when put together, cannot be individually counted (see Lewowicz & Lombardi 2013). As Henry Laycock puts it, the key to the character of the general category of individual “*evidently rests in the notions of unity and singularity—and thereby perhaps, more generally, in the concepts of number and countability*.” (Laycock 2010, p. 8).

Individuals can be given names and fall under definite descriptions. An individual possesses properties (possibly including relations as *n*-adic properties); linguistically this is captured by predicates applied to a subject. The ontology of objects possessing properties is basic to classical thinking and has generated the fundamental subject-predicate structure of language. This mirror relation between the ontological category of individual and the linguistic category of subject was highlighted by Peter Strawson in his classical book, *Individuals*, in which he states that an individual is “[a]*nything whatever can be introduced into discussion by means of a singular, definitely identifying substantival expression*” (1959, 137), and“*anything whatever can appear as a logical subject*” (1959, 227). Ernst Tugendhat expresses the same idea as follows: “*There is a class of linguistic expressions which are used to stand for an object; and here we can only say: to stand for something. These are the expressions which can function as the sentence-subject in so-called singular predicative statements and which in logic have also been called singular terms*” (1982, 23).

The usual systems of logic follow this pattern and make use of constants and variables, subject to predication, and thus are tailored to represent classical individuals. For instance, in first order logic, the sentence ‘*Pa*’ says that the property corresponding to the predicate ‘*P*’ applies to the individual denoted by the individual constant ‘*a*’; likewise, in the expressions ‘’ and ‘’, the range of the variable *x* is understood to be a domain of individuals. To quote Wittgenstein: “*the variable name ‘x’ is the proper sign of the pseudo-concept object. Wherever the word ‘object’ (‘thing’, ‘entity’, etc.) is rightly used, it is expressed in logical symbolism by the variable name. For example in the proposition ‘there are two objects which…’ by ‘’.*” (1921, Proposition 4.1272). As Wittgenstein thus makes clear, “object” is not a concept that is *defined* within a logical language, but rather is a category that is presupposed by a language and *shown* by its structure: it can be read off from the use of constants and variables.

The essential role of individual constants and variables is not limited to traditional logic: the vast majority of systems of logic, even extensions of traditional logic and deviant systems (see Haack 1974, 1978), use them; an ontology populated by individual objects is thus universally presupposed. The appropriate background theory for all these logics is set theory: ‘’ expresses that the element ‘*a*’ belongs to the set of individuals represented by ‘*A*’. In short, it is a universal and basic characteristic of traditional logic, and traditional thought in general, that there are individuals that can possess properties and can be represented by a constant or variable subject to predication.

The concrete identification of individuals requires a criterion, a “principle of individuation”, in order to distinguish each individual separately (synchronic individuation) and to re-identify it over time (diachronic individuation). The first, synchronic problem can be expressed as: What makes an individual to be that individual and not another? Following Leibniz’s Principle of the Identity of Indiscernibles, which says that two individuals cannot have exactly the same properties, it seems natural to respond that we may base synchronic individuation on the individual’s properties. However, when we also address diachronic individuation we have to take into account that in general the properties of an individual change. Descartes in his Second Metaphysical Meditation discusses the example of a piece of wax: it has many sensory properties − it is white, has a certain smell, makes a certain sound when one raps it with one’s finger, is hard, and has a certain taste − but it may lose them all when placed by the fire. If properties thus change drastically, what allows us to say that we are dealing with the same individual both before and after the change? Funes, the main character of one of Jorge Luis Borges’s short stories (1942), “*was disturbed by the fact that a dog at three-fourteen (seen in profile) should have the same name as the dog at three-fifteen (seen from the front)*.” The example of the Ship of Theseus, whose planks where replaced one by one until finally it was composed of entirely different planks, also illustrates this problem of identity over time. What makes an individual the same at different times?

A traditional response to these questions is that there is an underlying unchanging *bearer* of properties, a *substratum* or property-less *substance* that is the seat of individuality. In this case each individual is distinguished from the others by its own substance. In this way it is justified to think of the same individual, even if all its properties change over time.

