

Structures as the objects of fundamental physics

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Abstract

The paper argues that there are structures rather than objects with an intrinsic identity in the domain of fundamental physics. We line out the standard metaphysics of objects with an intrinsic identity, recall the main objection against that position (section 1) and then retrace the development to epistemic structural realism (section 2) and to ontic structural realism (section 3). We elaborate on the arguments for ontic structural realism from quantum physics (section 4) and from space-time physics (section 5). Finally, we claim that the main objection against the standard metaphysics of objects with an intrinsic identity is countered by structural realism only if the fundamental physical structures are conceived as causal structures (section 6).

1. *The standard position*

Mainstream metaphysics takes for granted that in the domain of fundamental physics, there are objects that possess an intrinsic identity, being characterized by intrinsic properties. Consider what David Lewis says about the objects of fundamental physics in his famous thesis of Humean supervenience:

It is the doctrine that all there is to the world is a vast mosaic of local matters of particular fact, just one little thing and then another. (...) We have geometry: a system of external relations of spatio-temporal distance between points. Maybe points of spacetime itself, maybe point-sized bits of matter or aether or fields, maybe both. And at those points we have local qualities: perfectly natural intrinsic properties which need nothing bigger than a point at which to be instantiated. For short: we have an arrangement of qualities. And that is all. There is no difference without difference in the arrangement of qualities. All else supervenes on that. (Lewis 1986, ix-x)

According to Lewis, thus, the only irreducible relations are the ones of spatio-temporal distance between points. The fundamental physical properties are instantiated at those points. One may think of mass-energy, momentum, charge, spin among others as candidates for fundamental physical properties. It is of no importance for this position whether (a) the space-time points themselves instantiate the fundamental physical properties, or whether (b) there are material objects located at the space-time points that instantiate these properties, or whether (c) there are no space-time points at all, the spatial-temporal relations being relations among material point particles that instantiate the fundamental physical properties.

What is crucial for this position is that the fundamental physical properties are intrinsic properties. According to the standard view developed by Lewis himself, intrinsic are all and only those properties that an object possesses irrespective of whether or not there are other contingent objects; in brief, having or lacking an intrinsic property is independent of

accompaniment or loneliness (see Langton & Lewis 1998 and Hoffmann 2008, part 1, for a detailed discussion of intrinsic properties). All other properties are extrinsic or relational, consisting in the object bearing certain relations to other objects. The view hence is that the world is the distribution of fundamental physical intrinsic properties at points that are connected by spatio-temporal relations. The world hence consists of atoms in a philosophical sense, namely a plurality of objects that are characterized by certain intrinsic properties each and that are linked only by spatio-temporal relations.

There is an obvious problem for this position that is acknowledged by Lewis (2001) himself: if the fundamental physical properties are intrinsic ones, how can we get knowledge of them? Frank Jackson brings out this problem in the following passage:

When physicists tell us about the properties they take to be fundamental, they tell us what these properties *do*. This is no accident. We know about what things are like essentially through the way they impinge on us and our measuring instruments. It does not follow from this that the fundamental properties of current physics, or of ‘completed’ physics, are causal cum relational ones. It may be that our terms for the fundamental properties pick out the properties they do via the causal relations the properties enter into, but that at least some of the properties so picked out are intrinsic. They have, as we might put it, relational names but intrinsic essences. However, it does suggest the possibility that (i) there are two quite different intrinsic properties, *P* and *P**, which are exactly alike in the causal relations they enter into, (ii) sometimes one is possessed and sometimes the other, and (iii) we mistakenly think that there is just one property because the difference does not make a difference (as the point is put in information theory). An obvious extension of this possibility leads to the uncomfortable idea that we may know next to nothing about the intrinsic nature of the world. We know only its causal cum relational nature. (Jackson 1998, 23-24; see also Blackburn 1990)

The core of this argument can be reconstructed as follows: (1) We gain empirical knowledge owing to the causal relations that obtain between physical objects and our senses. (2) Knowledge thus gained may refer to intrinsic properties of physical objects. (3) But the way in which that knowledge is caused imposes a constraint on its content: physical properties can be identified only through the relations in which they enter. If we explain the meaning of the propositions that refer to the fundamental physical properties, it turns out that these propositions describe these properties as relational. (4) Identity of relations, however, does not imply identity of intrinsic properties. (5) We therefore do not know the properties of physical objects insofar as they are intrinsic.

