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SUBSTANTIVALISM, RELATIONISM, AND STRUCTURAL SPACETIME REALISM[1]

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1. Manifold substantivalism or metric field substantivalism?

A historian of 20th century philosophy of science that were to consider the recent renaissance of studies on the ontological status of spacetime would certainly notice a significant shift of interest toward metaphysical issues previously scorned by neopositivists philosophers.[2] Some philosophers more inclined toward historical analysis have complained about the audacious tendency of some contemporary philosophers of space and time to portray Newton and Leibniz (see Alexander 1956) as defenders of views that, like substantivalism and relationism, do not always represent in an accurate way the positions really taken by these historical figures (see Stein 1967 and DiSalle 1994). However, worse than such moderate forms of "interpretive violence" perpetrated on 17th century natural philosophers – which in any case are not motivated by unfair attempts to add significance to one's pet philosophical problem by ennobling its historical pedigree – is the fact that the current participants to the debate don't even seem to agree about how to *formulate* "spacetime substantivalism"[3] within the fundamental spacetime theory of contemporary physics, the *general theory of relativity*. For example, it is not clear whether one should identify spacetime with the bare manifold or with the metric field. As is often the case when there is no agreement even about the nature of the problem, there is a natural tendency to affirm that

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[1] I want to thank Robert Rynasiewicz and Robert DiSalle for having read a previous version of this paper and having helped to remove some of my misinterpretations of their views. I am the only responsible for the remaining mistakes.

[2] Such foundational studies were revived in the late eighties by the so-called "hole argument" due to John Earman and John Norton (1987). See Earman (1989), Butterfield (1989), Maudlin (1990), Rynasiewicz (1994), Healey (1995), DiSalle (1995) for discussions of the philosophical and metaphysical issues. The tendency to misrepresent Leibniz and Newton as defenders of relationism and substantivalism respectively was decisively more present in the philosophy of space and time of the first part of the century, and especially in Reichenbach.

[3] Substantivalism is usually presented as the doctrine that space and time (spacetime) exist "over and above" the objects and events of the physical world, while relationism is regarded as a denial of just this thesis: a relationist about spacetime regards physical events and objects as the primary constituents of the world, and space and time as relations instantiated by such entities.

the problem itself is not genuine or is purely verbal, a matter of arbitrary choice between two preferred ways of speaking (Rynasiewicz 1996).

This confusing situation is especially evident in two of the most recent papers on the subject, Rynasiewicz's (1996) and Hoefer's (1998), the former claiming that the dispute between substantivalists and relationists is *outmoded*, as it was a genuine problem only at the time of Descartes, Leibniz and Newton (before the emergence of the so-called "electromagnetic view of nature" in the late 19th century), the latter arguing that the debate "for better or worse still goes on", as it plays an important role even in current attempts at building a quantum theory of gravity. The fact is that while Rynasiewicz presents substantivalism as a doctrine presupposing a clear difference between "matter" and "space", or between "content" and "container", Hoefer proceeds by simply ignoring such a critical point, and by claiming that spacetime substantivalism has to do with the ontological status of the *metric field* in the general theory of relativity, thereby advocating *metric field substantivalism*. To the extent that the metric field, as is well known and universally recognized, *cannot* be identified with "empty" spacetime or with the bare manifold – which is, essentially, a set of points with a topological and a differential structure – in order to answer to Rynasiewicz's challenge one faces the question of showing that the choice of *metric field substantivalism* over *manifold substantivalism* to represent spacetime is not arbitrary.

An argument against the arbitrariness of such a choice had already been given by Earman and Norton, who claimed that *the metric field, qua physical field, cannot be regarded – unlike the manifold, in their opinion – as the "container" of the other physical fields* (1987, 518-19). As a consequence, they defended the view that substantivalists should embrace manifold substantivalism, which they then claim to have rejected *via* the hole argument.[4] Against this view, however, Maudlin correctly points out that a manifold, devoid of a metric (and affine) structure, can be attributed "none of the paradigmatic spatio-temporal properties" (distance, difference between spatial and temporal intervals, light cone structure, etc.) (1988, 87), and cannot be considered to be representing, let alone be *identical* with, *physical spacetime*.

Consequently, I take it that arguing pro or against substantivalism or on the meaningfulness of the related debate really presupposes that we try to establish first which of these two versions of substantivalism is more plausible within the general theory of relativity,[5] by keeping our mind open to the possibility defended by Rynasiewicz that in that theory *neither* version is plausible. Rather than a battle about words, I claim that *this*

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[4] Rynasiewicz (1994) argues that the hole argument does not establish this conclusion, but is just an example of the problem of the indeterminacy of reference.
[5] Maudlin (1988) and Hoefer (1996) have begun to study this problem.

question is just another piece of evidence that *the general theory of relativity is* – like quantum mechanics, though for different reasons – *in need of an interpretation*.[6] Such an interpretive task should not viewed as the addition or juxtaposition of a philosophical/metaphysical view to the physical theory, but as a necessary restructuring of our understanding of the latter in terms of new concepts, always remaining in the safe tradition of plain, old "natural philosophy".

Once we agree on this diagnosis, it will be easier to see why the debate can be solved by advancing a *tertium quid*, or a third option between classical substantivalism and relationism. This option, which I call *structural spacetime realism*, sides with the latter doctrine in defending the *relational* nature of spacetime, but argues with the former that spacetime *exists*, at least in part, *independently* of particular physical objects and events, the degree of "independence" being given by the extent to which *geometrical laws* exist "over and above" physical events exemplifying them. By showing that structural spacetime realism is the natural outcome of a semantic, model-theoretic approach to the nature of scientific theories – an approach to which Marisa Dalla Chiara has given significant contributions during her scientific carrier[7] – in the last part of the paper I will argue that the notion of *partial isomorphic representation* is the most plausible candidate to act as a natural "bridge" between physical models and reality.

2. The metric field as a guide to a "third way" between substantivalism and relationism

It must be recognized that Rynasiewicz is correct in pointing out that, within general relativity, any philosophical view presupposing a clear separation of space and matter – available in various brands of the 17th century "corpuscular" philosophies – would be grossly misleading. But then it could be replied that a charitable reading of the *current* debate between substantivalists and relationists should *not* be construed as presupposing a distinction between empty space-time and a matter-filled universe *à la* Descartes, precisely because such a distinction in the general theory of relativity is *not* available. Are we thereby changing the subject to which early modern "natural philosophers" dedicated so much efforts? Perhaps, but what matters is whether the reformulated problem is genuine, fruitful, and similar enough to the original one to be worth calling it by the same name.

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[6] For quite different reasons, having to do with the quantum theory of gravity, this thesis has been advocated by Belot (1996).

[7] See, for instance, her seminal paper with Toraldo (1973).