The word ‘*substantia*’ is an (unfortunate) Latin translation of the Greek term ‘*ousia*’, and etymologically means “what stands (*stare*) under (*sub*)”. In the history of philosophy, the notion of substance has developed into one of the most complex notions of metaphysics. Aristotelian *primary substance* (*prôtai ousiai*) corresponds to ‘objects’ or ‘individuals’; it is composed of matter and form (form is the *secondary substance*) and is fundamental in Aristotelian ontology. But in modern philosophy the notion of substance has come to refer to a substratum (“bare particular”), so that an individual consists of substance plus properties. This is famously made explicit by Locke when he writes: “*The idea then we have, to which we give the general name substance, being nothing but the supposed, but unknown, support of those qualities we find existing, which we imagine cannot subsist sine re substante, without something to support them, we call that support substantia; which, according to the true import of the word, is, in plain English, standing under or upholding*.” (Locke 1690, Book II, Ch. 23). This is the notion against which Hume directed his devastating criticism (more about this later).

This concept of substance can be characterized by a number of core characteristics (see Robinson 2013):

* ontological fundamentality: substances are the ontological principles that metaphysically sustain everything else;
* the ability to bear properties;
* permanence in spite of change of attached properties;
* ground for individuation and re-identification.

This concept of substance does not sit well with present-day science, however: it represents an element of reality that is unobservable *by definition*. The name *substance* conjures up the idea of ordinary physical or chemical substances − but this is a misleading analogy since ordinary substances possess physical or chemical properties, whereas the substance we are discussing here has no physical properties on its own: it is the mere *possibility* for a system to possess properties. Nevertheless, the arguments that we have reviewed seem to make it plausible to accept some substance-like principle; how else could we make sense of predication and individuality? The scholastic notion of *haecceity* (“primitive thisness”, from the Latin *haec*, this) is such a substance-like notion that occurs even in recent philosophy of quantum mechanics.

Such a mere possibility remains mysterious and one wonders whether one cannot do without it. From a scientific viewpoint it is natural to wonder whether it is not possible to work directly with the physical properties themselves that characterize a system. The situation in quantum mechanics reinforces this question. For example, the problems surrounding “identical particles” in quantum mechanics give us a hint that quantum systems may be very unlike classical objects: there is at least one tradition in the philosophy of quantum mechanics saying that quantum particles are not individuals at all. This suggests that even if the substance-plus-properties picture is completely adequate for the treatment of classical systems, a quantum system may be better analyzed differently. It is therefore appropriate to pay attention to a rival of the substance view, namely the *bundle theory* according to which physical systems are just collections of properties, without a substance underlying them.

The idea of dismissing the category of substance from the ontology is anything but new in philosophy and dates back from far before any quantum challenges. In fact, many philosophers with an empiricist bent of mind have objected to substance because of its empirical unobservability in principle, following Hume’s classical criticism. This stance has led them to suggest that individuals are just bundles of properties, so that properties obtain ontological priority over individuals and become the fundamental items of the ontology.

The question of whether an object is a substratum supporting properties or merely a bundle of properties has been and still is one of the big controversies in metaphysics (Loux 1998). In this classical debate the decision which side to choose has more or less remained a question of metaphysical taste (see Benovsky 2008). But quantum mechanics changes this situation. The traditional view of individuals as substances-plus-properties now more than before begins to show *scientific* limitations: limitations that are open to empirical investigation. In particular, the empirically well confirmed central principle of quantum mechanics that the total state of a system of “identical particles” must be symmetrical or anti-symmetrical hints that no physical meaning attaches to the notion of an exchange between “quantum particles”, which seems to suggest the absence of a substance-like principle of individuality.

Before proceeding, a word of caution is in order. It is true that if one is determined to retain the idea of a classical particle one can do so without inconsistencies, like in Bohm’s theory. The peculiar quantum statistical results can then be explained by supposing that correlations between measurements results are the consequence of peculiar initial or boundary conditions on particle states (see discussion in Dieks 1990, van Fraassen 1991), or by assuming that quantum particles exert “exchange forces” on each other (repulsion between fermions and attraction between bosons; see Mullin & Blaylock 2003 for a critical discussion). The evaluation of such proposals and comparison with the more standard ideas about quantum mechanics that we are discussing here is intricate. However, it does not merely depend on metaphysical taste: we are dealing with problems of scientific choice and scientific methodology, and although conclusive arguments for one position over another will certainly remain out of reach, empirically informed discussion about the pros and cons of the various alternatives is possible (see Acuña & Dieks, 2014). If anything, arguments from the quantum realm point in the direction of problems with the classical notion of an object, and much more so than in classical physics are we driven into the direction of a properties ontology. In the next section we are going to introduce the general structure of such an ontology and explain in more detail why it accords well with quantum mechanics.

