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ARTICLE

The Structural Metaphysics of Quantum Theory and General Relativity

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Abstract The paper compares ontic structural realism in quantum physics with ontic structural realism about space–time. We contend that both quantum theory and general relativity theory support a common, contentful metaphysics of ontic structural realism. After recalling the main claim of ontic structural realism and its physical support, we point out that both in the domain of quantum theory and in the domain of general relativity theory, there are objects whose essential ways of being are certain relations so that these objects do not possess an intrinsic identity. Nonetheless, the qualitative, physical nature of these relations is in the quantum case (entanglement) fundamentally different from the classical, metrical relations treated in general relativity theory.

Keywords Entanglement · Hole argument · Metric · Modes · Ontic structural realism · Relations · Structures · Weak discernibility

1 Introduction: OSR as a Metaphysics for Fundamental Physics

Quantum mechanics (QM), together with quantum field theory (QFT), and general relativity (GR) are our current fundamental and experimentally extremely successful physical theories. Each of them exhibits features that are deeply intriguing, in particular for the traditional metaphysical conceptions of fundamental physical objects possessing an intrinsic identity and of space and time being some sort of a passive background. Ontic structural realism (OSR) is a metaphysical framework that provides for an appropriate understanding of the intriguing features of these fundamental physical theories. According

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to OSR, there are structures in the first place in the fundamental physical domain in the sense of networks of concrete physical relations, without these relations being dependent on fundamental physical objects that possess an intrinsic identity, that is, an identity constituted by intrinsic properties or a primitive thisness (haecceity).

QM and QFT on the one hand and GR on the other are very different physical theories. GR is a classical physical theory in that it takes all the physical properties that it considers to have always a definite numerical value each, but it regards space–time as a dynamical entity instead of a passive background. QM, including QFT, by contrast, breaks with classical physics through the superposition principle including entanglement, but retains the assumption of space–time as a passive background, treating notably time as an external parameter. Consequently, the concrete physical relations on which OSR draws in both cases are very different: relations of entanglement in the quantum case, and metrical-gravitational relations in the case of space–time as treated in GR. This fact raises the question whether OSR can with reason claim to be a metaphysical framework that covers both QM, including QFT, and GR. In particular, the concern is that OSR is either that abstract a metaphysical framework that it is not in the position to bring out reasonable metaphysical consequences of QM and GR, or that there are in effect two different conceptions of OSR, one conception of OSR tailor-made for QM, and another one tailor-made for GR.

The aim of this paper is to address this concern. We first spell out the physical support for OSR in QM (Section 2), then go into OSR in GR (Section 3) and on this basis compare these two conceptions under the aspect of what they say about the objects that they take to be fundamental (Section 4).

2 The Structural Metaphysics of Quantum Theory

Schrödinger (1935b, 555) claims that entanglement is not "*one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought". This assessment is well founded, since entanglement contradicts the principle of separability. Einstein stresses this principle in a letter to Schrödinger from 19 June 1935 (quoted in Howard 1985, 178–179). In a later paper, Einstein (1948) goes as far as maintaining that "Without such an assumption of the mutually independent existence (the 'being-thus') of spatially distant things … physical thought in the sense familiar to us would not be possible" (Einstein 1948, 321; English translation quoted from Howard 1985, 187).

Entanglement contradicts the principle of separability in that two or more quantum objects whose states are entangled are only taken together in a well-defined state (a pure state). Consequently, the state of the whole does not supervene on states that can be attributed to these objects taken individually. Consider the simplest example of entanglement, the singlet state of two quantum objects of spin 1/2 such as two electrons (Bohm 1951, 611–622): only the whole of these two objects taken together is in a pure state, in which a spin property—namely total spin—has a definite numerical value (zero); there are no spin states of each of the parts that determine the spin state of the whole. Quite to the contrary, the state of the whole—and only the state of the whole—determines correlations between the possible definite numerical values of the spin in any spatial direction of the parts, namely correlations of the type that if one of the two objects has spin up in a given direction, the other one has spin down in that direction. Consequently, the state of the whole, as represented in a Hilbert space, is a superposition of the correlation "first object spin up and second object spin down" with the correlation "first object spin down and second object spin up". These correlations cannot be retrieved from any information that can be gathered from each of the parts considered in isolation. If one considers each of the parts in isolation, one always gets probability 0.5 for measurement outcome spin up in any spatial direction, and probability 0.5 for measurement outcome spin down in any spatial direction. One does not obtain any information about the correlations between the possible definite numerical values of spin in any spatial direction of these two objects.

In other terms, a pure quantum state cannot be attributed to each entangled quantum system separately. It is possible to ascribe a reduced density operator to each system (obtained by 'tracing out the other system', that is, partial traces of the total density operator in the relevant Hilbert spaces), which however represents an improper mixture of states. Consequently, each single system cannot be considered to be in any definite state (since there is no other possible description in principle, in contrast to a proper mixture). Furthermore, the interpretation of Bell's theorem (1964) in terms of the violation of the condition of outcome independence (Jarrett 1984; Shimony 1993, chapter 11) leads to the view that there cannot be any intrinsic properties belonging to each of the objects considered in isolation on which the correlations in which the entanglement consists could supervene (to prove Bell's theorem, one has to consider slightly more complicated cases; but this fact is immaterial for present purposes).