To the extent that spacetime substantivalism implies, as Rynasiewicz correctly has it, the issue of the *independent* existence of space and time, the fact that the main *spatiotemporal* properties in the general theory of relativity (except perhaps the topological relation of "betweeness") are provided by the *metric field* cannot be disregarded as ininfluential to the nature of the debate. However, Rynasiewicz mentions the status of the metric field only in a footnote (1996, 301, fn 45), where he contrasts Earman and Norton's filing the metric tensor in the folder labeled "physical contents of spacetime" (1987, 519) with Friedman's remark that the criterion of being unoccupied for spacetime points can only be yielded by the vanishing of the *stress-energy tensor*, and not by any features of the *metric tensor* (1983, 221-2). Here, I take Rynasiewicz to be suggesting that the metric tensor can count neither as "matter" nor as "space", if these terms are now given the meaning they had in the 17^{th} century. Once we agree with this remark, it is still not clear to me why it implies, as Rynasiewicz has it, that the dispute about the ontological status of spacetime after 1916 has become merely verbal.

Suppose that, following Einstein, we agree, as I claim we should, that "there can be no space nor any part of space without gravitational potentials [that is, without the metric/gravitational field]; for these confer upon space its metrical qualities, without which it cannot be imagined at all" (Einstein 1923, 21, my addition in square brackets). Then we should simply *reject* those views advocating that substantivalism is committed to the independent existence of the bare manifold *without the metric field*, or to the existence of unoccupied spacetime points endowed with primitive identity (Field 1980, Mundy 1983, Friedman 1983). In view of well-known difficulties raised by the identification of spacetime points independently of a prior assignment of a metric to the manifold (Stachel 1993), it has been plausibly argued that manifold substantivalism cannot be the correct option, so that the substantivalism/relationism dispute must involve the ontological status of the metric field (Hoefer 1996).

To this, Rynasiewicz could perhaps retort that his diagnosis of the whole debate applies to Hoefer's specific proposal of *metric field substantivalism* as well: the question whether the metric tensor should be understood as being more like empty space or rather more like any other matter fields is either to be regarded as a matter of an arbitrary choice of a preferred manner of speaking, or has a negative answer in both alternatives. Furthermore, he could add that such an ambiguity might even explain why, in the literature, we find *two possible actors* for the role of substantival spacetime – namely, the manifold and the metric field. The choice between them might depend on the equally acceptable and therefore *arbitrary* options of regarding the metric field (1) as being more "matter-like" – which then pushes one toward consider the *manifold* as being the object of the ontological debate – or (2) as being more "spacetime-like", in which case the metric field itself becomes the object of the controversy. Clearly, if we cannot decide in a non-arbitrary way whether the metric field should be equated with a matter field like any other or not, then we cannot conclude that it is the best candidate to become the subject of the dispute between substantivalism and relationism, and the project of clarifying the ontological status of spacetime in the general theory of relativity should be abandoned.

Despite these skeptical remarks, I take it that Earman and Norton's hole argument, besides the various responses that have been given to it, can be interpreted as showing that the "bare manifold" with its points is *not* a good candidate for being the main character in the debate, *and that the metric field is the only candidate for that role*. The reason for this claim is two-fold, involving (*a*) the issue of the individuation of spacetime points on the one hand, and (*b*) a methodologically pregnant remark about the relation between models and reality on the other. Given that such arguments have mainly been given elsewhere, here I will report them in a very brief fashion as a recapitulation, with the main intent to lay my cards on the table and prepare the field for my own analysis of the issue.

As to (*a*), Stachel (1993), Healey (1995) and Pauri (1996) have made abundantly clear that, against Earman and Norton's principle of Leibniz equivalence, the assumption that *two* diffeomorphically related models[8] should represent the *same* physical state of affairs must be regarded as being eminently plausible even for a substantivalist, no matter how different such models are from a purely mathematical viewpoint. As Pauri put it: "physically, a gravitational field does not correspond to a single metric tensor, but to an equivalence class of metric tensors, related one to the other by "active diffeomorphisms" (Pauri 1996, 104, my translation).

The essential remark in this context is that *spacetime points can only be identified by the relational structure provided by the gravitational field*. Given that the points of a manifold have no *intrinsic identity*, on the basis of the well-known principle due to Quine, neither can they be regarded as *entities*.[9] The additional, less noted difficulty for manifold substantivalism is that if the points of a manifold, its elementary parts, are *not* substances, and any substance has usually other substances as its parts, it becomes difficult to defend the view that the "*fusion*" of such non-substantial parts (the manifold) *can* be a substance.[10] Finally, another reason pointing in the same direction is given by the already mentioned fact that the topological structure of the manifold, an essential component of its definition, *depends on the metric field* in the sense that not only must

[8] A diffeomorphism of a manifold onto another is a bijective, infinitely differentiable map preserving topological and differential structure.
[9] The slogan is "no entity without identity".
[10] This remark, which here I cannot expand, could cause trouble to Healey's proposal of a substantial spacetime composed of parts (points) that "are less than substances".

the former be chosen in such a way as to be compatible with the latter, but it also cannot be determined *prior* to the solutions to Einstein's field equations (see Pauri 1996, 105). It is in this sense that we must interpret Einstein's above quoted remark that "there cannot be spacetime without the gravitational potentials".

With respect to the latter reason (*b*), and by recalling arguments due to Maudlin (1988), Stachel (1993), Auyang (1995), and Hoefer (1996), here I will just say that the bare manifold with its points and its other purely mathematical properties (differentiability, orientability, etc.) simply *cannot* be identified with physical space-time, since this would be an instance of a fallacious identification of the properties of a mathematical model with the physical objects which it purports to *represent*. In a word, we would exchange the map for the territory. As Healey put it: "Minimal substantivalist holds that spacetime exists, but not that it is identical to any model of a local spacetime theory. Given the highly abstract character of such models, this identification would make the minimal substantivalist into a Platonist!" (1995, 290). This quotation presents the additional advantage of calling attention to a point that will become crucial in the following: unless we say more about how mathematical models in general, and the metric field in particular, represent the physical properties they are supposed to denote, we will be at a loss in trying to give a clear formulation to the problem of the existence of spacetime.

If these remarks are sufficient to establish that debates about the ontology of spacetime should concern the reality of the metric field and not of the manifold, it is certainly much more difficult to respond to Rynasiewicz's challenge if it is also taken to involve the question whether such a field "resembles" more "space" or should be treated like any other matter field. Even though such a question does *not* seem just a matter of an arbitrary linguistic choice – after all, it lies at the core of currents attempts at building a quantum theory of gravity[11] – I think it fair to side with Rynasiewicz in claiming that the metric field can *neither* be equated with space-time *nor* with any other matter field, since it has features that are typical of *both* of these classical notions. Here we are facing another – much less studied but not less important – case of *inapplicability of "dual" classical notions*, similar to the more familiar difficulties raised, say, by the classical concepts of *waves* and *particles* with respect to quantum entities. In an analogous way, the metric field, by carrying energy and momentum, and by being capable of both "acting" and "being acted upon", should be regarded, on the one hand, as *material*. On the other, by providing a distinction between the spatial and the temporal directions of all the other material fields, it performs the typical individuating functions of classical *space and time* regarded as *principia individuationis*, and is therefore *not* a matter field like any other.