*3. The structure of the quantum properties ontology*

The idea of a quantum ontology of properties lacking substantial individuals was introduced in the context of modal interpretations of quantum mechanics (see the overview in Lombardi & Dieks 2013). In these interpretations definite values of physical quantities are ascribed to physical systems, according to criteria that depend on the specific interpretation. The idea was later developed (da Costa, Lombardi & Lastiri 2013, da Costa & Lombardi 2014) with the aim of exploring the general structure of the quantum domain, independently of the decision about the specific rule of definite-value ascription. But the applicability of the notion is not restricted to modal interpretations: also in other interpretations one can speak about properties of physical systems, albeit relativized to a (measurement) context - in particular, this is also true for the Copenhagen interpretation.

In quantum theory the descriptive concepts used in experimental practice (physical quantity, value of a physical quantity, state produced in a preparation procedure, etc.) have mathematical counterparts in the Hilbert space formalism (self-adjoint operators on a Hilbert space, eigenstates and eigenvalues of an operator, vectors in the Hilbert space, etc.). The general strategy we are going to follow is to endow this mathematical-physical language with ontological content, even outside the context of measurements in the usual sense. In this, we attempt to avoid adding ontological categories that have no empirical counterparts. Generalizing standard interpretational ideas, we establish the following semantic relations:

* *Observables* (self-adjoint operators on a Hilbert space) represent *type-properties* (like “electron energy”; these can themselves be seen as instances of *universal* type properties, like “energy”).
* *Eigenvalues of an observable* represent the possible values of an observable, i.e. instances of the corresponding type-property; they stand for the possible *case-properties*.
* *The quantum state* (mathematically, a vector in the Hilbert space or, more generally, a functional on the space of operators) yields the *probabilities* for actualization of possible case-properties.

We have here made use of the distinction between type-properties and their instances. The question about the ontological status of (universal) type properties leads us back to the problem of universals, which bedevils philosophy since Plato’s *Parmenides.* We will only remark that our proposal is meant to be neutral with respect to this general question: we will not enter into the question of whether the type-properties are primitive or built up from their instances. A *realist* interpretation of universals should be compatible with our proposal, but it would not essentially change under many different forms of *nominalism*, such as predicate nominalism, concept nominalism, or class nominalism (see Rodriguez-Pereyra 2011). The essential point for us is that any type-property can be multiply instantiated. Moreover, a distinct feature of our proposal is that we will *not* assume that properties or their instances possess a form of individuality (except of course for the differences between numerically distinct eigenvalues). Our proposal does therefore not accord with views in which there is such an individuality, e.g. a tropes view in which the tropes possess a primitive identity (see, e.g., Ehring 2011).

The difference between type-properties and case-properties runs parallel to the distinction between *determinables* and *determinates* (Johnson 1921, Prior 1949). For instance, the property color is a determinable, a universal type-property. Redness and whiteness are determinate instantiations of this universal type-property. Similarly, mass and a mass of 1 kilogram are a determinable universal type-property and an instantiation of it, respectively (Sanford 2013). Redness, whiteness and mass of 1 kg are type-properties themselves, and can be instantiated in many cases. As a quantum example, the type-property “energy of the hydrogen atom” (itself an instance of the universal property “energy”) has the particular energy values of the hydrogen spectrum as its possible case-properties.

On the basis of these fundamental distinctions we now build up our ontological structure:

* *Bundles of properties* define physical systems. The *type* of the system is determined by a bundle of *type-properties* (represented by an operator algebra on a Hilbert space); the concrete *case* is a collection of *case-properties*. Note: the fact that we use the familiar term “quantum system” does not imply that we are assuming that quantum systems are individuals (this point will be discussed below).
* An *atomic system* is a system that cannot be decomposed into smaller bundles. Its physical correlate is an elementary particle. Mathematically we should think of an irreducible representation of the theory’s symmetry group; for example, the Galilean group in non-relativistic quantum mechanics.

Our ontological starting point is thus the idea of multiply instantiable type-properties, without a principle of individuation, and their case-properties. So we start with a realm that does not contain substantial objects: there is no substratum or other principle of individuation.[[1]](#footnote-1) At the basis of our ontology is a tree-like categorical structure, in which universal type-properties (like “energy”) have many instances (like “electron energy”) and in which each such instance has, in general, many (possibly uncountably many) possible case-properties. The type-properties characterizing a quantum system are represented by an operator algebra on a Hilbert space. The question is how this ontology, to be further explained below, will allow us to face the quantum challenges, for example contextuality and indistinguishability. This will be the subject of the two following sections.

