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The Metaphysics of Super-Substantivalism

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Abstract

Recent decades have seen a revived interest in super-substantivalism, the idea that spacetime is the only fundamental substance and matter some kind of aspect, property or consequence of spacetime structure. However, the metaphysical debate so far has misidentified a particular variant of super-substantivalism with the position per se. I distinguish between a super-substantival core commitment and different ways of fleshing it out. I then investigate how general relativity and alternative spacetime theories square with the different variants of super-substantivalism.

1. Introduction

What does the universe consist of? A popular answer, at least among physicists, might be well expressed by the title of a famous book by Hermann Weyl: *Space-Time-Matter*. The shouting and screaming starts when one asks about the *relationship* between space and time (or spacetime), on the one hand, and matter, on the other.

The modern debate normally distinguishes between two positions with regard to the ontological status of spacetime. Either spacetime is fundamental, i.e. a substance in its own right (*substantivalism*), or only material bodies are fundamental, and space and time are just abstractions of or derive from the relationships between material bodies (*relationalism*). The first position is often traced back to Newton, the second to Leibniz.[1] But there is a third possibility, a position about which most remain silent, as if it were a cautiously guarded family secret—and even though it has an equally magnificent set of forefathers as the other two camps, among them Plato, Descartes, Spinoza, Clifford and also Newton.[2]

Sklar (1974) has called this position *super-substantivalism*. The idea is simple. Substantivalists claim that there are two kinds of fundamental substances in the world: spacetime and matter.[3] Relationalists claim that there is only one kind of fundamental substance: matter. Super-substantivalists agree that there is only one (kind of) fundamental substance in the world. But, they hasten to add, this fundamental substance is not matter but spacetime. According to the super-substantivalist, *every-thing in the world is spacetime*.[4]

This position may seem logically possible but slightly non-common-sensical, and so I hastened to refer to its famous ancestors. Yet they are not what matters in the end; the question is which position is the best to adopt. There are different reasons one can have for judging one of the three positions to be better than the other two. One oft quoted criterion is Occam's Razor: the most parsimonious position is regarded as having a clear advantage. However, parsimony has to be balanced with explanatory power: if a position can explain more than its rivals, then we may be willing to accept that it postulates more fundamental entities or kinds of entities.[5]

We should note that both criteria can be stated without explicit recourse to the theories of space, time and matter provided by physics. One might be tempted to regard this as an advantage. However, one may also defend the view that *good* metaphysics should rest on a conceptual analysis of physics; whether we should adopt substantivalism, relationalism or super-substantivalism depends to a large extent on which position is most compatible with our best physical theories of space, time and matter.

It is exactly this idea that has driven many philosophers of physics since the completion of the General Theory of Relativity (GR for short) in 1915. The question was not so much whether we find substantivalism or relationalism more intuitive or more advantageous for purely philosophical reasons. Rather, the question was whether, *given GR*, which has been accepted as at least approximately true, we should adopt a substantivalist or a relationalist position with regard to the nature of spacetime and matter. Pursuing this question turned out to be enormously fruitful for philosophy, for it facilitated the insight that substantivalism and relationalism were not positions but *families of positions*. This development started with the rediscovery of Einstein's 1913 hole argument by Stachel (1989), a paper first presented at the 1980 conference on General Relativity and Gravitation in Jena. Earman & Norton (1987) used the argument as the basis for the claim that a substantival position in the context of GR would lead to indeterminism—a position that should be avoided if there was a philosophical position available (notably relationalism) that did not commit one to either determinism or indeterminism. The subsequent philosophical discussion brought about an entire family of substantivalist and relationalist positions, and, as it turned out, the hole argument carries the threat of indeterminism only for some of them; positions that many regarded as disadvantageous anyhow.[6]

No such discussion, with GR and other relativistic spacetime theories as background, has yet taken place for super-substantivalism. Instead, in recent years the position has mostly been discussed in the field of pure metaphysics, and has been argued (e.g. by Lewis (1986), Sider (2001) and Schaffer (2009)) to be philosophically advantageous to substantivalism at least.

However, just as in the philosophical discussion prior to the rediscovery of the hole argument, much of the literature does not clearly distinguish between the *core commitment* of any super-substantival position, on the one hand, and the properties, advantages and shortcomings of different concrete variants of super-substantivalism on the other. I shall proceed as follows. In section 2, I will isolate the core commitment of super-substantivalism. Section 3 will deal with the two most promising arguments in favour of super-substantivalism as compared to the substantivalist and relationalist core commitments. In both cases, I will show that these arguments do not speak as clearly in favour of the super-substantivalist programme as their recent proponents have claimed. Instead, I argue, both arguments can serve merely as a strong *motivation* to work out the landscape of super-substantival positions in detail. Any entirely convincing argument in favour of super-substantivalism, just as in the cases of substantivalism and relationalism, can be had only with respect to concrete variants going beyond the core commitment. Section 4 suggests that the general theory of relativity can serve in an argument for what I call the minimal extension of the core commitment, which states that spacetime is ontologically prior to matter. Section 5 then distinguishes between different ways of extending further the minimal extension of the core commitment, especially by considering different options of defining the notion of ontological priority. Finally, section 6 distinguishes between two classes of extensions, two sets of super-substantival positions: *modest* and *radical* super-substantivalism. I conclude with a discussion of the advantages and disadvantages of the two families of positions and their different variants. I argue that radical super-substantivalism has the potential of inspiring research in physics, as well as tempting philosophical fruit it promises us for a future harvest. However, its closeness to research programmes in physics also means that radical super-subtantivalism, in contrast to its modest cousin, may stand and fall with developments in physics.

2. The Core Commitment of Super-Substantivalism

In order to characterise the core commitment of super-substantivalism, we first have to isolate the core of substantivalism.

Both Norton (1989) and Maudlin (1989) assume that a substantivalist has to accept that if a piece of matter is translated three feet in some direction, he then faces a new physical situation, even if the relationships between that piece of matter and all other matter in the universe (if there is any) have not changed. The intuition is that for a substantivalist something important has changed: the piece of matter is located in *this* part of spacetime here rather than in *that* over there, where it was before it was moved.

Norton and Maudlin are in substantial agreement with Leibniz and Clarke:[7] they both believe that *if* one is a substantivalist (using the modern term), *then* one is committed to seeing a world where 'everything is translated three feet in some direction' as a different possible world from the actual one.