The argument is not that since we gain knowledge through the way in which physical objects impinge on our senses, we know only the way in which they are related to us. The argument is one about the content of empirical predicates, namely that they reveal only relations among objects. The argument applies to all relations; the relations in which physical objects stand to us do not have any special status as far as the content of empirical knowledge is concerned. The laws of physics, in short, describe relations among physical objects, and only relations, but without relations of measurement having a special status.

If it is true that our basic physical theories give us knowledge only of the relations in which physical objects stand and if those relations do not reveal the intrinsic properties, the metaphysics of intrinsic properties is committed to two uncomfortable consequences: the properties possess a primitive qualitative character, and we cannot know that qualitative character, but only the causal and nomological relations in which the properties stand. These

consequences are known as quidditism and as humility. Lewis (2001) endorses both these consequences. However, these consequences amount to a gap between metaphysics and epistemology: metaphysics has it that the world consists of objects that are characterized by intrinsic properties each. On epistemological reflection, however, we have to concede that we do not have access to these properties insofar as they are intrinsic qualities.

2. *Epistemic structural realism*

These consequences of the metaphysics of intrinsic properties constitute a purely philosophical motivation to go for structural realism. One can reformulate the problem that Jackson among others raises in such a way that its conclusion is a position known as *epistemic structural realism*, namely the view that *structure in the sense of relations among physical objects is all that we can know*. Epistemic structural realism in the current discussion goes back to a paper that John Worrall published in 1989 (see in particular pp. 117-123).

Worrall's aim is to employ epistemic structural realism as an argument to establish a mitigated version of scientific realism. He sets out to pay heed to both the argument from pessimistic induction – that is, the claim that since most of our past scientific theories have turned out to be false, it is likely that our present and future scientific theories will endure the same fate – and the no miracle argument, that is, the claim that the predictive success of our scientific theories would be a miracle if they were not tracking truth. Worrall's middle way consists in three theses:

- 1) Structure in the sense of relations among physical objects and as captured by the mathematical equations of a scientific theory is all that we can know.
- 2) There is continuity in our views about structure despite theory change: the views about structure of a predecessor theory can be construed as an approximation of the views about structure of the successor theory.
- 3) We cannot know the intrinsic properties of the physical objects that underlie structure.

Thus, in a nutshell, the no miracle argument applies to structure, and the argument from pessimistic induction applies to our – futile – attempts to gain knowledge of intrinsic properties.

Worrall's first claim is supported by the argument introduced above by means of the quotation from Jackson. If, however, this argument is sound, then it is evident that there is a tension between Worrall's first and his second claim. According to this argument, structure in the sense of relations is all that our scientific theories describe. Thus, it is not possible to draw a line within a scientific theory between what is the description of structure and what is a purported description of intrinsic properties. Hence, if there is a theory change, there is a change in our views about structure. But in that case, all the well-known arguments from the history of science against cumulative progress on the conceptual level – including the argument from pessimistic induction – apply to our views about structure as well. Consequently, structural realism as such does not rescue scientific realism from the standard objections mounted against this position (see also Psillos 1999, chapter 7).

If epistemic structural realism is separated from the ambition to make a case for scientific realism, its main claims can be put in this way:

- 1) Physical objects have intrinsic properties over and above the relations (structure) in which they stand.
- 2) We cannot know the intrinsic properties, but only the relations.

This position hence maintains that there is something beyond structure that we cannot know. That is why this position can with reason be described as *epistemic* structural realism.

However, if it is claimed that there is something that exists but that we cannot know, we need an argument why we should accept that there is any such thing. The master argument for intrinsic properties can be summed up in this way:

- 1) Relations require relata, that is, objects that stand in the relations.
- 2) These objects have to be something in themselves, that is, they necessarily have some intrinsic properties that constitute their identity over and above the relations that they bear to one another, even if we cannot know these intrinsic properties (see e.g. Langton 1998, chapter 2, in particular p. 22).

But why should one accept the second claim? Far from expressing a metaphysical necessity, there are good physical arguments for holding that this claim is empirically false.