*4. Contextuality in an ontology of properties*

One of the first reactions to the probabilistic character of quantum theory was the attempt to interpret it as a statistical theory, in the style of classical statistical mechanics, so that the probabilities can be explained as frequencies in ensembles of systems with definite but “hidden” values of their observables. The *coup de grace* for such classical-like statistical interpretations was the Kochen-Specker theorem (1967), which proves the impossibility of ascribing precise values to *all* the observables of a quantum system simultaneously, while preserving the functional relations between commuting observables. It follows that which observables can be ascribed precise values must be contextual, i.e. situation-dependent (e.g., dependent on the measurement context).

This contextuality of quantum mechanics has far-reaching ontological consequences. Contextuality implies the violation of the *principle of omnimode determination*, a principle that has been generally accepted in modern philosophy. For example, it appears in the works of Wolff[[2]](#footnote-2), in the famous treatise on the calculus of probabilities by Bernoulli[[3]](#footnote-3), and is also repeated several times by Kant in his lectures on metaphysics[[4]](#footnote-4). The idea, which is almost self-evident in the context of pre-quantum thinking, is that in every individual all determinables are determinate: if the determinable “color” applies to an object, it necessarily has some determinate color, say red, independently of its other determinate properties, and also independently of our knowledge about what that determinate color is. Quantum mechanics, on the contrary, tells us that that a system will generally be associated with determinables that are not determinate. For example, we can have a physical system to which the type-property position applies but which nevertheless has no definite position.

This feature of quantum mechanics has often been considered an interpretative problem in need of a solution. One approach has been to accommodate contextuality by adapting the logic: starting from the fact that contextuality relates to the non-Boolean structure of elementary quantum propositions, a non-classical propositional logic can be formulated in terms of the non-distributive, orthocomplemented lattice of the theory (see, e.g., Jauch & Piron 1969, Piron 1976, Beltrametti & Cassinelli 1981). From a more physical perspective, other authors have dealt with quantum contextuality by selecting a context, via an interpretive assumption (see, e.g., Bub and Clifton 1996, Dieks 2005), or by a physical process as decoherence (see, e.g., Zurek 1982, 2003). However, the general problem of what a physical system *is*, and what structure the quantum ontology should have in order to make contextuality natural has not been answered in a systematic way.

When the contextuality of quantum mechanics is considered from the viewpoint of our property ontology, it appears as a limitation regarding actual case-properties. Since the quantum system is a bundle of type-properties, with their corresponding *possible* case-properties, it is immune to the challenge by the Kochen-Specker theorem, since this theorem imposes no restriction on possibilities and on type-properties. The theorem states that the idea of a fully determinate bundle of *actual* case-properties for *all* the type-properties of the bundle cannot work in the quantum world: it is not possible to ascribe definite case-properties to all the type-properties of a bundle in a non-contradictory manner. In other words, the Kochen-Specker theorem places restrictions on which possible case-properties of a bundle can enter actuality: not every type-property of the bundle have an actual value for one of its possible case-properties. For example, in elementary quantum mechanics of systems without internal degrees of freedom all systems have both momentum and position as characteristic type-properties, in spite of the fact that these two quantities cannot both enter the realm of actuality in the form of definite case-properties.

In the light of contextuality it is interesting to notice the relation between the determinable/determinate distinction and the possible/actual distinction. The traditional principle of omnimode determination makes the distinction between determinables and determinates superfluous, since all determinables are determinate. But in the quantum case, given the Kochen-Specker theorem, it makes sense to consider the realm of possibility, since not all determinables can be determinate in a given system: there are determinables such that none of their possible determinates are actual.[[5]](#footnote-5)

The limitations imposed by the contextuality of quantum mechanics lead us to reflect on the difference between the traditional bundle theory and the present proposal. In the traditional version of the bundle theory a bundle is a combination of case-properties such that all the type-properties corresponding to that bundle are unequivocally determined. For instance, a particular billiard ball is the combination of a definite value of position, a definite shape, namely roundness, a definite color, say white, etc. So, in the debates about the metaphysical nature of individuals, the question is whether an individual is a substratum to which a definite position, roundness and whiteness belong, or whether it is rather a substance-less bundle of these same case-properties. In both cases all type-properties taken into account are actual.

It has been argued in the literature (Benovsky 2008) that in this case the difference between the substratum theory and the bundle theory is only verbal: in the bundle theory the bundling per object is done by a “compresence relation” that is specific for the object in question, and this relation fulfils exactly the same purposes as substance in the traditional theory. However, in our quantum proposal not all the type-properties that define a system have an actual case-value, and the status of a quantum system is consequently that of a bundle of *type-properties,* specified by an algebra of observables. The bundling, on this level, does not require a relation of compresence that is specific for a particular system: all the algebras for a system of, e.g., electrons are the same. There really is only *one* algebra that is multiply instantiable; we do not suppose a compresence relation that bestows individuality on any particular electron.