The main claim that I want to advance in this paper is that such a "dialectical" synthesis between space and matter enacted by the metric field calls for a new philosophical view on the nature of spacetime. Having established that the interpretative task raised by the substantivalism/relationism debate essentially involves the metric field, the undeniable "ambiguity" between matter and space that such a field embodies suggests dropping both substantivalism – insofar as it requires empty spacetime – and relationism – insofar as it requires an antirealist stance about spacetime – and embracing a new position as an often invoked *tertium quid* to the debate, which I will refer to as *structural spacetime realism*. As I see it, such a position allows us to capture the best assumptions up to now *separately* associated with substantivalism and relationism, that is, those assumptions that, at least within the general theory of relativity, substantivalists and relativists *must share*. Structural spacetime realism is a synthesis between these two traditional positions in exactly the same sense in which the metric field is *both* matter *and* spacetime,[12] since it defends at the same time the *relational* character of space and time (by defending a structural-role identity for spacetime points), while claiming that the geometrical structure used to represent them is "really", mind-independently exemplified by the physical world.[13]

As a final comment on Rynasiewicz's thought-provoking paper, I should add that the historical importance of the substantivalism/relationism debate in 20th century physics should in any case not be downplayed. Considered it in an historical light, the question of substantival versus relational spacetime can in fact be also described as a conflict between two *heuristically conflicting research programs of 20th century physics,* appropriately labelled by Tian Yu Cao "strong and weak geometric program" respectively (Cao 1997, 99-103). Even though this distinction seems to presuppose an implausible separation between the metric and the gravitational field, the essential difference between the two programs can still be clearly formulated. While the strong geometrical program regards the *geometrical* structure of spacetime as physically real as the other fields, and seeks to reduce the latter (gravitational, electromagnetic etc.) to the world geometry in the sense of Weyl (1918a,b) Eddington (1921) and Wheeler's geometrodynamics (1962), the weak program – which at the moment seems much more popular – treats spacetime as a "*structural quality*" of other fields or, more generally,

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[11] See for instance Rovelli (1997), who considers the metric field as a matter field like any other, and stresses the *relational* character of any measurement in general relativity.

[12] A different sort of *tertium quid* has been advocated by Earman with the Leibniz algebras program (1989, 190-3). See Rynasiewicz for a critical evaluation of this program (1992).

[13] In this paper, I am not discussing the problem whether structural realism is a tenable interpretation of the ontological status of other fields as well, like the electromagnetic field, or more in *general*, of the so-called "theoretical entities" (see Psillos 1995). What I claim is that it is particularly appropriate for interpreting the metric field.

of other entities, and not as existing independently or in a fundamental way.[14] As Cao puts it: "according to this view [the weak program], the geometrical structure manifests itself only in the behavior of rods and clocks, and is determined wholly by the interaction between the gravitational field on the one hand, and rods and clocks a on the other. Rods and clocks, in addition to their function as probes of the metric of spacetime, can also influence the gravitational field. But the field itself, according to Einstein, is sufficient to constitute the metric of spacetime" (Cao 1997, 101, my addition in square parentheses).

Leaving aside for the time being the fact that in the formulation of the weak geometrical program, the notion of "field" may in its turn be taken to presuppose spacetime,[15] the essentially *heuristic* nature of the two programs calls forth two methodological *caveats*. The first is that any extensive philosophical discussion of the strong and the weak geometrical program (or alternatively, of substantivalism and relationism) should be supplemented by an historical analysis or a case study, something that here cannot be provided. The second is that even though the following comments are rigorously limited to *classical* (non-quantum) general relativity, the substantivalist-relationist debate and structural spacetime realism as its possible solution should always be judged in terms of their heuristic role in supporting current (and future) efforts at unifying quantum mechanics and general relativity.

3 Structural spacetime realism as a "synthesis" of relationism and substantivalism

The idea of applying to the philosophy of space and time the principles of structural realism as elaborated by Worral (1989), Zahar (1994), Cao (1997), Chakravartty (1998) Ladyman (1998) and French (1999), has never been explored, despite a seminal but quite condensed anticipation contained in a widely-read paper written more than thirty years ago (Stein 1967). In trying to reconstruct Newton's doctrine of absolute space and time *vis à vis* Leibniz's relationism, Stein in fact writes: "If the distinction between inertial frames and those that are not inertial is a distinction that has a real application to the world; that is*, if the structure I described [...] is in some sense really exhibited by the world of events*; and if this structure can legitimately be regarded as an explication of Newton's "absolute space and time"; then the question whether, in addition to characterizing the world in just the indicated sense, this structure of space-time also "really exists", surely *seems* supereroga-

[14] The expression "structural quality of the field" is Einstein's.
[15] This problem will be discussed below.

tory" (1967, 193, my italics). I suggest that, *mutatis mutandis,* we should apply the same lesson to the issue of spacetime substantivalism in the general theory of relativity.

Note first of all that Stein does not claim that spacetime "exists over and above the physical world of events", as in typical definitions of substantivalism: he rather regards the question whether the structure of space-time "really exists" as "supererogatory".[16] By using a later paper of his, I read him as claiming that the traditional dispute between substantivalism and relationism is completely analogous to that between realism and antirealism as he views it: neither position is tenable (Stein 1989). *Antirealism* in spacetime theories would amount to a position denying that the world of events "really exhibits" a certain geometrical structure, something that he instead explicitly grants, while *realism* would be equivalent to the supererogatory claim that the spatiotemporal structure "really exist", where "really exists" plausibly refers to the *independent existence* ("over and above physical events") required by standard substantivalism.

Isn't Stein's view as it is expressed in the quotation relationism in disguise? After all, why couldn't a relationist be a *realist* about the spatiotemporal relations? Since I regard these objections as plausible, I have to disagree with Stein by claiming that there are at least *three* different senses in which one can *meaningfully* ask whether spatiotemporal structure "really exists". In a first sense, the 'really' is synonymous with 'mind-independently': someone like Kant, for instance, would deny the mind-independence of the spatio-temporal relations.[17] In a second sense, the "really exists" may refer to a kind of platonic realism about the mathematical structure used to describe the physical world. In a third sense, the question of the independent existence of spatiotemporal structure calls into play the status of natural laws and their existence as being partially non-supervenient upon physical state of affairs and events.