Quantum theory describes entanglement as ubiquitous and generic (entangled states are dense in the corresponding product Hilbert space), occurring in virtue of the very nature of quantum systems. Of course, it is possible to consider pure quantum states that are not entangled and for many practical purposes, they are of great importance. But we should not lose sight of the fact that quantum systems embedded in the interacting physical world are strictly speaking almost always entangled.

Furthermore, there is no limit in the formalism of QM as to the size of objects to which entanglement applies. The famous case of Schrödinger's cat (Schrödinger 1935a) is a superposition of the correlation "no atom decayed, hammer mechanism not triggered, cat alive" and the correlation "one atom decayed, hammer mechanism triggered, cat dead". Adding an observer does not change that situation. As far as the formalism of QM is concerned, there then simply is a superposition of the correlation "no atom decayed, hammer mechanism not triggered, cat alive, observer being conscious of live cat" and the correlation "one atom decayed, hammer mechanism triggered, cat dead, observer being conscious of dead cat". Even if one acknowledges real physical processes of the dissolution of entanglement, as in dynamical collapse theories (Ghirardi, Rimini and Weber 1986—GRW), entanglement remains fundamental and (quasi-)classical states have to be accounted for on the basis of there being entangled states in the first place: these states come into existence through a process that leads from entanglement to state reductions (by means of spontaneous localizations in GRW).

QFT does not change anything as regards entanglement: one can maintain that entanglement is even more important in QFT than in QM (Lam 2011a). Within the rigorous framework of algebraic QFT, it can be seen that generic QFT states between space-like separated regions are entangled (most famously, the vacuum state; see the Reeh-Schlieder theorem). This result can be clearly discussed within the algebraic approach, but it is also valid within 'standard' (effective) QFT (Wallace 2006). Moreover, in all physically relevant algebraic models, the state on a space–time region is 'intrinsically' entangled with its space-like complement in the straightforward sense that no product states exist. Within such models, ('intrinsically') mixed states cannot be represented as a mixture of pure states, as opposed to mixed states in non-relativistic QM (Clifton and Halvorson 2001; Ruetsche 2004).

The principle of separability is the cornerstone of atomism in the philosophy of nature: the objects in the domain of fundamental physics are characterized by intrinsic properties (that is, properties that each object can have independently of whether or not there are other objects in the world), and the relations among these objects, apart from the spatio-temporal relations, supervene on the intrinsic properties that each object has independently of the other ones. Quantum entanglement, by contrast, suggests a sort of holism: instead of the intrinsic properties of the parts fixing the relations among them and thus the state of the whole, only the state of the whole fixes the relations among the parts, namely the superpositions of correlations that characterize entangled states (Esfeld 2001; chapter 8; see also Healey 1991).

This sort of holism has been spelled out in terms of non-supervenient relations by Paul Teller (1986). In his 1986 paper, Teller takes for granted that these relations, although being non-supervenient, hold nevertheless among individuals. However, the latter presupposition is questionable. State-independent properties such as charge and rest mass, which are not subject to the superposition principle and thus not touched by entanglement, having always a definite numerical value, can indeed be considered as intrinsic properties of quantum objects. They are allow to distinguish each kind of quantum objects from all other kinds of fundamental physical objects. But they cannot establish a distinction among quantum objects of the same kind. All quantum objects of the same kind, such as all electrons, always have the same definite numerical value of state-independent properties such as charge and rest mass. Furthermore, if the states of two or more quantum objects of the same kind are entangled, there are no state-dependent properties whatsoever either that establish a distinction among these objects (French and Redhead 1988). Quantum objects therefore do not possess an identity grounded in intrinsic properties or relations that distinguish each of these objects from all the other ones. In short, they do not possess an intrinsic identity.

These two features—entanglement as non-supervenient relations holding among objects that do not have an identity constituted by intrinsic properties—motivate developing ontic structural realism as an appropriate metaphysics for the quantum domain. In distinction to *epistemic* structural realism (Worrall 1989), *ontic* structural realism (OSR) claims that not only what we can gain knowledge of, but also what there is in the fundamental physical domain are structures in the first place—in the sense of networks of concrete physical relations that do not presuppose relata with an intrinsic identity (Ladyman 1998). The founders of OSR, Steven French and James Ladyman, build this position on what they regard as a case of underdetermination left open by QM—quantum systems can be objects qua non-individuals, or they can be objects qua individuals whose individuality is constituted by a primitive thisness (haecceity) (French and Ladyman 2003). They take this alleged underdetermination to be a sufficient motivation for waiving the commitment to objects altogether: there are structures in the sense of networks of relations all the way down, without there being objects at all in the domain of what is most fundamental in nature. For them, OSR either is an eliminativism about objects tout court (French 2010), or if there are objects, they are somehow constituted by relations, being nodes of relations (Ladyman et al. 2007, chapters 2–4; see furthermore French and Ladyman 2011, section 3).