The traditional bundle theory aimed at reproducing the concept of an individual without reliance on the concept of substance or haecceity. A crucial ingredient needed to make this program work is the assumption that each thus-reconstructed individual can be characterized by at least one property that makes it unique and which allows re-identification over time (a form of Leibniz’s Principle of the Identity of Indiscernibles). In classical physics *position* is the standard property that fits this bill: different particles have different positions and the continuous trajectories of particles make it possible to follow them over time. Therefore, in the context of classical physics the bundle theory leads to the same “surface” picture as the substance theory: although the substance itself is lacking, its role is taken over by position. By contrast, in the quantum case the example of identical particles suggests that in general we cannot expect that systems can be individuated and re-identified over time by case-properties: quantum systems may lack the basic characteristics of individuals. The variation on the traditional bundle theory that is presented here embodies these features: *bundles are not individuals*, they have no “principle of individuality” that makes them to be a particular individual and not another. Accordingly, our quantum bundles do not aim at reproducing the same general picture as the traditional substance theory: whereas the substance theory is meant to ground an ontology of individuals, our quantum bundle theory leads to an ontology of properties, without individuals. As we already noted, this non-individual version of bundle theory does not make use of a notion of compresence that is just a substitute for substance or bare particular (Benovsky 2008).

The concept of an individual system does not fit comfortably in our quantum property ontology. In our proposal, to be further developed in the next section, properties will in general not build up individuals: there will just be properties, in general multiply instantiated, without generally valid individuating characteristics. This feature relates directly to the subject of indistinguishability.

*5. Indistinguishability in an ontology of properties*

It is a peculiarity of quantum mechanics that states of “*n* identical particles” are invariant (except for a possible change of sign) under any permutation of “particle labels”. Therefore, permutations of these labels do not lead to any differences in the probabilities for measurement outcomes and consequently do not give rise to any empirical differences at all. This raises questions concerning Leibniz's Principle of the Identity of Indiscernibles (PII), according to which there cannot be two different completely indistinguishable objects: according to PII two indiscernible candidate-objects, i.e. objects with exactly the same properties, are in reality one and the same object. The principle admits different versions, depending on the set of properties over which we quantify. Quantum indistinguishability raises problems for even a (logically speaking) weak version of Leibniz’s principle, according to which it is not possible for two distinct individuals to have *all* *physical* properties and relations in common. This seems to indicate that the notion of individual quantum particles can only be reconciled with a form of PII if we include non-physical ingredients (like haecceity or substance) in the definition of individuals. This is a disturbing situation: it is certainly against the spirit of modern physical science to introduce such metaphysical and unobservable-in-principle things at a fundamental level.

Various solutions have been proposed to this problem of quantum indistinguishability. Following a suggestion from the work of Quine (1976), Simon Saunders (2003, 2006) has argued that two fermions in an anti-symmetric state are *weakly discernible.* For example, in the singlet state two electrons stand in the relation of “having opposite spins”, and this makes it possible to individuate the particles by means of PII after all, in a weak sense (i.e., without making it possible to refer, by means of a physical description, to a specific individual; PII here only says that there must be *two* particles, but cannot effectively distinguish them). Muller and Saunders (2008) and Muller and Seevinck (2009) have made (controversial) attempts at extending this analysis to the case of bosons. There is a threat of *petitio principii* here: the argument may beg the question to the extent that it relies on the idea of a multiplicity of entities from the start. As French and Krause (2006, pp. 170−171) remark: “*the worry is that in order to appeal to such* [irreflexive] *relations, one has already had to individuate the particles which are so related and the numerical diversity of the particles has been presupposed by the relation which hence cannot account for it*”. The objection has been developed by Dieks and Versteegh (2008; see also Dieks 2014), a recent defense is proposed by Muller (2014); the subject remains controversial.

Among the attempts to salvage individuality along more traditional lines, we find the suggestion that the quantum restriction to symmetrical and anti-symmetrical identical particle states is not law-like, but rather due to contingent initial conditions; and suggestions that the quantum states describe traditional individual particles in an incomplete, statistical way, e.g. in the way proposed by Bohm. As French (1989, 1998) points out, strategies of this kind can keep the quantum mechanical formalism formally consistent with the traditional ontological view of identical particles as individuals. One can object that these attempts at salvaging the notion of individual particles have an *ad hoc* character, and add structure to the formalism of quantum mechanics without adding to the predictive content of the theory. Or like Michael Redhead and Paul Teller (1992) put it, this way of retaining the notion of individual can be accused of introducing *surplus structure* in the formalism; the individuals are put in by hand.