3. *Ontic structural realism*

Steven French and James Ladyman have transformed Worrall's epistemic structural realism into an ontic structural realism, claiming that all there is in the domain of fundamental physics are structures. French and Ladyman, however, goes as far as rejecting both parts of the mentioned master argument for intrinsic properties: according to them, there are structures all the way down, in the sense that all objects ultimately turn out to be dissolved into structures, the structures being self-sufficient, not needing objects that stand in them. If there are objects at all, these are derived from the structures as being nodes of structures, instead of structures presupposing objects (Ladyman 1998, French & Ladyman 2003, French 2006; but see also the more balanced position in Ladyman & Ross 2007, chapters 2 to 5). French and Ladyman thus provoke the objection that the notion of structures without objects is simply not intelligible (e.g. Psillos 2006, 562-566). More precisely, a Platonist may maintain that relations as such exist as abstract structures, that is, abstract entities that are universals. However, when it comes to the physical world, the point at issue are concrete relations that are instantiated in the physical world and that hence are particulars in contrast to universals. For the relations to be instantiated, there has to be something that instantiates them, that is, something that stands in the relations.

In reply to that objection, a more moderate version of ontic structural realism has recently been developed, proposing that physical structures are networks of concrete, qualitative physical relations among objects that are nothing but what stands in these relations, that is, do not possess an intrinsic identity over and above the relations in which they stand (Esfeld 2004, Esfeld & Lam 2008; see also Floridi 2008). This position accepts the first part of the master argument for intrinsic properties; it only rejects its second part:

- 1) Relations require relata, that is, objects that stand in the relations.
- 2) *It is not the case* that these objects necessarily have some intrinsic properties that constitute their identity over and above the relations that they bear to one another.

On this more moderate version, no paradox arises, since objects are admitted as standing in the relations. Consequently, there is no need to change standard first order logic. In the following, we shall base ourselves on this moderate version of ontic structural realism.

According to this position, neither objects nor relations (structure) have an ontological priority with respect to the physical world: it makes no sense to assign an ontological priority to objects, because instead of having fundamental intrinsic properties that constitute their

identity, there are only the relations in which they stand. In other words, an object as such is nothing but that what bears the relations. As regards the relations, it makes no sense to attribute an ontological priority to them, for at least insofar as they exist in the physical world, they exist as relations between objects. We can therefore say that *the relations (structures) are the ways (modes) in which the objects exist*.

However, one may wonder whether relations are capable of individuating objects. If there are objects, do they not require intrinsic properties as identity condition? Recall that, according to ontic structural realism, (1) objects are not atoms that exist independently of each other and that (2) structure always consists in certain specific, concrete relations, these relations being as determinate as intrinsic properties are supposed to be. Consequently, relations are exactly on the same footing as intrinsic properties as far as identity conditions are concerned: insofar as intrinsic properties account for identity conditions, relations can perform that task as well. For instance, if A is bigger than B , heavier than C , etc., these relations individuate A and distinguish A from B and C . It goes without saying that there is in ontic structural realism no question of identity conditions for an object independently of other objects. But this does not mean that relations cannot provide identity conditions. Which relations make up for identity conditions for which types of objects depends obviously on the case under consideration.

Consider an analogy: since Quine's seminal paper on "Two dogmas of empiricism" (1951) and the subsequent development of semantic holism (inferential role semantics), we are familiar with the notion of a web of beliefs. We are used to thinking of beliefs as points in a web that are individuated by their position in the web, that is, their relations to other beliefs. Content (meaning) is not an intrinsic property of a belief, but consists in inferential relations to other beliefs (the same goes for other properties of beliefs such as confirmation or justification). Semantic holism has no problem in individuating beliefs on that basis: each belief is defined by its position in the web, being distinguished from all the other beliefs in the web, for no two beliefs stand in exactly the same relations to all the other beliefs in the web. The problem is that we do not want any old change of relations in the system to amount to a change in the content of *all* the beliefs in the system. Some inferential relations thus have to be distinguished as being more important than others. But this problem does not touch the central issue that it is relations that provide the identity conditions for the members of the system. Ontic structural realism can be received as proposing to transfer this idea from semantics to metaphysics, the objects being now physical entities instead of beliefs. If this idea is intelligible in semantics, then so it is in metaphysics.