However, one can with good reason deny that there is such an underdetermination in QM: the commitment to a primitive thisness (haecceitism) is a purely metaphysical move that one can make physics be as it may, there being no reason whatsoever in QM that could support the commitment to a primitive thisness (Cao 2003, 62). There are three strong objections against the eliminativist (‘objectless’) understanding of OSR: a metaphysical objection according to which relations require something that stands in the relations, that is relata, although there is no need for the relata to have an intrinsic identity independently of the relations in which they stand (Cao 2003); a logical objection according to which there is no reason to abandon the quantification over objects in standard first order logic and the use of set-theoretical concepts in the formulation of physical theories; and a physical objection according to which there is nothing in QM that suggests abandoning the idea of there being quantum objects, although these are not individuals (Ainsworth 2010, 53).

We take these objections to be well founded. We therefore regard QM as supporting a moderate version of OSR that does not waive the commitment to objects: according to moderate OSR, there are objects that stand in the relations, and the relations—such as the relations of entanglement in the quantum case—are essential properties of the objects (so that in any possible world in which there are quantum objects, these are subject to entanglement). Consequently, the objects do not possess an intrinsic identity independently of the relations in which they stand (Esfeld 2004).

3 The Structural Metaphysics of General Relativity

3.1 The OSR Conception of space–time

At first sight, it seems quite straightforward that GR provides strong reasons for conceiving space–time in terms of OSR. According to OSR, space–time is a physical structure in the sense of a network of physical relations among physical relata (objects) that do not possess an intrinsic identity independently of the relations in which they stand. One of the main arguments in favour of such an OSR metaphysics of space–time is that this position can meaningfully take into account the fundamental GR features of diffeomorphism invariance and background independence (Esfeld and Lam 2008).

According to the OSR understanding, an active diffeomorphism does not amount to representing a physically distinct situation, since space–time points possess neither any qualitative physical properties nor an intrinsic identity grounded in a primitive thisness beyond the fundamental inertio-gravitational and spatio-temporal relations in which they stand. In particular, OSR dissolves the hole argument: within this framework, it is not even possible to formulate this argument in a physically meaningful way, since its very formulation requires to consider space–time points independently of their gravitational and metrical properties. In other terms, the physical equivalence of diffeomorphic GR models, sometimes called Leibniz equivalence, is directly encoded in the OSR interpretation of space–time. In particular, invoking symmetries of the metric (isometries) (Norton 1988) does not challenge this interpretation; in such specific cases, metrical properties do not (absolutely) distinguish space–time points anymore, but this feature, which is common in the quantum domain, is naturally accounted for within the framework of OSR (see Section 4.1).

In an analogous way, localization with respect to space–time points (or regions) conceived in the framework of OSR amounts to a dynamical and background independent localization, since the space–time points are characterized by their dynamical (relational) gravitational and metrical properties (which are related to the distribution of energy–momentum via the Einstein field equations), so that localization is diffeomorphism invariant (in particular, OSR can be understood here as encoding the Bergmann-Komar procedure to construct gauge invariant, i.e. diffeomorphism invariant, observables within

GR, see Sect. 4.1 below). Such a dynamical localization nicely encodes the GR feature of background independence understood in the sense that there is no unique fixed decomposition of the metric into an inertial (non-dynamical) part plus a gravitational (dynamical) part.

This brief account of OSR about space–time shows that OSR can clearly draw on physical support from GR. In particular, OSR brings to the point the way out of the hole argument (Leibniz equivalence) that most of the philosophers and physicists involved in the debate endorse (on the link between OSR and the substantivalist and relationalist positions that endorse Leibniz equivalence, see Rickles and French 2006; see also Section 3.3 below). However, it seems that things get less straightforward once one starts to spell out the OSR conception of space–time in more details. There are two main concerns. The first one revolves around the following question: to what extent do the GR description of space–time (and of the gravitational field) and the above understanding of diffeomorphism invariance (and background independence) really involve a commitment to OSR about space–time? The second one addresses the implications of the OSR metaphysics of space–time for the traditional debate between substantivalism and relationalism. We discuss these issues in turn.

3.2 The Worry from Infinitesimals

The argument for OSR about space–time is usually stated within the standard tensor geometric formulation of GR (Bain 2006 is a notable exception). This formulation represents space–time by a pair (M, g), where M is a 'nice' (connected, Hausdorff, paracompact, without boundary) 4-dimensional smooth differential manifold and g is a Lorentz metric tensor field on M satisfying the Einstein field equations. More precisely, space–time is represented by an equivalence class of diffeomorphic pairs (M, g). This precision is important, because it explicitly encodes the gauge-theoretic diffeomorphism invariance of the theory. The metric field and functionals of the metric such as the Riemann curvature tensor field, involving first and second derivatives of the metric, ascribe to every point p of M all the fundamental spatio-temporal, chrono-geometrical and inertio-gravitational properties (described by the corresponding tensors at each point): they provide for the fundamental spatio-temporal distinction between spacelike and non-spacelike (timelike or null) directions and thus define locally the lightcone structure. Most importantly, these properties fix the (infinitesimal) length of space–time curves (infinitesimal spatial distance and proper time, thereby determining the behaviour of 'rods and clocks'), the inertial trajectories of freely falling test particles (the geodesics of the space–time structure) as well as the gravitational tidal effects (which are determined by the Riemann tensor through the geodesic deviation equation). These properties highlight the fundamental GR fact that space–time geometry and gravitational effects are aspects of the same physical structure, which is given by the metric field.