We do not wish to add to this well-known methodological debate here, however. Rather, we want to work out a new picture, in terms of our property ontology, in the hope that interpretational puzzles will be dissolved in this new framework. As Teller (1998, p. 122) says: “*I suggest that belief in haecceities, if only tacit and unacknowledged, plays a crucial role in the felt puzzles about quantum statistics*”. Suggestions that a (silently) assumed classical ontology of individual particles is responsible for the conceptual problems surrounding indistinguishability can also be found with other authors, like Post (1963) and Maudlin (1998). However, these suggestions that an alternative ontology might be more suitable have not been developed in a systematic way. A possible exception is formed by proposals for new kinds of set theories: the semi-extensional quasisets theory developed by Newton da Costa and Decio Krause (1994, 1997, 1999; see also Krause 1992, and da Costa, French & Krause 1992) and the intensional quasets theory, developed by Maria Luisa dalla Chiara and Giuliano Toraldo di Francia (1993, 1995), describe collections of objects having cardinality but no ordinality. In these theories quantum particles are objects that are intrinsically indistinguishable; but they still are treated as individuals and, as such, are referred to by individual variables just as in classical set theory. The ontological significance of this formal description has not yet been clarified. Another drawback is that the problem of contextuality is left untouched: quantum systems violate the principle of omnimode determination, and this fact is not accounted for by the new set theory.

Our own positive proposal is not formal but is based on reflections about fundamental ontology. In our picture, quantum systems are not individuals but rather *bundles of properties* that can merge with each other and form new wholes, without individual components. Our claim is that this type of description is only natural, both within quantum mechanics and the framework of our property ontology.

Let us consider a system that corresponds to two elemental bundles of the same kind (i.e., generated by the same algebra of observables). We do not assign individuality to these bundles: we are dealing with a doubly instantiated algebra of observables, without additional distinguishing characteristics. We refrain therefore from using terminology like “bundle 1”, “bundle 2”, “each bundle”, and so on. Rather, we wish to introduce such “individuality” concepts *a posteriori*, in cases in which this is possible, on the basis of the physical details of the situation.

So we say of any type-property ***A*** that it can be *twice* instantiated, with its own twice-instantiated case-properties. A twice-instantiated case-property of the twice-instantiated ***A*** may consist of two different values *a*1 and *a*2, or twice the same *a* value. Obviously, in the first case there is a physical distinction that makes it possible to speak about different bundles, namely the bundle containing *a*1 and the bundle containing *a*2, respectively. For ease of reference we may call them bundles 1 and 2; but we should not take this as showing that there is some metaphysical principle of identity that grounds these labels.

In the second case, the one in which *a* occurs twice, we cannot introduce distinguishing labels and we should therefore now say that we have *one* bundle in which *a* is *doubly* *instantiated*. If this situation arises during temporal evolution, we are entitled to say that two different original bundles have “merged”. Within the framework of our property ontology there is now just one whole, in which the original bundles can no longer be identified. Indeed, the resulting *a*-*a* system is defined in such a way that it makes no sense to hold that one *a* comes from bundle 1 and the other from bundle 2, or *vice versa*.

The crux here is that individuality is not something given *a priori*, in terms of substance, haecceity, or system-specific compresence, but needs to be defined on the basis of differences in physical case-properties. In this sense individuality may be said to be *emergent,* since it is a notion whose applicability depends on physical facts, namely the values of the case-properties (we will come back to this point in the following section).

This ontological picture does not so much offer a solution to the problem of indistinguishability, but rather *dissolves* it. Indeed, the difficulties in standard discussions come from considering indistinguishability as a relation between particles whose individuality is already assumed to exist; and one would then like to relate this individuality to physical differences, via PII. By contrast, from the point of view introduced here the problem of indistinguishable individuals does not arise because now there simply can be no individuals with the same properties. A “merger” of two bundles, in the manner discussed above, produces one new whole. In the final situation there is no violation of Leibniz’s principle since we are not dealing with two items, but with a single item to which the application of the principle makes no sense.

In order to represent these ontological ideas mathematically for a system of “identical particles”, we may consider operators  and , both representing instances of the universal type-property ***A***, acting on isomorphic Hilbert spaces  and , respectively. Note here that the indices 1 and 2 are not supposed to refer to individual particles (this would be question begging!), but only have a mathematical function, namely of referring to two copies of the same Hilbert space.