Pooley (forthcoming) argues that this commitment does *not* follow from the central metaphysical commitment of the substantivalist position. He writes (p.85):[8]

> As I understand the position, substantivalism is simply a commitment to the real existence of space and its parts (the possible places of material bodies) as concrete, basic entities in the world. The emphasis on 'basic' is intended to underline the contrast with the relationalist, who can agree that there is a sense in which places (i.e., the actual and possible locations of bodies) exist, but who will deny that they are elements of the world's ground-floor ontology. For the relationalist only the (ultimate constituents of) material bodies are basic in this sense. The existence of places, and thus of space, is derivative. It is parasitic on the actual and possible spatial relations that can hold between material

> objects. For the relationalist, space is thus ontologically dependent on bodies. For the substantivalist, space is (at least) ontologically on a par with its material content.

This *does* seem to be the core commitment of the substantivalist, and it does indeed not imply that parts of space or spacetime possess primitive thisness, i.e., the substantivalist as such is not committed to regard two parts of spacetime as intrinsically different from one another. As a matter of fact, the position does not even commit the substantivalist to the claim that the parts of spacetime are points—they could be atomistic regions, or something else entirely. Nor does the substantivalist as such have to be sure about which mathematical object(s) represent spacetime, how many dimensions it has, or whether the causal structure of spacetime is compatible with its path structure.[9]

Of course, the substantivalist will want answers to all these questions eventually; and especially the discussion originating with the rediscovery of the hole argument and Earman's and Norton's discussion of it produced more than one answer to the question of how a *smart* substantivalist should answer at least some of the questions above. But the point is that the substantivalist core commitment *as such* does not commit to any particular answer to any of these questions.

Thus, we can summarise the commitment in the following way:

> *Substantivalist core commitment*: Spacetime is a (kind of) substance, and a substance is a basic (or fundamental) concrete object that is not derivative of anything else.[10]

This is the commitment shared by all variants of substantivalism. Every characterisation that goes beyond the core commitment is already a particular, more concrete, variant of substantivalism.[11] And we *do* need these variants, for as it stands the core commitment is just the skeleton of a position; it needs flesh and muscles in the form of answers to the above questions in order to wrestle with physics' theories of spacetime. Of course, different reasons will speak for the adoption of different variants.

Let us now come to super-substantivalism. Super-substantivalists agree with substantivalists that spacetime is a substance in the sense described above. But substantivalists allow that spacetime is *just one* of the (kinds of) substances in the world, whereas they typically accept matter as the second (kind of) substance. This is the step whereby super-substantivalists break ranks with substantivalists; they thus have the following core commitment:

> *Super-Substantivalist core commitment*: Spacetime is *the only* (kind of) substance.

The super-substantivalist core commitment leaves open whether spacetime is the only substance (i.e. the only fundamental entity) or the only kind of substance. In the latter case, one would say that *parts of spacetime* are substances (i.e. basic), rather than (just) spacetime as a whole. If one were to claim that spacetime is *the only* entity, one would link super-substantivalism to priority monism, i.e. the position that the whole (here spacetime) is ontologically prior to its parts. While one may defend this position, it is not part of the super-substantivalist core position: one can believe that spacetime is ontologically prior to everything else without necessarily believing that the whole of spacetime is in turn ontologically prior to its parts.[12]

Note that, just as the substantivalist core commitment, the super-substantivalist one does not say anything about matter. However, every super-substantivalist will agree that they have to say *something* about matter right after uttering the core commitment; what is the relationship between spacetime as the only (kind of) substance, and matter?

Maybe the most well-known answer has been given by what Schaffer (2009) has called 'the identity view'. According to this position, the core commitment is followed by saying that matter is *identical to* spacetime regions. Depending on how this view is cashed out further (I will write more on this in section 5), one may well argue that rather than showing that spacetime is in some way *more* fundamental than matter, the position alleges that there is no real distinction between the two in the first place. After all, spacetime and matter are identified, and one might as well have written 'Matter is the only kind of substance' in the core commitment. Then, this version of super-substantivalism has been extended in such a way that it goes full circle and becomes identical to a version of relationalism. What started out as a project to base ontology on spacetime rather than on matter might then end up abandoning the very distinction of spacetime and matter.[13]

Thus, instead of extending the super-substantival core commitment to the identity view, we could extend it by adding the sentence 'Thus, spacetime is ontologically prior to matter'. I will call the core commitment ammended thus the 'minimal extension of the super-substantival core commitment which takes spacetime as ontologically prior to matter', or 'MESC' for short. The extension is minimal because it does not yet spell out the notion of 'ontological priority'. What is it supposed to mean that something (in this case spacetime) is ontologically prior to something else (in this case everything)? Different accounts of ontological priority (and, connected to that, ontological dependence) have been put forward. The rough idea is that A is ontologically prior to B iff the existence of A implies or contains the existence of B but not vice versa. Depending on your precise notion of ontological dependence (and any other metaphysical commitments you may have), B supervening on A might be sufficient for A to be ontologically prior to B; or supervenience might only be necessary and reducibility sufficient. For our purposes, the missing consensus of what 'ontologically prior' means is actually an advantage, for it allows us to use the term in the MESC position, and to have different ways of cashing out 'ontologically prior' correspond to different ways of extending MESC further, to different concreter versions of super-substantivalism.[14]

What speaks in favour of the super-substantivalist core position? Not common sense, surely. But if other arguments speak in favour of it compared to its rivals—e.g. its parsimony or its higher compatibility with modern physics—then we may decide not to worry about common sense too much. Either way, just as in the case of substantivalism, isolating the core commitment is just where work begins. The real interest of super-substantivalism lies in its particular variants rather than in the core commitment shared by all of them, and we will look at some such variants in sections 5 and 6. Nonetheless, we need first to review the two main arguments that have been put forward for super-substantivalism in general (i.e., the core commitment).

3. The Two Main Arguments for Super-Substantivalism per se

3.1 Parsimony

Even though philosophers of physics have looked at super-substantivalism only in passing in recent decades,[15] metaphysicians have argued with passion on behalf of super-substantivalism, although, in many cases, surprisingly briefly. For example, Lewis (1986, p.76), states:[16]

> There are three different conceptions of what the spatiotemporal relations might be. There is the dualist conception: there are the parts of spacetime itself, and there are the pieces of matter or fields or whatnot that occupy some of the parts of spacetime. [. . .]
>
> There are two simpler monistic conceptions. One of them does away with the occupants as separate things: we have the parts of spacetime, and their distance relations are the only spatiotemporal relations. The properties that we usually ascribe to occupants of spacetime—for instance, properties of mass, charge, field strength—belong in fact to parts of spacetime itself. When a part of spacetime has a suitable distribution of local properties, then it is a particle, or a piece of a field, or a donkey, or what have you.
>
> The other monistic conception does the opposite: it does away with the parts of spacetime in favour of the occupants (now not properly so called), so that the only spatiotemporal relations are the distance relations between some of these. I tend to oppose the third option, at least as applied to our world . . . . I tend, more weakly, to oppose the dualist conception as uneconomical.