From this geometrical point of view, it seems that properties defined at space–time points (described by the metric tensor and its functionals) encode all fundamental spatio-temporal and gravitational features. For instance, the proper time elapsing between two events in space–time or two space–time points along some smooth timelike curve supervenes on the metric tensors defined at each point along the curve segment. However, the metric tensor at a space–time point cannot strictly speaking be understood as an intrinsic property, since it involves infinitesimally neighbouring space–time points through the notion of tangent space on which it is defined. Strictly speaking, the metric tensor should be conceived as an extrinsic or relational but local property, whereby "local" is understood in the following sense: "[…] a mathematical object (structure) is local if it is associated with a point by being determined (defined) by the mathematical structures defined on *any* neighbourhood, no matter how small, of the point" (Butterfield 2006, 187).

Nonetheless, it seems that this geometric formulation of GR does not support the above presented intuitive OSR metaphysics of space–time. Some authors (e.g. Bartels 2010a, b, 2011) explicitly suggest that the local character of the metric tensorial properties provides a good reason for understanding them as genuine intrinsic properties—in the sense that they do not depend on what happens (e.g. on the metrical properties) at distant space–time points beyond some infinitesimal neighbourhood. In brief, the standard tensor geometric formulation of GR seems to ground a conception of space–time as a set of points instantiating quasi-intrinsic properties in the sense of local properties, being intrinsic to some infinitesimal neighbourhood of any space–time point. Such a conception seems to trivialize OSR about space–time: the fundamental space–time properties would be relational only in an infinitesimal sense so that the fundamental relations are only infinitesimal relations.

There are several interrelated fundamental physical reasons to resist the conclusion that OSR is not the appropriate metaphysics of space–time as represented in GR. First and perhaps most importantly, the metric tensor is a mathematical object (a symmetric non-degenerate bilinear form on the tangent space of the considered space–time point) whose physical significance concerns fundamentally space–time intervals or spatio-temporal (squared) distance relations (besides gravitational effects), encoding the local space–time geometry. In general, the distance between any two points is obviously path-dependent, so that within the framework of differential geometry the metric tensor at some point strictly speaking describes infinitesimal intervals between that point and infinitesimally neighbouring points. However, this mathematical representation in terms of infinitesimals (and tensors) should not be taken to conceal the fundamental physical significance of the metric within GR (besides gravitational effects), namely that the metric (tensor) is primarily about spatio-temporal distance and thus relations. Indeed, the physics of GR is about space–time and gravitational relations; the relationship between these two aspects can of course be further investigated (see below), but what is important here is that these physical relations are fundamental. As a consequence, the conception of space–time as a mosaic of points instantiating intrinsic metrical properties is misleading; in brief, what mathematically could be (wrongly) understood as such a mosaic—namely metric tensors defined at space–time points—actually represents a physical network of space–time relations.

Further evidence for the OSR metaphysics of space–time as represented in GR can be gained from the physical understanding of the Riemann tensor and related tidal effects via the geodesic deviation equation. From this perspective, the Riemann tensor at a space–time point characterizes the relative acceleration of infinitesimally nearby geodesics, that is, the change in the infinitesimal separation between the geodesics. For instance, it encodes whether two such initially parallel geodesics converge or whether they diverge. In other terms, the Riemann tensor, which can be understood as a functional of the metric (involving first and second derivatives of the metric), is also clearly about (changes in the) relations between the fundamental space–time curves that are the geodesics.

The claim that GR is fundamentally about (possibly infinitesimal) space–time relations—by contrast to being about a distribution of intrinsic metrical properties over space–time points—can moreover be supported by considering the conformal and projective structures. The set of physical curves describing the behaviour of point particles (freely falling or not) and light rays—defining the conformal and projective structures—completely determines the metric (up to a constant factor). This result is at the heart of the constructive approach to GR (see Ehlers 1973; more recently see Malament 2006, Sect. 2.1). From this point of view, GR is fundamentally about these physical space–time trajectories, and the metric tensor field is a derived notion. The direct physical (and experimental) meaning of this constructive approach notwithstanding, the question here is not to replace the standard metric formulation with another formulation. The point is that this alternative formulation of GR highlights the fact that the physical content of the theory is fundamentally and irreducibly about space–time trajectories, curves and relations and so genuinely constitutes a case for OSR. Of course, as discussed above, OSR not only maintains that GR is about space–time relations rather than intrinsic metrical properties, but also that the relata of these relations do not possess an intrinsic identity independently of the relations in which they stand; again, such a view is vindicated by the fundamental features of gauge-theoretic diffeomorphism invariance and background independence.