All observables must be symmetrical in 1 and 2, like the operator  or the operator $A\_{1 }⊗A\_{2}$ (acting on the Hilbert space ). Indeed, “twice-instantiated” (said of the algebra) means that the order of 1 and 2 must be without physical significance (see da Costa, Lombardi & Lastiri 2013). This symmetry is anchored in the ontological picture: there is not a physical type-property 1 and a physical type-property 2, but only ***A*** that can be instantiated more than once. In fact, this agrees with standard wisdom that all observables of an identical particle system have to be symmetrical in order to preserve the symmetry properties of the states over time. But in the usual treatment this is a requirement that has to be imposed, in addition to and independently of the symmetrization of the states. By contrast, in our approach we ground this property in the structure of the properties ontology; and we are going to deduce the symmetrization properties of the states from this symmetry of the observables.

It is clear from the above that in the mathematical language that we use we cannot easily dispense with indices, because the usual language of mathematics itself is, as that of the classical set theory on which it is based, a language that operates with the notion of individuals. However, it is essential to note here that although the differently indexed operators  may be seen as different *mathematical* objects (even though they are identical copies of one mother object), we do not assume that they refer to different *physical individuals*. The indices are here employed as mere mathematical tools without physical and ontological significance.

When the idea of a property ontology without traditional individuals is taken seriously, it no longer is self-evidently natural to represent it by a formalism whose primitive symbols are variables referring to individual objects. An alternative possibility for handling such a property ontology could be a logic of relations in the spirit of the “calculus of relations” proposed by Tarski (1941), where individual variables are absent. This strategy was suggested by Lombardi and Castagnino (2008), and has begun to be worked out by Krause (2005).

An important point is that the ontology of properties not only provides a justification for the symmetry of observables, but also makes it possible to derive the symmetry and anti-symmetry postulates of quantum mechanics. Summarizing this derivation very briefly, we start with the observation that any operator can be decomposed into a symmetric and an anti-symmetric part. Then, when a state-operator  is used to assign a value (expectation value) to a symmetric observable operator, its anti-symmetric part plays no role: the value assigned by the state operator  is completely determined by its symmetric part (see Lombardi & Castagnino 2008, da Costa, Lombardi & Lastiri 2013). From this it follows that in the particular case of pure states the state can be expressed as either a symmetric state vector or an anti-symmetric state vector. Therefore, that state vectors of identical particles can only be symmetric or anti-symmetric is not the consequence of an *ad hoc* symmetrization or anti-symmetrization rule, but has an ontological background: these symmetry properties of the states are a consequence of the symmetry of the observables of the aggregate, and this symmetry is, in turn, a consequence of the fact that properties and not individuals are fundamental.

*6. What are quantum particles?*

As we have argued in the previous sections, there are no individuals in our fundamental quantum ontology. However, the practice of physics is rife with talk about particles, and particles seem individuals *par excellence*. How can we understand this apparent conflict? In the previous section we have already indicated the essential answer, but let us be more specific here.

In everyday language the concept of an individual is central, and this is justified by the fact that this concept can be used very well to describe ordinary situations, also in the practice of experimental physics. It thus has become more or less self-evident to assume that even in the formalism of fundamental quantum mechanics individuals should be represented, and this is behind the almost universally accepted notion that the labels in a state of many “identical particles” refer to these particles as individuals −one could say that the labels are interpreted as haecceities. However, as we have explained above, this is an interpretation that is not unavoidable or even cogent: the labels can be taken to refer to different mathematical objects, different Hilbert spaces, and need not at all be considered as “particle names” (Dieks & Lubberdink 2011).

To see a simple illustration of this point, consider an Einstein-Podolsky-Rosen type of situation in which two identical particles are involved. Usually EPR experiments are discussed in terms of two particles at a large distance from each other, on which measurements are performed. According to this customary view, there is a left-side particle *L* and a right-side particle *R*, both treated as individuals that differ from each other in their positions. However, it is important to realize that the correct quantum mechanical state of the total system must be (anti-)symmetric. As a consequence, the indices 1 and 2 that occur in the quantum state *cannot* correspond to the wave packets on the left and right, respectively. These labels refer to Hilbert space 1 and Hilbert space 2, and in each of these Hilbert spaces we find a mixture of the *L* and *R* wave packets. This shows that the labels in the standard formalism in fact do not correspond to what we intuitively call particles. Rather, our intuitive notion of a particle is linked, in this example, to the two localized wave packets *L* and *R*. This shows that our ordinary intuitions actually follow the idea that what defines a particle is a set of physical *properties*, and not a metaphysical notion of identity. The notion that such an identity is inherent in the Hilbert space indices is simply wrong.