Lewis effectively claims that the monistic position which takes only spacetime as basic, i.e. super-substantivalism, is preferable to at least classical substantivalism because of the latter's lack of parsimony (it being uneconomical) when postulating two rather than one fundamental kind of substance. Sider (2001, p. 109–110), gives the same argument with more force:

> First, assume that substantivalism is true, that there are such things as points and regions of spacetime. There is then the question of whether there is anything else, whether spatiotemporal objects occupy, but are distinct from, regions of spacetime, or whether they simply are regions of spacetime.
>
> There is considerable pressure to give the latter answer, for otherwise we seem to gratuitously add a category of entities to our ontology. All the properties apparently had by an occupant of spacetime can be understood as being instantiated by the region of spacetime itself. The identification of spatiotemporal objects with the regions is just crying out to be made.

Here too, the main argument put forward in favour of super-substantivalism is its parsimony. While relationalism can always claim that it is more parsimonious than substantivalism because it postulates only one kind of fundamental object, namely material objects, the super-substantivalist can claim that he does even better: he does not only get by with *one kind* of substance but with only *one instantiation* of that kind of substance: there is only one spacetime.

But things are not so simple.[17] Even in the context of the classic substantivalism/relationalism debate, substantivalists have claimed that, despite first appearances, relationalism may not be more parsimonious than substantivalism after all. For while the substantivalist can refer to one interrelated corpus of properties of relations possessed by spacetime, the relationalist has to postulate them as unconnected primitive relations between material objects.[18]

By contrast, the core commitment of super-substantivalism does not commit one to the belief that there is only one entity, spacetime. One may be a monist on the categorical level but a pluralist with regard to the number of elements in that category. Thus, rather than saying 'there is only one concrete object, spacetime', one could also be of the opinion that 'there is only one *kind* of concrete objects: parts of spacetime'.[19]

A pluralistic super-substantivalist, of course, faces the same challenges as the relationalist, who believes that the only fundamental kind of object in the world is that of material objects. The pluralistic super-substantivalist has to explain why and in what sense the parts of spacetime are related so as to give rise to the multitude of phenomena we observe: from extended regions of spacetime, light cones allowing us to distinguish between past and future, to red billiard balls allowing us to smash windows. He may be able to give a far simpler account than the monistic super-substantivalist, or he may not; and indeed it may be that in the end the (normal) substantivalist, who allowed for two rather than one category of fundamental objects (parts of spacetime *and* material objects), can give the simplest account of all.

In the end, this is just speculation, and speculation has to stop at some point. Neither substantivalism, relationalism nor super-substantivalism *as such* can be judged more parsimonious than its competitors; the respective core commitments are just not rich enough. We need to compare a *particular version* of super-substantivalism with particular versions of substantivalism and relationalism, even to hope for a reliable judgement of which position tells the simplest story of how the different parts of the world are related. The core commitments are just the prologue, and knowing the prologue is not enough to judge a story.[20]

But, even if we had a definite answer to the question of which approach is the most parsimonious, what would it tell us? Sure, parsimony is rather attractive philosophically. But, in the end, we don't know if the world is simple, and so we don't know if the simplest approach gives the best possible fit to the world. Let's be honest and admit that in the end striving for parsimony amounts to not much more than a 'principle of laziness', or 'principle of pragmatism', if you will: we look for the simplest approaches because they are the ones that seem easiest to handle at first sight. Having only one kind of screwdriver has its advantages: you never have to look where you put the other ones. But it may turn out that operating with only one kind of screwdriver limits you in how you can handle *the actual world*.

Thus, in the end, super-substantivalism has to face the same hard tests that substantivalism and relationalism faced in the debate following the rediscovery of the hole argument: its compatibility with modern physics has to be checked. In order to do this, we have to forge different concrete variants of super-substantivalism going beyond the core commitment—concrete enough to be compared to the different variants of substantivalism and relationalism in the light of modern physics. Of course, the relevant part of modern physics is field theory, and general relativity in particular.

3.2 Modern field theory

Hartry Field has argued that even though there is a genuine dispute about whether substantivalism or relationalism is the right metaphysical stance with respect to a theory based on a particle ontology, like Newtonian mechanics, this changes when we come to the theories of modern physics. Here, *fields* are fundamental entities, either solely or in addition to particles.

Field argues that a field theory presupposes a substantivalist conception of spacetime. He writes (Field 1989, p.181):

> As I see it, a field theory is simply a theory that assigns causal properties to space-time points or other space-time regions directly (as opposed to indirectly, via matter that occupies those points or regions). (Or to be more accurate, it is the theory that *employs causal predicates* that apply directly to space-time points or regions.) For instance, in electromagnetic field theory we assign to each point in space-time an electromagnetic intensity, irrespective of whether this point is occupied by matter. Obviously this presupposes a substantival view: on a relational view, there are no points or other regions of unoccupied space-time, so the assignment of a property to such a point or region makes no sense. Consequently, it seems to me that for a physical theory to accord with anything reasonably called relationalism, that physical theory cannot be a field theory.

To follow Field's arguments with respect to a *pure* field theory, i.e. a theory in which *only* fields exist—rather than fields alongside material particles—means presupposing a super-substantivalist conception of spacetime.

But is this true? Does field theory (be it pure or not) commit us to interpreting the fields as properties of spacetime points? Earman (1989, p.115), sides with Field to some extent by admitting that super-substantivalism is a *natural* interpretation of a pure field theory:[21]

> The second embellishment comes into its own under what can be called *supersubstantivalism*, the view that space is the only first-order substance in the sense that space points or regions are the only elements of the domains of the intended models of the physical worlds.
>
> [...]
>
> To realize super-substantivalism, one doesn't have to revert to the view that space is stuff that forms the corpus of bodies, nor does one have to resort to some outlandish theory. Indeed, modern field theory is not implausibly read as saying the physical world is fully described by giving the values of various fields, whether scalar, vector, or tensor, which fields are attributes of the space-time manifold *M*.