Hence, insofar as intrinsic properties can provide identity conditions, so can relations. However, there are cases in physics where neither relations nor intrinsic properties are able to establish identity conditions. Quantum systems of the same kind whose states are entangled are indistinguishable (French & Redhead 1988), although in the common cases considered by quantum mechanics there is a definite number of them that is greater than one. These systems do not have an identity in time. An analogous consideration applies to space-time points on certain symmetric solutions of the Einstein field equations (such as the physically important Friedmann-Lemaître-Robertson-Walker (FLRW) solutions): space-time points can stand in exactly the same spatio-temporal relations and, yet, be of course numerically distinct.

One may receive these cases as speaking against a bundle theory of objects: quantum systems and space-time points can neither be bundles of intrinsic properties nor can they be

bundles of relational properties; for the intrinsic or relational properties may be as concrete as is physically possible and, nevertheless, fail to establish a distinction between quantum systems or space-time points. A bundle theory of objects accords ontological priority to intrinsic properties or relations over objects: objects are constituted by intrinsic properties or relations on that theory. As mentioned above, insofar as the radical ontic structural realism of French and Ladyman admits objects at all, it has to reconstruct them as something like bundles of relations (more precisely, nodes of relations).

The other big position in the metaphysics of objects apart from the bundle theory is the view that objects are bare particulars: each object has a primitive thisness (haecceity). It is that primitive thisness which individuates the object and provides its identity conditions (see Adams 1979). Primitive thisness is not a property. It functions rather like a proper name. If there are one hundred entries under the name “Jones” in a telephone directory, this does not mean that there are one hundred instantiations of the property of being Jones in the space-time region to which the telephone directory applies. However, as far as quantum systems are concerned, one can complain that primitive thisness is a purely metaphysical position for which there cannot be any empirical argument stemming from science (Cao 2003, 62). And as far as space-time points are concerned, there is a strong argument against primitive thisness, namely the hole argument (see section 5 below). The view of each object having a primitive thisness accords ontological priority to objects over intrinsic properties or relations: objects are first constituted by a primitive thisness that provides for their identity and then equipped with intrinsic properties or put into relations (“first” and “then” in a logical sense, not a temporal one). The view of objects being constituted by a primitive thisness contradicts ontic structural realism.

The bundle theory and the view of objects as bare particulars are not the only options in the metaphysics of objects. In the cases where neither intrinsic properties nor relations provide for identity conditions one can simply accept a numerical distinction (diversity) – among quantum systems or space-time points – as primitive (a similar view is held by Pooley 2006, section 4; see also Hoefer 1996, 18-20). A numerical distinction tells us that there is a number of objects that is greater than one – in many cases of quantum entanglement even a definite, finite natural number of objects –, and that is all that it tells us. A numerical distinction is not a primitive thisness, for it does not establish an identity in time – or any other sort of an identity – that is not empirically accessible. Accepting a numerical distinction as primitive is motivated by the physical cases – quantum entanglement, space-time points – in which there is a plurality of objects without these objects being distinguished from one another by any intrinsic properties or relations in which they stand and without primitive thisness being an open way out, since there are strong physical arguments against primitive thisness. This empirical situation – and thus the motivation for acknowledging numerical distinction as a primitive – is independent of structural realism. Any position in the metaphysics of science has to come to terms with this empirical situation. Hence, in short, insofar as there are factors that individuate objects over and above numerical distinction, intrinsic properties and relations are on a par. If there are no such factors, we either have to accept a numerical distinction as primitive or we have to go for primitive thisness. The moderate version of ontic structural realism is committed to the former view.

4. *The argument from quantum physics*

Up to now, we have considered the shift from the metaphysics of intrinsic properties via epistemic structural realism to ontic structural realism on the basis of purely metaphysical and epistemological arguments that are not concerned with the ontological commitments of the current fundamental physical theories. Let us therefore now consider quantum physics as well as the theory of general relativity.