Structural spacetime realism as I view it accepts the first and last senses of realism and rejects the second, by developing what, in effect, could be called a *quasi-Platonic* view of scientific theories, where the "quasi" comes from the fact that the "Forms", i.e., the geometrical structure, do not exist separately from the world of phenomena: this claim would indeed be "supererogatory". Such a world, however, is understandable only insofar as it truly and mind-independently "participates" ("exemplifies") the Forms.[18] On the one hand, to the extent that the "Forms" (the structure) are denied separate existence, structural spacetime realism *does* indeed

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[16] As Kant uses this term, an act is *supererogatory* when it is neither against one's duty, nor called by it, despite the fact that it may appear as particularly saintly.

[17] Of course, this question would take us to a different aspect of the problem, but it is important to remind ourselves of this side of the debate.

[18] The issue of how such an exemplification is achieved will be analyzed in the last section of the paper.

sound like relationism, in the trivial sense that geometrical structure does not exists as a non-instantiated universal. On the other hand, *to the extent* that relationists are usually instrumentalist about spacetime – that is, they deny its existence *tout court* – it is extremely important to note that structural spacetime realist *is non-relationist either, simply because it need not be antirealist about spacetime*. In other words, structural spacetime realism can *dissolve* the substantivalism/relationism debate on the basis of the plausibility of the following meaning stipulation:

(MS) *To say that spacetime exists just means that the physical world exemplifies, or instantiate, a web of spatiotemporal relations that are described mathematically.*

According to (MS), spacetime is granted existence *not as a substance*, but rather as a bundle of universals or a web of relations contingently exemplified by physical systems. Since a mathematical structure necessarily involves *relations*,[19] structural spacetime realism can embody the best intuitions associated to relationism, namely the fact that in relativity all the most important spatio-temporal determinations are essentially *relational* in character ('later than', 'simultaneous with', 'to the future of', 'being spacelike separated with', etc., 'being a certain invariant spatio-temporal distance from' etc.). Furthermore, to the extent that real relations, as it is plausible, presuppose the existence of *relata*, *then spatiotemporal relation presuppose physical systems and events*, as classical relationism has it.

However, this supervenience of relations on relata is not metaphysically necessary for structural spacetime realism. An ontology in which individuals simply *are* bundles of (polyadic) universals (Armstrong 1989), with no enduring haecceity, may well make room for non-supervenient relations. In such a thoroughly relationalist ontology, the identity of individual physical entities (say, pointlike events) would be constituted, in the limit of inquiry, by a growing number of relations in which they are embedded. Cao has recently defended this structuralist ontology with respect to 20th century field theories in general: "while structural relations are real in the sense that they are testable, the concept of unobservable entities that are involved in the structural relations always has some conventional element, and the reality of the entities is constituted by, or derived from, more and more relations in which they are involved." (Cao 1997, 5).

Be that is it may, given its conceptual proximity with relationism, one could saddle structural spacetime realism with the difficulties usually associated with the former position. We have seen that a spacetime realist should be a realist about the metric field; in the general theory of relativity, however, the metric is a variable, dynamical entity, depending in part on the distribution of matter, as dictated by the equations of the theory. As far as I can tell, the strongest argument in favor of substantivalism is the fact that a general relativistic spacetime is not a passive arena in which events and processes unfold, but is essentially *dynamical* in that "it acts and is acted upon" by other physical fields. In view of the unity of the gravitational and the chronogeometrical field, such an argument makes direct reference to the spatiotemporal, geometric structure as a *cause* – as when physicists say that "the curvature of spacetime *deflects* the orbits of massive bodies" – and seems to require the independent existence of spacetime as a cause, and therefore substantivalism.

However, a *realist about the spatiotemporal structure* has no difficulty in responding to such arguments. By using the spatiotemporal structure as an explanatory tool, and declaring it to be a mind-independent *property* of certain physical systems, structural realists about spacetime may rely on the fact that *properties* (spatiotemporal ones included) *simply are*, in any respectable metaphysical theories, *the causal powers of the entities having them*. It is in this sense that structural spacetime realism is a *synthesis* of both relationism and substantivalism. What causes the deflection of the orbit of the massive body is the gravitational field, a thoroughly *physical* field, *via* its geometrical, causally active relational properties: in this way, however, one avoids a superfluous reification of spacetime regarded as a substance possessing causal powers.

Well, a substantivalist could reply, doesn't the gravitational *field* presuppose space by being, exactly as any other field, a "physical state of space"? This objection, if it does not beg the issue, is however ineffective and misleading, because it erroneously presupposes the possibility of separating the spatiotemporal features of the gravitational field from the field itself, as if we could initially have an empty space with topological and metric properties but devoid of physical qualities, subsequently to be filled with some physical "content". We have already seen that the general theory of relativity forbids any such separation between empty space and material fields.

In this sense, even though structural realists *can* adopt causal talks typical of substantivalists, they *need not do so*, and can thereby refuse to accept causal explanations invoking spacetime as a "theoretical entity". If need arises, they can easily avoid the sort of criticism recently raised by DiSalle against arguments regarding spacetime as a possible cause of spatiotemporal relations or observable motions: "the nature of spacetime is a question, not of whether a theoretical entity [spacetime] provides a causal explanation for appearances, but of whether the physical processes of measurement conform to geometrical laws [...] Spatial measurement has been

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[19] Plus certain mappings connecting elements of the models with individuals in reality to which we will soon

defined by coordination with a basic physical process (motion of rigid bodies). To claim that space is Euclidean *only means* that measurement agree with the Euclidean metric; Euclidean geometry, if true, can't *causally explain* those measurements, because it only expresses the constraints to which those measurements will conform" (1995, 323-4). On the other hand, being able to attribute any causal efficacy to spacetime structure rather than to spacetime itself, a structural realist could also flexibly reply to critics that might want to charge her position with an underestimation of the importance of causal explanations in spacetime theories.[20]

Coming now to the third, most important sense of "really exists" broached above, a structural spacetime *realist* must admit that geometrical laws exist independently of our minds, to the extent that such laws partially constitute the structure (or the relations) that phenomena exemplify.[21] The laws I am referring to are relational constraints making it the case that, say, "free particles travel on geodesics of the spacetime", and in which geometry and physics are inextricably coordinated with our experience. A new, interesting question to ask in a context equating the structure of a physical theories with its laws involves the degree of independence structures have from entities they relate. Given the assumption of the beginning of the paragraph, this question is basically equivalent to asking how independent geometrical laws are from the entities (bodies or events) they "structure".[22] An answer to this question depends in its turn on the plausibility of a Humean view about the supervenience of natural laws on the intrinsic properties of local events or physical bodies. A Humean regularist will tend to regard laws or structures as being strictly supervenient on the latter entities, and therefore as being more dependent on the properties of bodies, while the non-Humean will be willing to grant a higher degree of independence to such a nomological structure. This question, by involving the nature of natural laws, cannot be developed here. Nevertheless, I will not refrain from suggesting the following thesis as a possible line of future research: *to ask the typical substantivalist question about the independent existence of spacetime is really to ask a question about the supervenience of geometrical laws on the intrinsic properties of physical events*.