The second half of the quotation alludes to the distinction between modest and radical super-substantivalism that we will look at in detail in section 6. Field's view has been criticized, especially since he does not really give an argument for why field theory should be interpreted as asserting that spacetime points (or regions) are substances and fields properties of these substances; Field merely states this to be the case. Malament (1982, p.531–532), points out that surely an argument is needed here: after all, Malament argues, it is *fields* such as the electromagnetic field that possess mass-energy content, not the points of spacetime.[22]

A similar argument can be found in Teller (1996), who writes (p.382):

> Hartry Field (1980, p.35) argued, very simply, that to do field theories we must have the space-time points as the things of which the field quantities are predicated.
>
> But consider the fact that relativity theories drop the distinction between mass and energy, so that the field quantities, themselves carrying energy, can be seen as substantival. Thus we can reverse the role of predicate and subject. Instead of attributing a bit of mass-energy, in the form of a field, to a substantival space-time point, we can, on the present proposal, attribute a relative space-time location to a bit of a field—a bit of mass-energy in the form of an electromagnetic field, a matter density field, or the like. The relative location is just a relational property, that is, a space-relation to some actually exemplified trajectory.

Field could now answer that mass-energy is represented by the mass-energy-momentum tensor field $T_{\mu\nu}$, and hence should also be considered as a property of spacetime points, albeit one that is associated with the spacetime point also possessing the property of an electromagnetic field (say) being present. In any case, Malament and Teller effectively show that Schaffer (2009, p.142), is too quick when he claims that "everyone in the debate understands [$T_{\mu\nu}$] as a feature of spacetime"—many understand it as a property of material systems, described by a field.[23]

What remains is that it seems *plausible* (Earman) rather than *necessary* (Field) to interpret (pure) field theories in super-substantivalist terms, to regard fields as properties of spacetime points or regions.[24]

4. General Relativity as an Argument for the Minimal Extension of the Core Commitment?

In the introduction to this paper I said that the modern substantivalism/relationalism debate became more sophisticated, more interesting, when, following the philosophical analysis of the hole argument within GR, the community modified the question 'Is substantivalism or relationalism the more attractive philosophical position?' to '*Given our best scientific theory of space and time, GR,* is substantivalism or relationalism the more attractive philosophical position?'

We have now seen, in the previous section, that field theory as such does not speak clearly for the super-substantivalist core commitment: that spacetime is the only substance that exists. But maybe this is not that surprising: most field theories are not really *supposed to be about* space and time. But GR *is* a field theory that is supposed to be about space and time: the metric tensor $g_{\mu\nu}$ of GR famously plays a double role as a potential for the gravitational field on the one hand, and as encoding spatiotemporal distances and the distinction between past and future one the other. But GR is not *just* about spacetime structure, it's also about how spacetime structure, and the metric field in particular, interact with matter fields like an electromagnetic field or the fluid that makes up a star.[25] This interaction is expressed in the Einstein field equations.

Let us assume, for now, that the metric field $g_{\mu\nu}$ is the referent of 'spacetime (structure)', while the matter fields of GR are the referent of 'matter'. With this in hand we can move beyond the super-substantival core commitment towards its minimal extension (MESC). Thus we can ask: *Given GR*, should we subscribe to the minimal extension of the super-substantival core commitment? Given GR, should we believe that spacetime (structure) is ontologically prior to matter?

Indeed, one can make the following argument that has not been considered in the philosophcial literature so far. The Einstein field equations, the mathematical and physical heart of GR, describe how the metric field $g_{\mu\nu}$ and the matter fields interact. It is easy to proceed to the so-called vacuum field equations, in which the matter fields vanish and the Einstein equations describe only the dynamics of the metric field by itself. The solutions to the vacuum field equations then describe the different possible 'empty' universes allowed for by GR. The very existence of these vacuum solutions is one of the prime arguments to prefer substantivalism over relationalism, given GR: the GR field equations allow for countless non-trivial universes in the absence of matter. But is there a further argument for the claim that spacetime is ontologically prior to matter?

Well, yes: while GR allows for the possibility that the matter fields might vanish, the theory does *not* allow for the metric field to vanish at any point of spacetime.[26] So *if* one takes the metric field (or the pair of manifold M and metric field $g_{\mu\nu}$) to represent spacetime, then according to GR the theory can be seen as ontologically prior to matter in the sense that it allows for spacetime to exist without matter, but not for matter to exist without spacetime. Furthermore, as argued in Lehmkuhl (2011), in GR it is in general not possible to assign the property of possessing mass-energy, essential for a field to be a matter field, without reference to the spacetime metric.

In a way, this 'argument from GR', turns upside down Schaffer's and Thompson's 'argument from materialisation', discussed in footnote 24 above. While the latter claims that a priori matter cannot exist without spacetime, the argument presented above points out that a posteriori, given the Einstein field equations, spacetime can exist without matter whereas matter cannot exist without spacetime.

I do think that the argument from GR is the strongest available argument for the minimal extension of the super-substantival core commitment. But it, too, has a weakness. All it tells us is that, given GR, spacetime can exist by itself while matter must coexist with spacetime. But is that really enough to establish that spacetime is ontologically prior to matter? It depends on how we spell out the notion of ontological priority. Thus, before we can answer the question of whether GR speaks for adopting super-substantivalism, we have to go beyond the super-substantival core commitment and its minimal extension: we have to examine how MESC can be extended to different positions with flesh and muscles on the bones.

5. Extensions of the Super-Substantivalist Core Commitment and its Minimal Extension

Above I have formulated the minimal extension of the super-substantival core commitment (MESC) as follows: spacetime is *the only* substance in the world; and spacetime is ontologically prior to matter. If 'ontologically prior to' is identified with 'reducible to', a shorter version would be: *All there is is reducible to spacetime*.

But identifying ontological priority with reducibility already goes beyond MESC. Indeed, it is an advantage of MESC that it leaves plenty of possibilities to make the super-substantivalist position more precise, make it more concrete, bringing into being a veritable *family* of positions, rivaling the different forms of substantivalism and relationalism created in the last few decades.