Andreas Bartels (2010a, b, 2011) insists on the conceptual distinction between the metric on the one hand and the affine connection on the other hand. While it is clear that the affine connection is a distinct concept and can be defined independently of the metric (indeed, the Palatini or first-order formulation of GR considers the metric and connection as independent variables), the metric determines a unique (so-called compatible) symmetric (or torsion-free) affine connection within the standard formulation of GR. Moreover, considering the connection as an independent entity does not affect the central claim here, since both the metric and the connection describe space–time and gravitational relations; indeed, as we have just seen, the conformal and projective structures can be considered as primitive, without altering the interpretation of space–time.

In sum, our claim is this one: the standard geometrical formulation of GR in terms of a field g defined over a set of points M can be ontologically misleading. The divide between M and g is a representational by contrast to an ontological one (otherwise, one runs into the hole-type problems). M and g separately do not represent distinct ontological entities. They together represent space–time and the gravitational field as a network of physical relations. Within this geometrical formulation, it makes no physical sense to ontologically consider either M in isolation (again, because of the diffeomorphism invariance and background independence of the theory) or g in isolation (in the sense that g is about physical relations without physical relata). Ontologically speaking, there are metrical relations between space–time points, and that is all. That is why GR supports an OSR metaphysics of space–time.

3.3 The Nature of Space–Time

It is evident that some traditional aspects of the debate between substantivalism and relationalism about space–time become irrelevant within GR, such as, for instance, the container/content distinction (see Rynasiewicz 1996). Other aspects seem to have been always ill-defined and are best put aside, such as, for instance, the question of whether and in what precise sense space–time is a substance (see Dorato 2008). Nonetheless, we take the central questions of the traditional debate about the nature of space–time to concern the relationship between space–time on the one hand and matter on the other hand. In particular, the question is whether or not space–time points (or regions) exist (in other terms, whether there are fundamental physical relata out there that can be interpreted as spatio-temporal rather than material in some genuine and not purely verbal sense). These questions remain meaningful within GR. In other words, the issue of the relationship between space–time and matter remains a genuine one even if GR teaches us that there is no sharp distinction between space–time and matter (against Rynasiewicz 1996).

The crucial point of GR in this context is the dual nature of the metric field. It encodes both the fundamental spatio-temporal and gravitational relations, thus including characteristic aspects of both sides of the alleged divide between space–time and matter: on the one hand, the metric field provides for the distinction between space and time, between past and future and thus for the very notion of spatio-temporal distance—length and duration; in other words, it yields the geometry of space–time (and as such it cannot vanish anywhere) as well as the causal constraints that all physical interactions have to satisfy. On the other hand, the metric field is identical with the gravitational field, it satisfies non-trivial dynamical equations and carries energy and momentum (although gravitational energy and momentum are tricky notions that are in general not well-defined within GR, so that any argument built on these notions should be considered cautiously, see Hoefer 2000 and Lam 2011b). But we do not think that this fundamental GR feature of the metric field entails that the question about the relationship between space–time and matter is not genuine anymore within GR. The question now concerns the relationship between the metric field on the one hand and the fields of non-gravitational energy-matter on the other. In particular, the question is whether the metric field has a specific ontological status, being an entity *sui generis* that is qualitatively distinct from the fields of non-gravitational energy-matter (possessing a specific spatio-temporal nature), or whether it is just a material field, carrying energy and momentum like the other material fields.

By way of consequence, we do not think that OSR about space–time is a *tertium quid* beyond substantivalism and relationalism (against Dorato 2000, 2008). The brief presentation of the OSR conception of space–time above rather suggests that OSR constitutes a substantivalist claim about space–time in the straightforward sense that it holds that space–time exists, namely as a physical structure. In particular, in the above presentation, we have quantified over space–time points and we have taken space–time points to be the objects that stand in the relations in question, namely metrical relations. We are thus committed to acknowledging the existence of space–time points. In particular, in regarding the metrical relations as the essential properties of space–time points (in any possible world in which there are space–time points, they stand in metrical relations), OSR about space–time thus conceived is a version of what is known as metrical essentialism (contrary to Maudlin 1988, we of course endorse Leibniz equivalence, see Bartels 1996): it is committed to space–time points, it takes the metrical properties to be the essential properties of space–time points, and it turns metrical essentialism into an OSR about space–time by laying stress on the fact that the metrical properties as conceived in GR are relations rather than (quasi-)intrinsic properties.

There are good reasons for metrical essentialism: this position avoids the hole argument by taking the metrical field properties to be the essential properties of space–time points (in contrast to manifold substantivalism), and it pays heed to the fact that the field equations of GR admit vacuum solutions, in which there is the metrical field, but no fields of non-gravitational energy-matter. By contrast, the field equations do not admit solutions in which the metrical field as represented by the metric tensor g vanishes, whereas the fields of non-gravitational energy-matter as represented by the energy–stress tensor T remain intact. The vacuum solutions are a weighty argument in favour of upholding a version of substantivalism within GR. The hole argument then teaches us that this version of substantivalism has to be metrical essentialism, and OSR highlights that the metrical field properties are relations rather than (quasi-)intrinsic properties.