4. The semantic conception of scientific theories and structural realism

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come back.

[20] As DiSalle has kindly explained to me in private correspondence, he claims that the same kind of theoretical supposition is involved both in saying that "spacetime has a certain structure", and in saying that "there are certain spatio-temporal relations", a position not altogether different from the one defended here.

[21] I say "partially" because, of course, not all relations between entities are lawlike.

[22] This point is implicitly suggested by DiSalle, where he suggests that Newton's essential point is "that there is a geometrical system of constraints of the motion of bodies that is independent of those bodies" (1994, 274).

Interestingly, the various forms of spacetime realism that we have been discussing so far can be regarded as a by product of different views of the nature of scientific theories. If spacetime is understood as a *theoretical entity* in the tradition of a *linguistic* approach to scientific theories, attempts at justifying its introduction as an unobservable entity typically usually call into play *causal* explanations. If, on the contrary, the *semantic*, model-theoretic aspect of scientific theories is emphasized in the sense of Dalla Chiara and Toraldo (1974), van Fraassen (1980), Giere (1988) and Suppe (1989), strategies advocating some form of *partial isomorphism* between spacetime models and the physical world are much more plausible, and structural spacetime realism emerges as a natural outcome. Since defenders of manifold substantivalism have often fallen prey of a confusion between aspects of the manifold as an *abstract* mathematical model and features of physically *concrete* spacetime, some reflections on how mathematical theories represent the physical world seem particularly appropriate, given that they will also help us to give some more detail on the notion of a "structure" associated to a physical theory.

In the recent years a new approach to scientific theories has called attention to a *non-linguistic* dimension of science. The neopositivists had regarded theories mainly as sets of *sentences*, to be analyzed by purely *syntactic* means within a formalized *language*. Reacting to such an obsession with language, philosophers like Marisa Dalla Chiara and Giuliano Toraldo (1973) in Italy, or Patrick Suppes (1967), Bas Van Fraassen (1980), Ronald Giere (1988) and Frederic Suppe (1989) in the United States, have begun to regard scientific theories mainly as *abstract, non-linguistic structures* or, simply, *models*. In the technical sense of logic, a model $M = <D, f>$ is whatever satisfies a set of axioms couched in a language L, namely an abstract domain of discourse D (a set of individuals), together with a function f assigning n-tuples of individuals in D to predicates ($n = 1$) and relations ($n > 1$) of L.

Within the semantic conception of theories, the general theory of relativity is standardly constituted by the structure $\mathbf{M} = < M, g, T >$, where M is a four dimensional, Riemannian manifold, g is the metric tensor and T is the stress energy tensor, or the matter field. If we try to formulate structural spacetime realism in this semantic framework, we basically have two different options: (O_1) the set of theoretical relations holding among spacetime points in $M + g$ is *totally* or *partially isomorphic* to the set of spatio-temporal and physical relations *exemplified* by real events; (O_2) the set of mathematical relations among spacetime points in M postulated by g *resembles*, or is *in some sense similar* to, the set of temporal and physical relations *exemplified* by real events.

A *third* option (O_3), which, however, does *not* typically belong to the semantic, but rather to the linguistic conceptions of theories, consists in claiming that the abstract, mathematical objects $M + g$ in the structure $\mathbf{M}$

genuinely refers to physical spacetime. The way (O_3) is put, and in particular the use of the verb 'to refer', makes it evident that the reality of spacetime in this case is regarded as a particular instance of the more general problem of establishing the reality of the so-called "theoretical", "unobservable entities".[23] Within the "received view of scientific theories" (Suppe 1977), such entities are those that are putatively referred to by terms of the language of the theory *T* that belong to its so-called "theoretical vocabulary".

It should also be obvious why, within such a linguistic framework – in which the realist tries to establish some sort of referential relation (typically a causal one) between the word 'Riemannian manifold' and its putative *denotatum* – the model-theoretical approach, with its emphasis on *relational structure* rather than on relata, loses its relevance. Note that I am *not* claiming that within the semantic approach the third option cannot be formulated, or that a causal account of theoretical entities *cannot* be advocated by semantic theorists believing in entity realism.[24] Nor do I mean to endorse a distinction between observable and theoretical entities in van Fraassen sense, as I mention it only to present an antirealist argument essentially related to the received, linguistic view of science. By discussing these three options in turn, my two-fold aim is rather to argue that the spatiotemporal structure postulated by our best models (spacetime theories) is really exemplified by the physical world and to further clarify structural spacetime realism by defending it from some foreseeable objections.

4.1 Structural spacetime realism and isomorphic representations

According to the first option (O_1), any claim about the reality of spacetime is equivalent to the claim that a model of general relativity *correctly represents* the physical universe *via* isomorphic relations between models and world. The idea that the relationship between a model and reality is one of isomorphic representation is essentially due to van Fraassen (1980, 43-46): given a bijection *F* from the model *M* (or a part thereof) to a set *R* of real objects or events ('reality'), we can establish an isomorphism between *M* and *R* if and only if the relations between elements of the model and those between entities of the real world *are preserved* by *F*. If we claim that *F* holds only when it acts on the *empirical substructure* of the model, its domain is restricted to the 'part' of the model that is linked *via F* to observable entities. By such a restriction, we can draw the distinction, dear to van Fraassen's heart, between *accepting the theory as empirically adequate* and *believing it to be true* (1980, 46). The former epistemic attitude is reserved to the *theoretical* substructure of the theory *M*, since *F*

[23] Here 'unobservable' means 'unobservable with our unaided senses'.

guarantees *only* the existence of directly observable entities. Van Fraassen does not exclude that the isomorphism *F* can be extended to the theoretical substructure of *M*, but in this case the set of theoretical relations attributed to the theoretical entities *may or may not exist*.

Consequently, in van Fraassen's view, the problem of establishing whether the structure of spacetime is real would amount to decide whether the spatiotemporal substructure of the model corresponding to general relativity belongs to the empirical or the theoretical substructure. In this context, by insisting on a distinction between observable motions and spacetime regarded as a theoretical entity, one could argue, *against structural spacetime realism*, that if one has to be delivered by metaphysics, as Van Fraassen recommends, one must remain *agnostic* as to whether the spatio-temporal structure postulated by the Riemannian manifold is really exemplified by physical spacetime.