If we try to translate David Lewis' thesis of Humean supervenience quoted at the beginning of this paper into physics, we can make use of the principle of separability. Einstein based his criticism of quantum mechanics on this principle (see Einstein 1948 and Howard 1985). One can characterize separability in the following manner: physical systems have a state each in the sense that (1) this state completely encompasses the state-dependent properties of the system and (2) the joint state of two or more systems supervenes on the states which each of these systems has. Physical systems may be particles, field modes, space-time points, etc. In non-relativistic quantum mechanics, the state of a system at a time can be conceived as containing the complete information about the properties of the system at that time, the properties being limited to those properties whose value can change in time. These are known as state-dependent properties. Properties such as rest mass and charge, by contrast, are state-independent, since their value always remains constant. The principle of separability thus conceives the world as being built up of single systems each of which has a state independently of all the other systems, and the joint state of two or more systems – or, in the last resort, the whole world – supervenes on the states that these systems have independently of each other. In other words, the relations among the systems supervene on the states that the systems have independently of each other; consequently, the state-dependent properties are conceived as intrinsic properties.

Quantum entanglement violates separability. If the states of two or more quantum systems are entangled, only the joint state of the whole system is a pure state. The parts, the single systems whose states are entangled, do not have a state each that completely encompasses their state-dependent properties. Instead of the parts fixing the state of the whole, it is only the joint state of the whole that completely determines the state-dependent properties of the parts in the form of certain correlations among these properties, entanglement signifying that there is a superposition of all the possible correlations. This way of determining the properties of the parts in the form of correlations among them makes it superfluous to call for intrinsic properties underlying the correlations. Claiming that there are intrinsic and thus local properties of the parts that serve as a supervenience base for the correlations would come into conflict with the fact that the correlations of quantum entanglement violate the theorem of Bell (1964) (as regards the philosophical importance of that theorem, see e.g. the papers in Cushing & McMullin 1989). Quantum mechanics hence is not silent on the issue of whether or not there may be intrinsic properties underlying the correlations, but contains a strong argument against any such view.

Quantum non-separability fits well into moderate ontic structural realism as sketched out in the last section (for a detailed argument in this sense, see Esfeld 2004; see furthermore Ladyman 1998 and French & Ladyman 2003). The way in which the joint state of the whole determines the state-dependent properties of the parts in the form of certain correlations confirms the claim of a mutual ontological dependence between objects and relations: the objects (single quantum systems – “particles” in the framework of non-relativistic quantum

mechanics) cannot be presupposed as simply being there and then entering into correlations (for instance, through interaction). Quantum entanglement is generic and fundamental. We cannot but take as fundamental the joint state of the whole, in the last resort the joint state of the whole world. That state is such that it permits and calls for an internal differentiation in the form of correlations and thus correlata – although the correlata are nothing but that what stands in the correlations. We thus get correlations and correlata as internal differentiation of the world, these two being on the same ontological footing. In other words, *the entangled states are the ways (modes) in which the quantum objects exist*.

The interpretation of quantum entanglement in terms of moderate ontic structural realism is independent of the stance that one takes on the measurement problem. If one follows Everett (1957) in holding that the Schrödinger equation is the complete dynamics of quantum systems, there only is quantum entanglement. If one modifies the Schrödinger dynamics – as, for instance, along the lines of the proposal of Ghirardi, Rimini & Weber (1986) – to allow for state reductions and thus processes of the dissolution of quantum entanglement, nonetheless, quantum entanglement is fundamental. To the extent that there are pure states of single quantum systems, they are derived from entanglement.

5. *The argument from general relativity theory*

It may seem trivial that the spatio-temporal relations support ontic structural realism. After all, even David Lewis recognizes the spatio-temporal relations as irreducible relations that hold the world together. However, the situation is not as simple as that first glance may suggest. According to the theory of general relativity, the metrical field includes the gravitational energy so that the space-time relations are gravitational relations. The Einstein field equations admit of so-called empty solutions, that is to say, solutions in which there only is the metric field, without fields of non-gravitational energy-matter being there. Therefore, an empty space-time is physically possible according to the theory of general relativity, that is to say, a space-time that includes only the gravitational energy and no additional material entities. Consequently, space-time points with the metrical relations can be considered as physical entities on their right (Hofer 1996, Bartels 1996). This situation fits indeed well into moderate ontic structural realism, but we need an argument why this is so.