Nonetheless, OSR about space–time is not committed to regarding space–time points (or regions) as the objects that stand in the metrical relations. Again, the central issue here is the understanding of the metric field. New arguments on this issue might come from a more fundamental theory of the metric (gravitational) field, e.g. one which would reveal quantum aspects of it, and such new arguments might outweigh the argument from the vacuum solutions in favour of upholding a version of space–time substantivalism in GR. For instance, at some deeper level, novel (quantum) features of the metric (gravitational) field might reveal a nature of this field that is fundamentally similar to other known fundamental physical (quantum) fields—or, on the contrary, highlight its profound difference and peculiarity. Such empirical facts would provide for new arguments in the debate about the nature of space–time. For instance, within the canonical quantization programme of loop quantum gravity, Rovelli explicitly argues against space–time being a distinct physical entity, maintaining that, at the fundamental level described by the theory, “most of the ‘spatial’ and ‘temporal’ features of the gravitational field are probably lost” (2007, 1307). The quantum features of the metric-gravitational field (prominently entanglement among quantum states of the 3-gravitational field) would then constitute a case for OSR as applied to the quantum domain (see Section 2).

The issue of OSR about space–time and the gravitational field thus is distinct from the question of the relationship between space–time and matter. Both a substantivalist and a relationalist answer to this question can be an OSR about space–time. OSR hence is neutral with respect to the controversy between substantivalism and relationalism. OSR argues that the metrical-gravitational field has to be understood in the light of the fundamental GR features of gauge-theoretic diffeomorphism invariance and background independence as a physical structure without the relata possessing an intrinsic identity independently of the relations in which they stand. This claim can then be spelled out in terms of the relata being space–time points and the metrical-gravitational relations thus being fundamentally distinct from the relations constituting fields of non-gravitational energy-matter (quantum fields). But this claim can also be spelled out in terms of the relata being some fundamental material (quantum) objects and the metrical-gravitational relations consequently being ontologically on a par with the other material field relations (having lost their spatio-temporal features, as Rovelli puts it).

4 Quantum OSR and Space–Time OSR

4.1 Weak Discernibility

OSR is a metaphysics for fundamental physics that is opposed to atomism in the philosophy of nature. In this context, OSR can in the first place be understood as a claim about the nature of the fundamental physical objects of the theory under consideration, namely that these objects do not have an intrinsic identity (constituted by intrinsic properties or a primitive thisness). Fundamental entangled quantum (field) particles (systems) do not possess any qualitative intrinsic identity independently of the physical relations of quantum entanglement in which they stand. In an analogous way, space–time points (or regions) within GR do not possess any intrinsic identity independently of the physical spatio-temporal, namely metrical-gravitational relations, in which they stand. In both cases, the theory recognizes fundamental physical objects, but intrinsic properties (if they exist at all) do not provide identity conditions for these objects.

There is a close similarity between the quantum case and the space–time case in this respect, supporting our claim that OSR is a substantial metaphysical position that covers both quantum physics and space–time physics: in both cases, there is the possibility of two (or more) fundamental physical objects having all the same intrinsic properties and standing in the same symmetric, but irreflexive relations. Such objects are said to be weakly discernible (but absolutely and relatively indiscernible). Because of their quantum statistical features, which can be encoded in the symmetrization postulate, elementary quantum particles of the same kind are absolutely as well as relatively indiscernible. However, all fermionic cases as well as some bosonic cases exhibit anti-correlations, which can be considered as irreflexive and symmetric physically meaningful relations, so that the considered objects are weakly discernible (Muller and Saunders 2008). Even in the case of bosons in a symmetric product state, it can be argued that the canonical commutation relation constitutes a weakly discerning relation, expressing the physically meaningful fact that momentum and position are differently related in the single and multiple particles cases (Muller and Seevinck 2009). Similarly, quantum entanglement relations in general can be easily understood as weakly discernible physically meaningful relations, since nothing can be entangled with itself, so that entangled quantum (field) particles (systems) are always weakly discernible.

It should, however, be noted that the expression "weak discernibility" is misleading: what is known as weak discernibility of two objects is compatible with the two objects having all the same intrinsic properties and standing in the same relations, so that they cannot be distinguished. In other words, if the relations in which two objects stand only weakly discern them, the relations do not provide for identity conditions either. Weak discernibility merely means that there is a symmetric, but irreflexive relation between the two objects. Nonetheless, the fact that the relation is irreflexive makes clear that there are two objects and not just one object, since nothing can stand in an irreflexive relation to itself. Consequently, weak discernibility tells us how many objects there are in the domain under consideration and thus gives us an epistemic, empirical access to these objects, but it does not distinguish these objects from each other (see Ladyman and Bigaj 2010, 130, as well as Esfeld and Lam 2011, section 8.2).