There are two possible strategies to block this form of antirealism about the spatiotemporal structure. The first relies on the inapplicability of the distinction between observable and unobservable to spacetime; the second, more efficient to our purpose, consists in using the very weapons of the constructive empiricist to affirm that an essential component of the spacetime structure is real simply because it is *directly observable*.

Within the first strategy, but for somewhat different purposes, DiSalle has argued that *observations in physical geometry are essentially theory-laden*, so that any distinction between observable and non-observable is, at least with respect to spacetime structure, *groundless* (1995, 318). According to him, Reichenbachian "coordinative definitions" do not correspond to simple physical operations, but rather require a whole system of natural laws, and are therefore "theoretical" throughout. This point, however, does not detract from the fact that, at least within the special theory of relativity – and therefore within the local tangent space of any point of a general relativistic spacetime – we *do observe part of the spatio-temporal structure as directly as it gets*.

This gives us the second strategy: don't we directly perceive that an event is *before* another event, or that *two spatially contiguous events are simultaneous*? Recall that the relation of temporal succession ("before" or "after") is so important in Minkowski spacetime that it, by itself, suffices to build up its whole geometrical and causal structure (Robb 1914). On the other hand, the spatiotemporal coincidence of two events, ascertainable by a single act of perception, must be regarded as sufficient to attribute them *absolute simultaneity*, since if we cannot judge that, say, a light ray intersecting the surface of a mirror is simultaneous with a certain position of the hands of a spatially contiguous clock, no empirical foundation of any physical theory would ever be

[24] Giere is an example of a semantic theorist defending entity realism (1988, ch. 5).

possible. In this sense, and even independently from arguments *à la* DiSalle, within the constructive empiricist position advocated by Van Fraassen, spacetime structure must be regarded, at least in part, as belonging to the *empirical* substructure of the theory, and therefore as being as real as any observable relation between phenomena.

In the same vein we should interpret Einstein's often quoted "point-coincidence argument", on the strength of which, considering spatiotemporal coordinates as devoid of physical value, the only epistemically ascertainable relations are "meeting of the material points of our measuring instruments with other material points" (1916, 117). And though we certainly cannot reconstruct the global structure of a general relativistic spacetime just by patching together such strictly local intersections of worldlines, for our purpose it suffices to point out that if we don't admit that at least these intersections are directly observable, no spacetime theory can ever be built. Consequently, antirealist arguments claiming that spacetime structure is in any case unobservable are untenable.

4.2 Structural spacetime realism and resemblance theories of representation

The second option (O_2) has been defended by Giere, who claims that "*resemblance to a certain degree and in certain respects*" is the correct relation between models and reality (1988, 81). Such a requirement is clearly weaker than that of isomorphism but despite its vagueness, has some degree of confirmation from the cognitive sciences, in particular from empirical studies concerning mental images and schemes, whose representational features are mostly pictorial. According to Giere, the relationship between model and reality cannot be linguistic, because neither models nor reality are linguistic entities, but it must be expressed by *a linguistically formulated theoretical hypothesis*, which states the existence of some degrees of similarity (under certain respects) between model and world. According to Giere, the relation linking models and reality cannot be given by isomorphisms, because there are obviously many relationships between entities in the models that are not instantiated by corresponding entities in reality and *viceversa*: natural laws for Giere are strictly true only in the model. Resemblance, on the contrary, has the advantage of expressing a typical feature of the scientific enterprise, essentially involving *errors and approximations* (Mayo 1996).

Besides the obvious vagueness of the relation of 'resemblance under certain respects', another problem of this proposal is that it seems to hold, strictly speaking, only between images and aspects of objects; in this sense, it necessarily presupposes *visual* perceptions or intuitions. In fact, it is implausible to claim that other sensory modalities are capable of bearing the relation of resemblance with their intentional objects. Consequently, in order to claim the existence of a relationship of resemblance between models and reality, *one must give center stage to visual features of models*. So Giere's proposal can be challenged with the following dilemma: either the relation of resemblance has some definite meaning, and then it clearly implies preservations of spatial relations between images and represented objects (e.g. angles, distances, shapes, contiguity of parts, etc.), or it is so vague that it does not mean anything at all and cannot be used to specify the relation between models and reality.

With respect to the issue of the visualizability of models, the weakness of O_2 as applied to spacetime physics is evident. For features as abstract as those involved in the mathematical models of general relativistic spacetimes, it is extremely restrictive to ask that such models have visualizable features. Just to give an example: is the infinite differentiability of charts defining a manifold interpretable as resembling the continuity of perceived space or that of physical space? The trouble is that the vagueness of "similar under certain respect and in certain degrees" leaves too much freedom for establishing a precise correspondence between a model and parts of the world. What may work for a simple, one-dimensional spring with respect to real life springs will not work for theories as abstract as quantum field theory or general relativity. One need not subscribe to reconstructions of the development of contemporary physics stressing the progressive loss of *visualizability* of physical models (Capek 1961) to admit that the latter requirement cannot be imposed *a priori* to a theory for it to be representing the world.

Finally, as a last objection against (O_2), we should remark that despite the geometrization and the spatialization of time on the one hand, and the connection between our experience and measurement of time with the motion of objects in space on the other, time as it is represented in spacetime models portrays events as given in block, the spatiotemporal carrier of our body being a tube in four-dimensional spacetime. While this representation of time is certainly adequate for purposes of the physical description of the world, it would be quite outlandish to argue that it *resembles* in some respect to the time of our bodies regarded as physical systems. The least that we can say is that it certainly does *not* resemble the time of our experience, since, within the latter, we are always aware of a single, ontologically privileged moment that we call *present*, despite the fact that our experience may occur *in a tenselessly conceived time*. And even if one were to claim that the relation of "being greater than" on the real line (which we use to represent time and its instants) is *similar under certain respects* to the relation of temporal succession between instants, this certainly would not help, since it would amount to defend the empirically empty claim that any reflexive and transitive binary relation could represent the relation of temporal succession within a given inertial frame.

Since within the semantic approach to scientific theories option (O_1) is much more appropriate than (O_2) to defend structural spacetime realism, we can now go on to compare the former option with (O_3).

5.3 Structural spacetime realism and causal strategies

In order to show that the position defended here is really different from the form of substantivalism usually invoked by advocates of (O_3), it is necessary to stress once again that to the extent that physical spacetime is regarded as an *entity* (a substance), a model theoretical approach based on the idea that a "correct representation of the model" is realized *via* an isomorphism (whether restricted to the empirical substructure or not) *fails to capture its reality*. In this sense, and without further arguments, one should not accept the view that structural realism *implies* entity realism with respect to spacetime.