Elaborating on the remarks in the previous section about individuating case-properties, we note that under certain circumstances (decoherence is important here) narrow wave packets may occur in the description of a many particles system (see, e.g., Zurek 2003). Moreover, in classical limiting situations, such wave packets can remain narrow and more or less localized during a relatively long time. In this way, particle-like behavior can emerge: wave packets can represent approximately definite positions and can follow an approximately definite trajectory. In terms of case-properties, we thus have (approximate) positions and trajectories, and these features can be used to define and individuate particles. Note, however, that these particles do not correspond to the Hilbert space labels (as was just illustrated for the EPR case). Rather, their individuality resides in the distinctness of the case-properties that define them.

In the case of “identical particles” systems it may occur that there are no distinct case-properties; so in general we cannot expect that there are individual particles defined by these properties. In this sense particles as we know them from classical physics are *emergent*: the concept of a particle becomes applicable only in special circumstances, and the fundamental ontology is one of properties that do not possess inherent individuality.

*7. Conclusions*

Traditionally, contextuality and indistinguishability have been discussed as unrelated problems. Here we have proposed an encompassing framework in which the basic ontology is an ontology of properties, and in which physical systems of a specific kind are represented by sets of observables, not all of which need to take definite values. Actual states of affairs are represented by case-properties of the (contextual) subset of observables that is definite-valued. In this way both contextuality and indistinguishability become natural elements in one ontology, that of quantum properties.

An additional bonus of our approach is that the distance between non-relativistic quantum mechanics and quantum field theory becomes smaller. It is well-known that in quantum field theory the concept of a particle, as a fundamental entity, is problematic. In quantum field theory, as in the approach we have sketched, the particle picture is only emergent and approximate. The property ontology of quantum mechanics that we have proposed here thus forms a bridge to more general quantum theories.

Our discussion here has focused on the general features of the property ontology that are relevant for indistinguishability and contextuality. We believe, however, that these ideas about the ontology of quantum theory can also shed new light on other typical features of quantum mechanics, in particular non-separability. This will be the subject of another publication.

*8. References*

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1. There are partial similarities here with what a number of other authors, some of them also motivated by the ontological challenges of quantum mechanics, have proposed. In particular, in “structural realism” (Worrall 1989, Ladyman 1998), at least in its ontic version, there is an ontological shift from substantive objects to places in a network of relations (French & Ladyman 2003). This follows Cassirer (1936) in an older claim that elemental objects are not old-style individuals but rather “points of intersection” of certain relations: physical objects are “*reduced to mere ‘nodes’ of the structure, or ‘intersections’ of the relevant relations*” (French 2006, p. 173). This is similar to our proposal to the extent that it is a modern form of the bundle theory and tries to do without the *a priori* concept of an individual. These authors also note the difficulties in even expressing this position, because of “*the descriptive inadequacies of modern logic and set theory which retains the classical framework of individual objects represented by variables and which are the subject of predication or membership respectively*” (French & Ladyman 2003, p. 41). This echoes our earlier remarks about the relation between standard language and the classical notion of individuality. [↑](#footnote-ref-1)
2. “*Apparet hinc, individuum esse ens omnimode determinatum*” (“*Hence it appears that an individual is a completely determined being*”) (Wolff 1728, p. 152). [↑](#footnote-ref-2)
3. “*Sed quicquam in se et sua natura tale esse* [viz. *incertum et indeterminatum*], *non magis a nobis posse concipi, quam concipi potest, inde simul ab Auctore naturæ creatum esse et non creatum*” (“*That anything is uncertain and indeterminate in itself and by its very nature is as inconceivable to us as it would be inconceivable for that thing both to have been created and not created by the Author of nature*”) (Bernoulli 1713, p. 227). [↑](#footnote-ref-3)
4. “*Alles, was existirt, ist durchgängig determinirt*” (“*Everything that exists is continuously determined*”) (1902, AA 18:332, 5710; AA 18:346, 5759; see also LM XXVIII 554). [↑](#footnote-ref-4)
5. Because this might sound strange in the context of traditional discussions about determinables versus determinates, we have chosen to talk about *type-properties* and possible *case-properties*, among which not more than one can become actual. [↑](#footnote-ref-5)