In a manner that is analogous to the quantum case, space–time points within GR are always at least weakly discernible. In fact, in a completely general space–time (in a generic solution of the Einstein field equations), space–time points can be absolutely discerned by the metric and functionals of it (involving the first and second derivative of the metric). For instance, one can label (in a coordinate-free way) space–time points using four functions of the four functionally independent eigenvalues of the Weyl curvature tensor—the traceless part of the Riemann curvature tensor (Bergman and Komar 1960). In general space–times (without specific symmetries) such labelling provides physically meaningful identity conditions for space–time points, which makes it possible to discern them absolutely; according to the structural understanding of the metric and of its functionals (such as the Riemann and Weyl curvature tensors) advocated in the preceding section, the space–time points are then absolutely discernible in virtue of the space–time relations in which they stand. Hence, relations or relational properties can absolutely discern objects (space–time points in a generic GR space–time are a good physical example; very clear examples, although less physical, can be given using graphs—see Ladyman 2007). Accordingly, absolute discernibility does not imply intrinsic identity.

The Bergman and Komar labelling of space–time points degenerates in the presence of specific symmetries, such as the (spatial) homogeneity and isotropy assumptions of the standard model of contemporary cosmology (the Friedman–Lemaître–Robertson–Walker solutions). Such symmetric space–times form, however, a set of measure null within the set of the solutions of the Einstein field equations. In these very specific cases, the relational metrical properties fail to absolutely discern space–time points. Although such absolute indiscernibility of space–time points has been claimed to be problematic for OSR about space–time (Wüthrich 2009), it should be clear that OSR is not committed to absolutely or relatively discernible objects. Although the pseudo-Riemannian or Lorentzian structure of space–time requires some extra care (the pseudo-Riemannian distance relation need not be positive between any two distinct space–time points), any two space–time points are always at least weakly discernible (Muller 2011): for instance, the open geodesic connecting two space–time points always weakly discerns them. In such cases, from the point of view of the identity of the objects involved, the situation is completely similar to the case of entangled quantum particles, and the OSR account is similar in both cases: there are objects, they do not have an intrinsic identity, but they are at least weakly discernible due to some meaningful physical relations that are symmetric and irreflexive.

4.2 Relations as Modes of Objects

As mentioned in Sect. 2 above, there are strong objections from metaphysics, logic and science against waiving the commitment to objects in conceiving OSR. The fact that quantum objects as well as space–time points are weakly discernible does not alter that assessment. Weak discernibility establishes that there is a numerical plurality of objects, but it does not yield a distinction among quantum objects of the same kind in entangled states or space–time points in symmetric solutions of the field equations. Such objects have all the same qualitative intrinsic properties and stand in the same qualitative relations. They are hence not individuals, since they do not enjoy an identity in the sense of there being something that distinguishes each object from all the other ones of the same kind. Nonetheless, albeit non-individuals, these are objects, having properties and standing in relations. The facts remain that the relations in question require relata, weak discernibility yielding a numerical plurality of relata, that in the formulation of the theories in question, one quantifies over objects and that these theories admit a numerical plurality of objects, as is evident from their being weakly discernible.

In particular, weak discernibility does nothing to establish that objects can be derived from relations as nodes within networks of relations. It yields a numerical plurality of objects, but in no way shows how relations could form or constitute objects. By way of consequence, weak discernibility does not help to make the version of OSR intelligible according to which relations are ontologically prior to objects. Nonetheless, if one defends such a version of OSR (Ladyman et al. 2007, chapters 2–4) or even an eliminativist version of OSR according to which there are no objects at all (French 2010), QM, including QFT, and GR are on a par: they again lend support to an OSR in the same sense, since in both cases, one cannot rely on objects with an intrinsic identity.

However, it is in general misleading to set out the opposition between traditional metaphysics and OSR in terms of traditional metaphysics being committed to an ontological priority of objects over relations, whereas OSR is committed to an ontological priority of relations over objects. Conceiving OSR in that manner immediately provokes the mentioned metaphysical intelligibility objection of relations requiring relata as well as the mentioned logical and empirical objections. Conceiving OSR in that manner therefore draws the attention away from the well founded empirical support that OSR enjoys by dragging this position in a metaphysical and logical impasse.

We have argued elsewhere that the mistake that leads to this dead end lies in the presupposition of there being an ontological distinction between objects on the one hand and properties, including relations, on the other (Esfeld and Lam 2011). Our claim is that there is no *ontological* distinction between objects and properties, including relations, and thus no relationship of *ontological* dependence between objects and properties, including relations, so that the question of an ontological priority of the one over the other does not arise. The distinction is only a *conceptual* one, anchored in our thinking and language, and concerning our representation of reality, but not reality itself. In our representation of reality, we predicate properties, including relations, of objects, and we quantify over objects. However, as the hole argument in GR shows, it would be a mistake to conclude from this manner of representation that there are space–time points out there in the world as entities that are ontologically distinct from the metrical field properties. By the same token, it would be a mistake to conclude that there are quantum objects out there in the world as entities that are ontologically distinct from the state-dependent properties to which entanglement applies. However, as the above mentioned arguments from metaphysics, logic and science show, it would also be a mistake to abandon the commitment to objects or to take objects to be somehow derived from relations. The appropriate conclusion rather is to waive the presupposition of there being an ontological distinction between objects and properties, including relations. Properties, including relations, are the ways (modes) in which the objects are. There is no ontological distinction between objects and their ways of being, but only a conceptual one.