In the standard formulation of general relativity theory, space-time is represented by a four-dimensional smooth differentiable manifold – a set of points with topological and smooth differential properties – together with a Lorentz metric tensor field, or metric for short, defined on it. This latter geometric object encodes the fundamental space-time relations, like the chronogeometrical relations (space-time intervals), the inertio-gravitational relations (describing the behaviour of freely falling test particles in a gravitational field – the metric field and the gravitational field being one and the same field) and the causal relations (defining a light cone at each space-time point and providing a distinction between spatial and temporal directions). One of the major novelties of general relativity theory is that the metric, incorporating the fundamental relations of the space-time structure, is fundamentally dynamical: it is related to the behaviour of the (non-gravitational) energy-matter (“ordinary” energy-matter), represented by the stress-energy tensor field, through the (non-linear) dynamical equations – the Einstein field equations – that it satisfies.

The principle of active general covariance tells us that if we have a space-time model of general relativity theory, that is, a solution of the Einstein field equations, then any active

diffeomorphism applied on this model will generate a space-time model of general relativity theory. An active diffeomorphism is a differentiable, one-to-one and onto mapping (with differentiable inverse) acting on the Lorentz metric and stress-energy tensor fields defined on the manifold. Such diffeomorphic models are observationally indistinguishable. However, if one applies the traditional metaphysics of objects with an intrinsic identity to the space-time points, these diffeomorphic models have to be interpreted as describing distinct physical situations, since any given space-time point (merely represented by a manifold point from this perspective) is individuated by some intrinsic properties or a primitive thisness independently of the space-time relations represented by the metric. It will therefore be “coloured” by different metrical properties in the different diffeomorphic models. For instance, the question whether the metric (or gravitational) field is flat around some specific space-time point may receive different answers in the different diffeomorphic models.

The famous hole argument, originally due to Einstein (Einstein & Grossmann 1913, 260-261), shows that such an attitude towards diffeomorphic models leads to a kind of indeterminism (Earman & Norton 1987): we consider a hole in the space-time manifold, that is, an open subset of the manifold where all non-gravitational fields vanish. We furthermore consider a non-trivial active diffeomorphism on the hole that smoothly reduces to the trivial diffeomorphism, that is, the identity, on the boundary and outside the hole. A complete physical model outside the hole is then insufficient to determine a unique physical solution inside the hole, since, within the metaphysical framework of space-time points as objects that possess an intrinsic identity, diffeomorphic models represent distinct situations. More precisely, considering a space-time manifold that can be foliated, the “hole” can be chosen to be the portion of the manifold after a certain time t in the considered foliation. But then, two physically possible models, which are related by a ‘hole diffeomorphism’ and in which we consider the same foliation, may agree till a time t and then disagree for any time $t' > t$ in the foliation. This constitutes a breakdown of common determinism, and no unique evolution can be determined from a set of initial data (in the initial value formulation of the theory).

Since diffeomorphic models are observationally indistinguishable, it is generally accepted that such indeterminism is not an empirically supported feature of the physical theory, but rather an artefact of the metaphysical conception of space-time that implies the physical non-equivalence of diffeomorphic models. Indeed, a wide range of philosophers of physics and physicists agree on the fact that this non-equivalence and the hole argument itself are a consequence of the non-physical primary individuation of space-time points independently of the metric (see for instance Stachel 1993, Hofer 1996, Dorato 2000, Pooley 2006). In other words, space-time points are not individuals independently of the space-time relations they enter into, which are represented by the metric; they do not possess any primitive thisness (haecceity) or intrinsic properties that would turn them into individuals over and above bearing the space-time relations. Therefore, with respect to space-time, the fundamental principle of active general covariance, which underlies the hole argument, constitutes a strong empirical argument against the traditional atomistic metaphysics of individual objects with an intrinsic identity. On the contrary, the holistic metaphysical framework of moderate ontic structural realism yields a convincing and coherent account of the physical description of space-time provided by general relativity theory: with respect to active general covariance and the representation of space-time in terms of a manifold with a dynamical metric that encodes all the fundamental space-time relations, space-time can be naturally understood as a

relational physical structure, that is, a network of space-time relations among space-time points that do not possess any intrinsic identity.