Currently, the most prominent extension of the core commitment in the metaphysical literature is surely what Schaffer (2009) called *the identity view*. The latter forms a sub-family of super-substantival positions separate from the MESC-family, and all of its positions have in common that they *identify* material objects with spacetime regions.[27] Some variants identify *every* spacetime region with a material object (these variants are preferred by Schaffer; he calls them the unrestricted identity view),[28] others only with spacetime regions that fulfil certain conditions.[29] An alternative is the *composition view*, which regards material objects as *composed* of spacetime regions rather than as identical to them.[30]

The question of whether the identity and the composition view are really two distinct views turns on old questions of metaphysics, often discussed using a statue made of clay, and investigated by pondering the question of whether the statue is or is not identical to the clay it is composed of. I will not elaborate on the issue as it is clear that it does not pertain to super-substantivalism as such; whatever position you take with regard to the relationship between identity and composition will transfer from the statue and clay it's made of to material objects and the spacetime regions they are made of according to super-substantivalism.[31] However, I note that the composition view as applied to material objects and spacetime (just as in the case of the statue and clay) has the advantage that one can give a better account of a *process* that amounts to creating a material object from parts of spacetime. Furthermore, the composition view allows for the composed object to have properties different from those possessed by its constituents.[32] Indeed, this is the super-substantivalist position that Thomas (2013b, chapter 3), attributes to the early Newton: he denies the Cartesian identification of matter and space, but thinks of matter as created from space, whilst seeing them as belonging to two different categories nonetheless.[33]

We have seen that two ways to extend the super-substantivalist core commitment involve saying that material objects are either identical to or composed of spacetime regions. However, we should note that even just thinking of spacetime as composed of spacetime regions goes beyond the core commitments of both substantivalism and super-substantivalism. We should instead speak of the *parts* whereof spacetime is composed; this leaves open whether those parts are manifold points or regions, discrete grains not representable by a manifold, or structural aspects of spacetime like its affine or metric structure. Indeed, in the context of modern differential geometry it seems much more natural to think of the building blocks of spacetime not as regions but (in that hierarchical order) as the chain of manifold structure, topological structure, projective and conformal structure, affine structure, and, finally, metric structure. Different spacetime theories assume spacetime to be composed of different members of this list, and that they are related to one another in different ways. Speaking of spacetime as composed of spacetime regions does not do justice to this intricate network of ontological dependences; but either way, speaking of spacetime as composed of parts allows for (super-)substantivalists who believe these parts to be regions, and others who believe the parts to be the above structural aspects.

Let us come back to the question of what may be meant by the assertion that spacetime is ontologically prior to matter in the MESC extension of the core commitment. A minimal requirement for ontological priority is that the relation is asymmetrical and irreflexive: if A is ontologically prior to B then B is not ontologically prior to A; and nothing is ontologically prior to itself.

One way of spelling out what it means for A to be ontologically prior to B is to say that B is *reducible* to A. The follow-up question is then: what are the necessary and sufficient conditions for something to be reducible? Of course, there is a huge literature on this in metaphysics and philosophy of science. Even the proponent of the identity view can be a reductionist if he sees ‘being identical to’ as sufficient for reducibility; yet, he faces the problem that identity is a symmetrical relation while reducibility, on all accounts I think, is not.[34]

Another brand of super-substantivalism may think of spacetime as ontologically prior to material objects by virtue of the latter being *emergent* from the former, a position famously attributed to Samuel Alexander.[35] Just as with ‘reducibility’, the most important question is how ‘emergence’ is defined. A promising view, offered by Butterfield (2011*a*,*b*), defines emergence “as behaviour that is novel and robust relative to some comparison class”. Defined in this way, emergence is in principle compatible with reduction, if one follows Butterfield in defining reduction as deduction with the help of auxiliary conditions. Either way, without going into details of the different definitions of emergence that have been put forward: thinking of matter as emergent from spacetime also allows for it to have properties different from the spacetime parts it emerges from. However, matter being emergent from spacetime can only be a sufficient, not a necessary condition for spacetime to be ontologically prior to matter.

Also, it seems sensible to take reducibility of matter to spacetime to be sufficient for spacetime to be ontologically prior to matter; it is less clear whether the condition is also necessary (in which case ‘ontologically secondary to’ and ‘reducible to’ would be synonyms). Still it is clear that a big subset of the super-substantival family of positions will spell out ontological priority via reducibilty.

With this, let us come back to the question of whether GR gives us reason to believe in the ontological priority of spacetime over matter, and if so in what sense. The argument from GR elaborated in section 4 concludes that according to GR spacetime (structure) can exist without matter, but matter cannot exist without spacetime structure. This relationship of one-sided need for coexistence fulfils at least part of the above-mentioned minimal requirement of ontological priority: it is asymmetrical in that matter's existence depends on the existence of spacetime structure but not vice versa.[36] However, GR does not give us reason to believe that the existence of matter is either reducible to or even supervenient on the existence of spacetime structure; and if 'ontological priority' is spelt out in terms of reducibility or supervenience then GR does not give us reason to believe in the ontological priority of spacetime over matter. The reason is that the matter fields have dynamical degrees of freedom that are independent of spacetime structure: the matter fields interact with the metric field, but what they do, how they develop, cannot be reduced to and does not supervene on what the metric field does. Thus, GR gives us reason to believe in a minimal ontological priority of spacetime over matter, a specific way of cashing out the MESC position, but not to believe in more demanding versions. However, in the next section I will argue that, just as we presupposed GR in this section, presupposing certain extensions or modifications of GR *would* give us reason to embrace ontological priority of spacetime over matter in terms of matter being reducible to spacetime structure.

But before we look at such theories and their interpretation, let me say a few words about the choice of words in the last two sections. All of the above discussion suggests that we have a clear handle on what counts as 'matter' and what as 'spacetime (structure)', and that we can look at the two sides of the divide and wonder whether one is ontologically prior to the other. Of course, one of the most important lessons of modern spacetime theory is that the distinction between matter and spacetime has become more and more blurred. Indeed, most of the debate that resulted in spelling out different forms of (normal) substantivalism starts from the discussion of whether GR's metric field $g_{\mu\nu}$ should be classified as encoding part of spacetime (structure), or whether it is 'a field like any other', i.e. so close to matter fields like the electromagnetic field $F_{\mu\nu}$ that a categorical distinction is unjustified.[37]

However, I take it that both camps in this dispute agree that *if* one takes spacetime to be a substance, *then* the $g_{\mu\nu}$ field, among other things giving a measure of distance between points of spacetime, can be interpreted as encoding important properties of that substance, or as endowing spacetime with these properties. The question for the super-substantivalist now is which other properties can be taken to describe properties or aspects of spacetime. This brings us to the distinction between modest and radical super-substantivalism.