The view of properties being the concrete, particular ways (modes) in which objects are can be traced back to Spinoza's *Ethics*. In contemporary metaphysics, versions of such a view are set out by Heil (2003, chapter 13) and Galen Strawson (2008) among others. Whereas in pure metaphysics, it is usually taken for granted that the properties are intrinsic ones, this view can be applied to relations as well: relations can be, like intrinsic properties, the ways in which objects are. The metaphysical truth of the relations requiring objects as that what stands in the relations hence means that certain relations are the ways of being of the objects in question, these objects being tied together by certain relations and thus not possessing an identity independently of the relations. Consequently, a structure consists in objects whose essential ways of being are or at least include certain relations that they bear to each other. The objects hence do not exist apart from the structure they are part of. Qua ways in which the objects are, the structures are networks of concrete physical relations, by contrast to abstract second order structures defined on objects and their intrinsic properties (see Esfeld and Sachse 2010, chapter 2, in particular 2.5, for an elaboration of this view in the context of the metaphysics of properties).

From this point of view, the nature of the fundamental objects in the quantum case and in the space–time case again is similar so that both these cases give rise to an OSR in the same substantial sense. Relations of entanglement are the ways in which quantum objects are, metrical relations are the ways in which space–time points are. In the quantum case, certain state-independent properties such as rest mass and the various quantum charges are usually considered to be intrinsic (even if certain OSR proponents would deny that). However, this only means that certain ways in which fundamental quantum objects are consist of intrinsic properties; to the extent that there are always other essential ways (state-dependent properties) in which fundamental quantum objects exist that consist of relations, e.g. entanglement relations, there is no clash with OSR. In other words, there is no need for OSR to be opposed to recognizing intrinsic properties, as long as these do not give rise to an intrinsic identity of the objects among whose ways of being they count.

In the case of space–time points as treated in GR, their ways of being are exhausted by the metrical relations that tie them together in constituting a space–time. In this sense, as mentioned above at the end of Section 3.1, the standard geometrical representation of a field g quantifying over a set of points M is ontologically misleading and the divide between M and g is only representational rather than ontological.

4.3 Classical Versus Quantum Relations

Up to now, we have pointed out the similarities between OSR in the quantum case and OSR about space–time. Nonetheless, the qualitative nature of the physical relations in the quantum case and in the space–time case based on GR is of course fundamentally different. GR is a classical physical theory, whereas QM and QFT depart from the entire body of classical physics through the superposition, including the entanglement principle. Consequently, there is nothing like superpositions of correlations (entanglement) in OSR about (classical) space–time, and there is for this reason no question of non-separability for space–time points as treated in OSR (if, in a future theory of quantum gravity, space–time points or regions are treated as quantum objects, this assessment will of course change). Bartels' motivation for the interpretation of metrical properties as intrinsic properties is precisely to encode this distinction between the classical and the quantum cases (see Section 3.2). Besides the fact that the natural physical understanding of metrical properties is in terms of space–time (gravitational) relations rather than intrinsic properties, this motivation is ill-founded: the core of the OSR interpretation of physical structures—that the relata do not possess any intrinsic identity—straightforwardly allows to account for the distinction between quantum structures encoding non-separability and classical separable structures. No problem for OSR being a substantial metaphysical position for both quantum objects and space–time points arises from the mere fact that the concrete qualitative relations are physically different in both these cases.

The worry that one may have arises rather from the following fact: GR is a local theory. The relations that the metric tensor encodes concern the infinitesimal neighbourhood of any given space–time point. QM and QFT, by contrast, are non-local theories in the sense that the relations of entanglement are independent of the spatio-temporal distance of the related quantum objects (even in algebraic QFT, claimed to be a local theory by Haag (1992), there are of course relations of entanglement between operators at spacelike separated points or regions). All the experimental confirmations of quantum entanglement, violating Bell's theorem, exploit relations of entanglement between two or more objects or events that are separated by a spacelike interval. One can take this fact to be simply a consequence of quantum theory being a theory of matter and not a theory of space–time, revealing a type of fundamental relations that bind material objects together and that were ignored in classical physics. In other words, without intending to play down the importance of the non-local correlations in QM and QFT versus GR being a local theory, we submit that in both cases—QM and QFT as our currently best theories about matter, GR as our currently best theory about space–time—it is an important common point of both theories that they both admit objects—quantum objects, space–time points—that do not have an intrinsic identity, but are instead characterized by certain networks of relations that hold between them.

In conclusion, we contend that OSR is an appropriate and substantial metaphysics that covers both matter as treated in QM and QFT and space–time as treated in GR, showing that in both these cases relations are central, essential ways of being of the objects in question, these objects therefore lacking an intrinsic identity—although the qualitative, physical nature of the relations in both cases is of course fundamentally different, quantum physics departing from classical physics in a groundbreaking manner. Whatever directions a future theory of quantum gravity may take, we are confident that the features that support the outlined OSR metaphysics will be reinforced rather than weakened.

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