We have seen that if spacetime exists as a directly observable web of *relations*, a spacetime structural realist who is also a constructive empiricist can establish its reality directly. If it exists as a set of unobservable relations, or if the observable spatiotemporal relations are theory-laden, then the spacetime structural realist can argue in favor of its reality *via* an indirect argument showing that natural laws, *qua bearers of the structure*, are mind-independent components of the physical world. Furthermore, we have seen if the only reason to postulate spacetime is given by the need of finding a "hanger" for spatiotemporal relations, the fact that the gravitational field may play such a role makes the postulation of a substantival spacetime *metaphysically otiose*.

However, such an epistemological and ontological limitation to relations, typical of structural realism, my suggest a possible objection: does it make sense to claim that one can be a structural realist without also endorsing entity realism? After all, the detection properties of elementary particles, for example, are nothing but the properties they have *in relation* to other particles, fields, and macroscopic detection apparatus (see Chakravartty 1998). Furthermore, the gravitational field has momentum energy, therefore mass (via the equivalence between mass and energy) and having mass is a typical feature of substances.[25] Suppose that spacetime were indeed a substance, and that causal arguments to establish its reality were unavailable to the structural realist. How could she ever come to believe in its existence? In order to dispel the impression that I haven't given

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[25] I owe this objection to Rynasiewicz.

substantivalism all its chances, I will conclude by evaluating the general structure of causal arguments in favor of the existence of spacetime as a substance.

The idea of such arguments is simple: if *x* causally interacts with *y*, and *y* is real, then *x* is also real. If we could prove that spacetime (*x*) is causally active on some observable body (*y*) and *x* can be causally active only by being a substance, we could conclude in favor of substantivalism. This argument seems to be supported by the long historical evolution of our theories of space and time. When Newton and Leibniz were discussing about the nature of space and time, they took something for granted, despite the different positions they were defending: space and time were for both of them causally inert,[26] a sort of passive background for all events, which for Newton existed independently of them, and for Leibniz was a set of relations among them. In Einstein's general theory of relativity, however, space-time plays a dynamic role, as physicist usually say that gravity is an *effect* of spacetime curvature: in Wheeler's expressive words, "matter tells spacetime how to bend, spacetime tells matter how to curve".

In particular, this sort of dependence can be clearly exemplified by the link between time and matter: as is well known, relativistic time becomes *elastic*, since its rate of "flow" *depends* not only on relative velocity (in the special theory) but, what is more important to our purposes, on the intensity of the gravitational field (in the general theory). When we refer to such an intimate relation between time and gravity, we can either "explain" it either with the fact that spacetime itself is causally active, or we can, *more correctly*, *identify the rate of flow of time with gravity* (see Unruh 1995). The substantivalist usually argues that, on the basis of the first kind of explanation, there seems to remain little doubt about the reality of spacetime as a substance. However, the tacit premise that is relied upon for such a conclusion is that *something can be causally active only if it exists as a substance*.

The crucial premise in italics, however, simply does not hold water. In fact, events, states, or tropes (i.e., particular attributes, like *this redness*) *can be* causally active due to their properties, but – *qua* entities endowed with temporal parts – they are certainly *not* substances.[27] The event named by 'The First World War' does not have causal powers in virtue of the substances entering its constitution (the soldiers, the weapons, etc), but is commonly attributed causes (the assassination of Francis Ferdinand of Austria in Sarajevo) and effects (the

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[26] This aspect is stressed by Shapere (199?).

[27] My table yesterday (a substance) is the same as my table today, despite the fact that its left leg has been burnt by a fire that occurred between 5 and 6 p.m. yesterday. The table is wholly present both yesterday and today since it has no temporal parts, but the event given by its burning, at any instant of time between 5 and 6 p.m. yesterday, is *not* wholly present, since any non-pointlike event has *temporal parts*.

Russian Revolution, the emergence of various fascisms, etc.). But even if, quite implausibly, we could prove that only substances have, properly speaking, causal powers, it would be very difficult to show that the adoption of a causal talk involving spacetime as a substance is really indispensable to explain, say, the slowing down of clocks in strong gravitational fields. As a matter of fact, in order to rebut all causal arguments for substantivalism, it is sufficient to consider the simple and plausible claim that it is always possible to translate a talk attributing substantival spacetime some causal efficacy into a talk attributing causal powers to relational properties of other physical entities.

Consider for motivation the usual "explanation" of time dilations and length contractions in the special theory of relativity. After Lorentz's program has been superseded by Einstein's, one doesn't usually explain such relativistic phenomena *causally* or by invoking *molecular forces*. Belonging to the kinematics of the theory, such effects can at most be explained *structurally*, that is, by considering the geometrical constraints of the theory in the Minkowski four-dimensional formulation. In a perfectly analogous sense, except for the fact that in the general theory we have *dynamical* effects, it is not curvature by itself, *qua* property of a substantival spacetime, that *causes* the observable motion of a planet, but the gravitational field *and* its geometrical laws. In general, explanations involving geometrical features can only be structural and never causal, unless one believes that mathematical entities exist in a concrete way! If, for example, our *explanans* is Einstein's principle of equivalence and our *explanandum* the forward motion of a balloon inflated with helium in an aircraft at takeoff, we certainly cannot claim that such a Principle, in the geometrical interpretation it receives in general relativity, is the *cause* of the motion of the balloon.[28]

Likewise, every talk about the rate of flow of time as being slower in a more intense gravitational field can be reinterpreted as a talk about the motion of particular physical bodies acting as clocks under the influence of the gravitational field. This viewpoint is obviously more explicit in the second, more correct formulation of the relation between time and gravity, the one appealing to their *identity*. In this case, the argument in favor of the reality of time regarded as a property is even more straightforward: if time is identical with a particular, variable property of the gravitational field, it is real as any other material property. Also in this case, of course, the ontological status of time would not be that of a *substance*, but rather of a *property* or a relation: the gravitational field would be the basic bearer of such a property.

[28] For a discussion of this example, see Salmon (1992, 37-39).

This last point, however, offers the side to one last objection against structural spacetime realism: in view of the identification of time and gravity, or of the metric field with the gravitational field, *if* the latter is substantial, how can we deny spacetime (the metric field) the status of substance? The answer is simple: the gravitational field, *qua* field, is clearly *not* a substance! Being four-dimensionally extended, fields, like spatiotemporally extended events, have temporal parts, and don't retain their identity through time: any change in a field can only be accounted for by a difference of physical states in two different regions. A traffic light, on the contrary, being a substance, remains the same across a change from yellow to red.

In conclusion, structural spacetime realism remains as the only clear option, rejecting on the one hand the heavy metaphysical baggage of a substantival spacetime, and on other, the instrumentalist ploy of relationism, incapable of taking into account the explanatory role of geometrical laws and the causal potency of spacetime regarded as a property of the gravitational field.