6. Modest and Radical Super-Substantivalism

The metric field $g_{\mu\nu}$ allows us to define spatial distances, temporal durations and a distinction between past and future. If you believe there is spacetime, then you almost can't help taking the metric field as encoding at least some of its paradigmatic properties.[38] But the same is not true for the electromagnetic field and other matter fields: we *can* interpret an electromagnetic field strength as a property of the spacetime region it occurs in, but the way the electromagnetic field features in the theory (here GR) does not mean we *have* to.

Thus, there are some fields, which *can* be interpreted as properties of spacetime but where this possibility is only there because they are fields in the first place (cf. section 3.2). And then there are other fields where the role the field plays in a particular theory *offers* that field *in particular* to be interpreted as a property of spacetime; if one believes in the substantival existence of spacetime at all.[39] The question of whether one regards the distinction between geometric and non-geometric properties/fields as important neatly divides the super-substantivalist family of positions into two camps.

The two sets of family members correspond to what Skow (2005, p.66–68), called radical and modest super-substantivalism, respectively. The distinction comes from different answers to the question of which *fundamental* properties spacetime is allowed to instantiate.

For a *modest super-substantivalist*, there is no real difference between saying 'This spatial region has a diameter of 8 inches' and the statement 'This spatial region is red'. The modest super-substantivalist allows spacetime to instantiate (on the fundamental level) not only topological and geometrical properties but also the properties we normally regard as instantiated by matter, such as colour, mass, electric charge or momentum density.

As far as I can see, most if not all metaphysicians advocating super-substantivalism belong to the modest camp. Schaffer (2009, p. 139), makes this particularly clear when he asks

> Once one has pinned the geometrical and mereological properties directly onto the receptacle, why stop there? Why not also pin the masses and charges onto the receptacle as well? In general, is there some principled reason for using spacetime as the pincushion for only some of the fundamental properties?

It is completely clear to Schaffer that one can attribute to spacetime regions properties such as mass or colour just as much as extension or circumference. He thereby implicitly gives up on the importance of distinguishing between properties/fields that even the dualistic substantivalist would interpret as aspects of spacetime structure (like the metric field $g_{\mu\nu}$ in GR), and those where he would not do so (like the electromagnetic field $F_{\mu\nu}$ in GR).

The modest super-substantivalist just shrugs his shoulders when the dualistic substantivalist asks him whether attributing the properties 'red' or 'solid' to a spacetime region does not seem to have a different quality from attributing to it the property of being 'extended'.

But I do believe that the modest super-substantivalist has to give an argument here. *Why* should we assume that spacetime can instantiate as fundamental properties *both* geometric properties like extensions, shapes and distances, *and* non-geometric properties like colour and solidity? Rhetorical questions just don't cut it here.[40]

The *radical super-substantivalist* chooses a different path. He agrees with the dualistic substantivalist that only geometrical (and topological) properties should be attributed to spacetime and its parts. As a consequence, he has to offer an account of how *apparently* non-geometrical poperties like colour, electric charge or solidity can be *reduced to* (or indeed emerge from) geometrical or topological properties. Sklar (1974, p.166), is very clear about what he thinks of the two camps of super-substantivalism:

> The identification of all of the material world with the structured world of spacetime is not to be interpreted as the linguistic trick of simply replacing objects by the region of spacetime they occupy and some novel "objectifying feature"—say replacing 'There is a desk in the (X,T) region' by 'The (X,T) region desks'. The *scientific* program of reducing matter to spacetime is rather more on the order of the scientific program of reducing material objects to arrays of their microscopic constituents or identifying light rays with electromagnetic radiation. In the reduction, the assertion of the existence of a material object at some spacetime location is to be shown reducible to the assertion of some spacetime feature holding in the spacetime region, say its having a certain intrinsic curvature over the region.

Even though I sympathise with Sklar, it has to be conceded that he is somewhat unfair towards the modest super-substantivalist. True, modest super-substantivalism is *not* a scientific research programme. It is not a stance that could motivate research in physics, or serve as guiding principle for such research. Modest super-substantivalism is a purely metaphysical standpoint that can be taken quite independently from the physical theory we find to be true, and it is motivated mostly by purely philosophical advantages.

That is not bad in itself. But it cannot be denied that a philosophical standpoint like radical super-substantivalism that *can* be fruitful for physics, motivate it and in turn be questioned by it, is a very desirable thing.

This is what radically super-substantivalist positions offer: they are programmes that pose a real challenge to physics, offering fruitful heuristics for scientific research, and can in turn be challenged by it. One important example of a radically suber-substantival research programme is John Wheeler's 'Geometrodynamics'. His aims are best summarised in the following quotation:[41]

> Is space-time only an arena within which fields and particles move about as 'physical' and 'foreign' entities? Or is the four-dimensional continuum all there is? Is curved empty geometry a kind of magic building material out of which everything in the physical world is made: (1) slow curvature in one region of space describes a gravitational field; (2) a rippled geometry with a different type of curvature somewhere else describes an electromagnetic field; (3) a knotted-up region of high curvature describes a concentration of charge and mass-energy that moves like a particle? Are fields and particles foreign entities immersed *in* geometry, or are they nothing *but* geometry?

The programme gives us *one* example of how the super-substantival core commitment may be expanded into a precise position which brings metaphyics and physics closer together. Rather than saying that all properties we normally attribute to material systems are properties of spacetime (modest super-substantivalism), or even saying that non-geometrical properties have to be *somehow* reduced to geometrical properties, Wheeler suggests *which* apparently non-geometrical properties might be reducible to *which* geometrical properties. In his approach, the gravitational field is reduced to one kind of spacetime curvature, whereas the electromagnetic field is reduced to another.[42] Particles are reconceptualised as small regions of spacetime in which the curvature is particularly strong and of a certain form; for stable particles, gravitational and electromagnetic curvature have to keep each other in balance. Wheeler called such constructs '*geons*, gravitational-electromagnetic entities'.[43]

Wheeler's research programme was abandoned in the 1970s.[44] For Sklar is right: every version of radical super-substantivalism is a scientific research programme, and as such it can succeed or fail, or be revived after it was judged to have failed.[45] Wheeler wanted to reduce gravity, electromagnetism, and mass-energy to four-dimensional curvature. More recently, other research programmes motivated by radical super-substantivalism have been proposed. Wesson (2007) and collaborators have revisited Theodor Kaluza's and Oskar Klein's idea that spacetime is really five- rather than four-dimensional. Like Klein (1926, 1928), Wesson et al. postulate the vacuum Einstein equations as the field equations of the five-dimensional spacetime. In contrast to the founding fathers of the idea, they get much further in deriving the matter we see in four dimensions from the geometrical properties of the five-dimensional spacetime. In a different, quantum-mechanical, research programme, Bilson-Thompson et al. (2007) start out from the mathematics of Loop Quantum Gravity, introducing a canonical split of spacetime into space and time and assuming that space fundamentally consists of discrete 'grains' of space. The fundamental particles of the standard model of particle physics (and their most important properties rest mass, spin and different kinds of charge) are aimed to be reduced to different states of these grains. Thus, elementary particles would be nothing other than quanta of space.