Moreover, the space-time structure described by the theory of general relativity is such that the space-time relations and the objects that stand in the relations (the space-time points) are on the same fundamental ontological footing. On the one hand and in an analogous way to the general case discussed in section 3, it makes no sense to consider an actual (that is, instantiated in the physical world) space-time relation without relata standing in the relation – space-time points in the pure gravitational cases. On the other hand, the physical description of space-time within the theory of general relativity makes meaningless any individuation of space-time points independently of the space-time relations they enter into or independently of the space-time structure they are part of – both being represented by the dynamical metrical-gravitational field (this fact can indeed be directly interpreted as a consequence of the gauge-theoretic interpretation of general covariance (Earman 2006) and encodes the fundamental general-relativistic notion of background independence, see below). Space-time points do not possess any independent existence, but only exist in virtue of their standing in relation to other space-time points. There is no ontological priority, but rather a mutual ontological dependence between space-time relations and space-time points: *the metrical-gravitational relations are the ways (modes) in which the space-time points exist.*

6. Causal structures

Let us now come back to the considerations introduced in the first section by means of the quotation from Jackson. The argument was that the knowledge we have of the physical world is structural-cum-causal knowledge. If there were intrinsic properties beyond what is revealed by that knowledge, these would be primitive qualities (quiddities) of which we could in principle not gain any knowledge. Epistemic structural realism recognizes that consequence but maintains that nonetheless there are such intrinsic properties, whereas ontic structural realism abandons the commitment to such intrinsic properties. The latter position is supported by the fundamental physical theories: these theories show that if there were intrinsic properties underlying the structures in question, empirical consequences would ensue that do not fit into these theories. If there were intrinsic properties on which the relations of quantum entanglement supervene, Bell's theorem implies that there could not be those correlations that quantum theory predicts. If there were an intrinsic identity of space-time points, the hole argument shows that the determinism that general relativity theory assumes would break down. Nonetheless, up to now, we have only considered structures and not causation.

The structures to which the fundamental physical theories refer cannot stand in a direct causal relation to our cognitive apparatus. They are theoretical entities. The quantum relations of entanglement are not observable. What is observed are certain correlations among measurement outcomes (but no superpositions of such correlations, that is, no entanglement). One recognizes the existence of superpositions and entanglement in order to explain the measurement outcomes and the correlations between them. By the same token, the spatio-temporal, gravitational structures that the theory of general relativity acknowledges and that show that space-time is curved are not observable as such. A local observer cannot determine whether or not space-time is curved. It is only when one takes the various local observations together in order to form a representation of space-time as a whole that one gets to regard space-time as curved. In short, the fundamental physical structures are theoretical entities, and

we recognize them because they explain the observed phenomena. The explanation in question is a causal one: these structures are the causal origin of the observed phenomena.

In order to avoid the conclusion of being committed to the existence of entities that we cannot know, we therefore have to meet the challenge of including an account of causation in – moderate – ontic structural realism. Moreover, Psillos (2006, 567-570) objects that ontic structural realism cannot accommodate causation, and Chakravartty (2007, chapters 3 to 5) maintains that we are committed to underlying causal properties that produce the concrete physical structures to which quantum theory and the theory of general relativity refer. By contrast, our claim is that the fundamental physical structures are causal in themselves (see also French 2006, 181-182, for the possibility of this claim, and Esfeld 2008, chapter 5, for an elaborate argument).

In the philosophy of quantum physics, entangled states are often conceived as being the disposition to develop into product states, that is, states with classical properties, having definite numerical values that are correlated in a specific way. In that manner, taking quantum states to be dispositions is tied to an interpretation of quantum theory that admits state reductions and thus a transition from quantum properties to really existing classical properties (instead of the world merely appearing to be classical to local observers due to decoherence). The most elaborate physical proposal for such a transition is the one going back to Ghirardi, Rimini and Weber (1986) (GRW).

The interpretation of quantum theory by GRW lends itself to an account in terms of dispositions, conceiving the fundamental physical structures as causal powers: insofar as the structures of quantum entanglement are certain qualitative physical structures, they are the disposition or power – more precisely, the propensity – to produce product states, that is, classical physical properties with definite numerical values localized in classical space-time (Dorato 2006, Suárez 2007, 426-433). This disposition is irreducible: it is not grounded on non-dispositional, categorical properties. It belongs to the ontological ground floor. It is a real and actual property, not a mere potentiality. It is therefore appropriate to talk in terms of a power for spontaneous localization. Since entangled states are nonseparable (Howard 1989), it is evident that the disposition for spontaneous localization has to be inherent in the entangled state as a whole: the entangled state as a whole is the disposition or power (propensity) for spontaneous localization.