REFERENCES

Alexander H.G. (ed.) (1956) *The Leibniz-Clarke Correspondence*, New York, Barnes and Noble.

Armstrong D. (1989), *Universals and Scientific Realism*, Cambridge, Cambridge University Press.

Auyang S. (1995), *How is Quantum Field Theory Possible?*, Oxford, Oxford University Press.

Belot G. (1996), "Why general relativity *does* need an interpretation?", *PSA 96*, Part I, S80-88.

Butterfield J. (1989), "The Hole Truth", *British Journal for the Philosophy of Science*, 40: 1-28.

Cao T. Y. (1997), *Conceptual Developments of 20th Century Field Theories*, Cambridge, Cambridge University Press.

Capek M. (1961) *The Philosophical Impact of Contemporary Physics*, Princeton, New Yersey.

Chakravartty A. (1998), "Semirealism", *Studies in History and Philosophy of Science*, 29, 3:391-408.

Dalla Chiara M. e Toraldo G. (1973), "A Logical Analysis of Physical Theories", *Rivista del Nuovo Cimento* , Serie 2, 1-3: 1-20.

DiSalle R. (1994), "On Dynamics, Indiscernibility and Spacetime Ontology", *British Journal for the Philosophy of Science*, 45: 265-287.

____(1995), "Spacetime theory as physical geometry", *Erkenntnis*, 42: 317-337.

Earman J. (1989), *Spacetime and World Enough*, Cambridge, Mass., The MIT Press.

____and Norton J., (1987), "What price Substantivalism: the Hole Story", *British Journal for the Philosophy of Science*, 38: 515-525.

Eddington A. (1921), "A Generalization of Weyl's theory of the Electromagnetic and the Gravitational Fields", *Proceedings of the Royal Society*, A99: 104-122.

Einstein A. (1916), "The Foundations of the General Theory of Relativity", in A. Einstein et al. (1952), *The Principle of Relativity*, transl. By W. Perret and G. B. Jeffery, New York, Dover.

____(1923), "Ether and the Theory of Relativity", *Sidelights on General Relativity*, Dover, New York, pp. 1-24.

French S. (1999) "Models and Mathematics in Physics: the Role of Group Theory", in J. Butterfield and C. Pagonis (eds.) *From Physics to Philosophy*, Cambridge, Cambridge University Press.

Friedman M. (1983), *Foundations of Space-Time Theories*, Princeton, Princeton University Press.

Giere R. (1988), *Explaining science*, Chicago University Press, Chicago.

Healey R. (1995), "Substance, Modality and Spacetime", *Erkenntnis*, 42: 287-316.

Hoefer C. (1996), "The Metaphysics of Space-Time Substantivalism", *The Journal of Philosophy*, 43, 1: 5-27.

____(1998) "Absolute versus Relational Space-Time: for better or for worse, the debate goes on", *British Journal for the Philosophy of Science*, 49, 3: 451-469.

Ladyman J. (1998), "What is Structural Realism", *Studies in History and Philosophy of Science*, 29, 3: 409-424.

Maudlin T. 1988, "The Essence of Space Time", in A. Fine and J. Leplin (eds.), *Philosophy of Science Association 1988*, vol. II, East Lansing, Michigan, pp. 82-91.

____(1990) "Substances and Space-Time: what Aristotle Would Have Said to Einstein", *Studies in History and Philosophy of Science*", 21: 531-561.

Mayo D. (1996), *Errors and the growth of experimental knowledge*, University of Chicago Press, Chicago.

Mundy B. (1983), "Relational Theories of Euclidean Space and Minkowski Spacetime", *Philosophy of Science*, 50: 205-226.

Pauri M. (1996), "Oggettività e realtà", in F. Minazzi (ed.), *L'oggettività della conoscenza scientifica*, Milano, F. Angeli, pp. 100-112.

Psillos S. (1995), "Is Structural Realism the best of both Worlds?", *Dialectica*, 49, 1, pp.15-47.

Robb A. A. (1914), *A Theory of Time and Space*, Cambridge, Cambridge University Press.

Rovelli C. (1997), "Half-way through the woods: Contemporary Research in Space and Time", in J. Earman and J. Norton (eds.), *The Cosmos of Science*, Pittsburgh, University of Pittsburgh Press, pp. 180-224.

Rynasiewicz R. (1992) “Rings, Holes and Substantivalism: on the Program of Leibniz Algebras”, *Philosophy of Science*, 59: 572-589.

____(1994), “The Lessons of the Hole Argument”, *British Journal for the Philosophy of Science*, 45: 407-436.

____(1996) “Absolute versus Relational Space-Time: an Outmoded Debate?”, *The Journal of Philosophy*, 43, 1: 279-306.

Salmon W. (1992), “Scientific Explanation”, in M. Salmon J. Earman et al., *Introduction to the Philosophy of Science*, Englewood Cliffs, New Jersey, Prentice Hall, pp. 7-41.

Shapere D. (199?), “The origin and nature of time”, manuscript.

Stachel J. (1993), “The Meaning of General Covariance”, in *Philosophical Problems of the Internal and the External World*, J. Earman, A. Janis, G. Massey, N. Rescher (eds.), Pittsburgh, University of Pittsburgh Press, pp.129-160.

Stein H. (1967), “Newtonian spacetime”, *Texas Quarterly*: 10, 174-200.

____(1989), “Yes, but...Some Skeptical Remarks on Realism and Antirealism”, *Dialectica*, 43: 46-65.

Suppe F. (1977), *The Structure of Scientific Theories*, 2nd edition, Urbana, University of Illinois Press.

____(1989), *The Semantic Conception of Theories and Scientific Realism*, University of Illinois Press, Chicago.

Suppes P. (1967), “What is a scientific theory”, in *Philosophy of Science today*, S. Morgenbesser (ed.), Basic Book, New York, pp. 55-67.

van Fraassen B. (1980), *The Scientific Image*, Oxford University Press, Oxford.

Worrall J. (1989), “Structural realism”, *Dialectica*, 43/1-2, pp. 99-124.

Unruh W. (1995), “Time, gravity and quantum mechanics”, in *Time’s arrow today*, S. Savitt (ed.), Cambridge University Press, Cambridge, pp. 23-65.

Weyl H. (1918a), *Raum, Zeit, Materie*, Berlin, Springer.

____(1918b), “Gravitation und Elektrizität”, *Preußische Akkad. Wiss. Sitzungber.*, 465-478

Wheeler J. A. (1962), *Geometrodynamics*, New York, Academics.

Zahar E. (1994), “Poincaré’s Structural Realism and his Logic of Discovery”, in J. L. Greffe, G. Heinzmann and K. Lorenz (eds.), *Henri Poincaré: Science and Philosophy*, Berlin, Akademie Verlag, pp. 45-68.