We see that both in the classical and in the quantum domains there are very different ways in which one could aim to reduce the apparently non-geometrical properties of what we perceive as matter to geometrical or topological properties of spacetime. And each path corresponds to a particular variant of radical super-substantivalism. Many more than those already pursued in physics and described above are possible: e.g., the mass of an electron could be reduced not to the curvature structure of spacetime but to its affine structure, the spin of the electron related to the torsion structure of spacetime and its electric charge to the topological structure of spacetime.[46]

Which aspect of spacetime structure matter is associated with (curvature is only one possibility) will also determine whether an empty (matter-free) spacetime is allowed. If matter is reducible to curvature structure alone, then we can have empty spacetime without losing a grip on its fundamental structure; if it corresponds to certain topological properties, then we cannot have a spacetime without the presence of matter—even though it would still be derivative of spacetime, it would also be necessarily co-existent with it. We see that even within the radical category, there are plenty of distinctions to be made, different super-substantival outlooks.

It has to be noted that modest and radical super-substantivalism involve different conceptions of what philosophy is supposed to do, especially regarding the extent to which it ought to engange with physics. The modest camp takes the question of whether super-substantivalism is true to be an essentially philosophical question: maybe physics can be used to give *some* argument in favour of the already formulated position, but it is perfectly acceptable to adopt the position for purely philosophical reasons. The radical super-substantivalist insists that a philosophical position about the relationship between spacetime and matter needs to *start* with what physics tells us, or might end up telling us, about the relationship between spacetime and matter, and adopt the philosophical position that best fits the physics.

Not much can happen to the modest super-substantivalist, neither good nor bad things: however physics develops, there is a way for him to uphold his position, even though some developments might make this more difficult than others. In contrast, the different versions of radical super-substantivalism have the potential to provide physics with a fruitful interpretation and heuristic, albeit at the price of possibly failing arm in arm with the physics they motivated.

As pointed out by Sklar, radical super-substantivalism is more than a metaphysical position. It is a research programme, a challenge and motivator for physics. At the same time, it is philosophically even more attractive than modest super-substantivalism. For the latter has to allow both geometrical and non-geometrical properties as categories, whereas the radical super-substantivalist tries to get by with only geometrical and topological properties and structures. But the radical also allows for the distinction between physics and its philosophical interpretation to become blurred: He can expect *to learn something new* about matter once he has associated it with particular aspects of spacetime structure, for the relationships between different aspects of spacetime structure we know of are likely to direct our attention to as yet unknown relationships between the different kinds of matter and their properties.

The radical super-substantivalist may fail. But, if he succeeds, the reward is great.

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Notes

[1] See Section 2 for a more precise definition of the core commitment of substantivalism.

[2] For details on the predecessors of modern super-substantivalism see Graves (1972) and Skow (2005); for an argument that at least the early Newton was a super-substantivalist see Thomas (2013b, chapter 3).

[3] I will argue below that strictly speaking the substantivalist core commitment does not commit one to any assumption about the nature of matter, but just to the claim that *spacetime* is a substance in a sense to be specified. Still, most (spacetime) substantivalists presuppose that matter is a fundamental substance, too. As we will see, if one defines substantivalism as a commitment only to the fundamentality of space or spacetime, super-substantivalism is a (more radical) version of substantivalism.

[4] Of course, one can also be a super-substantivalist with regard to space rather than spacetime, and naturally Descartes and Clifford were super-substantivalists of this stripe (regarding space/matter; of course, Descartes was a dualist with regard to space/mind). However, after the development of the general theory of relativity, super-substantivalism with regard to spacetime seems promising. (Note, though, that the development of a super-substantival version of the 3-dimensional 'shape dynamics', see e.g. Barbour (2012), would be very interesting indeed.) For convenience, I will restrict the discussion to super-substantivalism with respect to spacetime, although much of what I say will also apply to the corresponding position that takes space as the only fundamental substance.

[5] Of course, judgements on how explanatory a given theory is may vary depending on one's account of explanation, and indeed on one's interpretation of the theory in question.

[6] In section 2, I will isolate what I call the 'core commitment' that all versions of substantivalism share; a similar isolation may be possible for relationalist standpoints. Some of the main variants of substantivalism produced by the debate can be found in Maudlin (1989), Butterfield (1989), Hoefer (1996) and Pooley (forthcoming); see in particular Pooley (2013) for a comprehensive overview and analysis of the debate.

[7] See Leibniz (1956).

[8] Pooley writes about substantivalism with respect to space here, but what he says generalises directly to spacetime.

[9] Ehlers et al. (1972) have argued that the causal structure of spacetime is identical to its *conformal structure*, i.e. to its being endowed with an equivalence class of metrics $g_{\mu\nu}$ at every spacetime point. They identify the path structure of spacetime with its *projective structure* and define a condition of compatibility between conformal and projective structure. Only if the condition is fullfilled do we have a unique *affine structure*, which distinguishes geodesics from non-geodesics. And only if the *curvature structure* defined by the affine structure fulfils another condition (that of the vanishing of Weylian length curvature) do we have the pseudo-Riemannian spacetime upon which the formulation of GR rests.

[10] Schaffer (2009) traces this notion of substance back to Aristotle, Descartes and Spinoza. For a discussion of the notion of being 'basic' see Schaffer (2008, section 3.1). (Note that Schaffer introduces 'basic' as a "lower bound of ontological priority"; I will use the latter concept in the definition of the super-substantivalist core commitment below.) Thomas (2013b) provides the most careful analysis of how the term 'substance' has been used as applied to space and spacetime from the Greeks to modern metaphysics; and argues that it is anachronistic to define 'substance' as a concrete irreducible object. She also isolates two core commitments of substantivalists, which contains the above core commitment as a proper subset. The second core commitment she argues the substantivalist to have is a commitment towards some relationship between space or spacetime and matter, while different substantivalists may differ with regard to the nature of this relationship. I agree that virtually all substantivalists hold such a commitment; but I do not think they have to *because* of their being space or spacetime substantivalists.