A quantum ontology in terms of dispositions is usually tied to those interpretations of quantum theory that admit state reductions, GRW being the most elaborate of them. If one does not countenance state reductions, one is committed to taking entanglement to be universal and touching all objects including the macroscopic ones and finally the minds of the observers (Albert & Loewer 1988, Lockwood 1989, chapters 12 and 13). Nevertheless, one has to account for the observed classical properties, including notably the observed measurement outcomes. The most widely accepted solution to that problem consists in saying that entanglement gives rise to a process known as decoherence, and that process accounts for the appearance of a classical physical world to local observers, although entanglement is not reduced. It seems that nothing hinders to conceive the process of decoherence as a causal one such that the structures of entanglement are the power to produce situations (branches of the universe, histories, etc., according to what is one's preferred interpretation within that framework) that appear as classical properties to local observers. Consequently, as in the interpretations with state reductions, one can take the structures of entanglement to be causal

structures, being the power to bring about decoherence and thereby to produce the appearance of a classical world to local observers. If this reasoning proves sound, the ontology of quantum structures as causal powers turns out to be independent of the stance that one takes on the measurement problem.

Whereas it is hence feasible to consider the quantum structures of entanglement as causal structures, the spatio-temporal relations are widely regarded as the paradigmatic example of non-causal relations. However, as mentioned above, the theory of general relativity teaches us that the metrical field includes the gravitational energy. This theory thereby rules out a dualism of space-time being a passive background arena and matter being inserted into such a space-time – the theory is said to be fundamentally background independent. One can regard the metrical field, which includes the gravitational energy, as a physical entity on the same footing as any material entity, and one can take gravitation to be a fundamental physical interaction on a par with the other fundamental physical interactions, such as the electromagnetic interaction for instance. On this view, the spatio-temporal, gravitational structures are material structures like the quantum structures of entanglement (see Rovelli 2004, § 6.7.1 and § 10.1.3) – although the relations of quantum entanglement and the spatio-temporal, gravitational relations are of course different types of concrete, qualitative physical relations. Against this background, it seems possible to take the spatio-temporal, gravitational relations to be a causal structure like any other material entity: the spatio-temporal, gravitational relations are causal powers (dispositions) that bring about gravitational effects that are in principle observable (see Bartels 1996, 37-38, and Bird forthcoming, section 2.3).

It is hence possible to conceive the fundamental physical structures as causal structures. Doing so has a further important advantage: it establishes a clear distinction between mathematical and physical structures. Mathematical structures, whatever they may be, do not cause anything. Real physical structures distinguish themselves from mere mathematical structures in that they are causally efficacious. Consequently, if ontic structural realism conceives the physical structures as causal structures, it avoids the objection of blurring the distinction between the mathematical and the physical at its roots.

As mentioned at the beginning of section 2, however, we lose a direct argument from structural realism for scientific realism on that way from the argument against fundamental, purely qualitative intrinsic properties via epistemic structural realism to ontic structural realism: if our knowledge is limited to structures, our views of structure change in the history of science. Nonetheless, the commitment to causal structures leads to a coherent account of science: the non-physical special sciences – such as biology, psychology and the social sciences – trade mainly in functional properties, that is, properties that are defined notably by the effects they bring about or can bring about. These properties can be reconstructed on the basis of the causal structures of quantum entanglement (via state reductions or via decoherence, as far as the appearance of such properties to local observers is concerned). The argument for moderate ontic structural realism in the form of a commitment to causal structures therefore is in the last resort that this position leads to a complete and coherent view of the world, including all the domains of empirical science, and avoiding a gap between metaphysics and epistemology by not having to postulate that there is something in the world whose qualitative character we can in principle not know. In our view, this is the best argument for scientific realism in the sense of being the best argument for a hypothetical,

realistic attitude towards that ontology of science that leads to a coherent view including all our knowledge.

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