[11] Note that the referent of 'spacetime' in this commitment is the spacetime of the *actual* world. It is perfectly possible to believe that spacetime is a substance in the sense defined above without believing that it *has to be* a substance in all possible worlds. Indeed, most substantivalists who have adopted the position because they think it is the best interpretation of GR and other modern spacetime theories would be happy to admit that in a world in which substantially different laws of nature hold (especially those governing the relations between spacetime structure and matter) spacetime might not be a substance. Either way, believing that spacetime is *essentially* a substance would go beyond the core commitment of substantivalism as defined here. Furthermore, the core commitment of substantivalism does not commit to seeing two regions of spacetime in distinct worlds as being primitively transworld identifiable with one another.

[12] I will discuss different options for extending the core commitment in section 5 and 6. Some of them involve adopting priority monism with respect to spacetime, others pluralism; and others still different options for what the parts of spacetime are.

[13] I do not believe that all versions of the identity view have to face this danger, but the position Schaffer (2009) calls the unrestricted identity view (discussed further in section 5), his favourite version of the identity view, definitely does. Of course he may well decide to embrace the breakdown of the spacetime/matter distinction; and he could draw on the discussion of substantivalism/relationism in philosophy of physics for support of said embrace (see the end of section 6).

[14] See sections 5 for different variants of super-substantivalism along these lines. For different accounts of ontological priority/ontological dependence see Fine (1995), Bricker (2006), and Correia (2008).

[15] This is likely related to a particular super-substantivalist programme in physics, John Wheeler's Geometrodynamics, being abandoned in the early 1970s, to the big disappointment of many philosophers of physics; see Stachel (1972) and Misner (1972) for details of the development of this research programme. Of course, one particular variant of super-substantivalism being unsuccessful does not say much about the promise of the family of positions as a whole (compare the abandonment of manifold substantivalism as a consequence of the hole argument and the subsequent development of more sophisticated versions of substantivalism).

[16] Note that Lewis' characterisation of super-substantivalism goes beyond what I call the core commitment: he claims the super-substantivalist is committed to taking only distance relations between the parts of spacetime as fundamental. However, it is completely compatible with the super-substantivalist core commitment to take the topological relations or affine structure as equally or even more fundamental than distance structure. (Indeed, differential geometry tells us that we need topological structure to have metric/distance structure but not vice versa. Affine structure can be derived from metric structure in pseudo-Riemannian spacetimes but not in generalisations thereof.)

[17] See Thomas (2013b) for a complementary discussion of the argument from parsimony.

[18] See Field (1985) and Maudlin (1993, p.194–196).

[19] Schaffer is a monistic super-substantivalist, thinking that the whole of spacetime has priority over its parts, while Sider is a pluralistic super-substantivalist, denying priority of the whole of spacetime. Both take the parts of spacetime to be regions; see Schaffer (2009) and Sider (2001, 2007), respectively.

[20] I will distinguish between different versions of super-substantivalism in sections 5 and 6.

[21] Schaffer (2009, p.142), reads Earman (1989) as "suggesting" super-substantivalism, yet the latter merely says that modern field theory is "not implausibly read" in a super-substantival fashion. Indeed Earman does not endorse this view, instead he ends up defending a view that he locates between substantivalism and relationalism, a view that gets rid of points and regions entirely and endorses the use of 'Einstein Algebras' as introduced by Geroch (1972), renamed by Earman as 'Leibniz Algebras'.

[22] French & Ladyman (2003, p.46) acknowledge both options when they write: "[A] form of metaphysical underdetermination arises here with the physics supporting both the view of fields as substances whose properties are instantiated at space-time points (or regions) and the view of fields as nothing but properties of those space-time points (or regions)".

[23] Of course, taking such a position does not mean that the properties of material systems do not depend on spacetime. In Lehmkuhl (2011), I argued that mass-energy-momentum density $T_{\mu\nu}$ is a property material systems have only in virtue of their relationship to spacetime structure. However, such a *dependence* of important properties of material systems on spacetime structure is not the same as a *reduction* of these properties to spacetime structure.

[24] In this section I have discussed what I regard as the two most promising arguments for super-substantivalism per se, i.e. for the core commitment. Both Schaffer (2009) and Thomas (2013b) put a lot of weight on a third argument, which they call the argument from materialisation. In short, the argument says that super-substantivalism is the only position that can readily explain the alleged fact that "[m]aterial objects cannot exist without occupying spacetime regions" (Schaffer 2009, p.141) or, more carefully put, "the fact that matter seems to be *necessarily* spatio-temporally located" (Thomas 2013b, p.120). My answer is that it is not at all clear that this really is a fact, that it really is *necessary* for something to occupy parts of spacetime in order to be material. This doubt is strengthened by the fact that there are now various approaches in quantum gravity research which start from certain quantum structures (which are not defined on a space- or spacetime manifold) as fundamental and which aim to derive spacetime as an emergent entity in the macroscopic limit. In these theories, (quantum) matter *does* exist without occupying parts of spacetime, and *gives rise* to spacetime in some domain. The very

conceivability of such approaches suggests that matter cannot *necessarily* be bound to a spatio-temporal existence.

[25] In astrophysics, the most often used models for stars are delivered by relativistic fluid dynamics, especially by the special cases of a 'perfect fluid' and 'relativistic dust'. Of course everybody knows that this is just an approximation to the atomistic makeup of the star, but the fluid approximations are often sufficient for the purposes of astrophysics.

[26] This follows directly from the mathematical properties of the metric tensor. It is always possible to choose a coordinate system such that the metric takes Minkowskian values at a point, i.e. it is always possible to make all components but those on the diagonal of the metric tensor (in its matrix representation) vanish. But the sum of the diagonal components of any matrix (its trace) is invariant under coordinate transformations. Thus, it is impossible for the trace to be non-zero in one coordinate system but zero in another. Since, as stated, it is always possible to find a coordinate system in which the diagonal components of the metric are non-zero (at any point), it is impossible to find a coordinate system in which all its components are zero (at any point). See e.g. Poisson and Will (2014) for details.

[27] I will argue below that one should generalize the category 'spacetime regions' to 'spacetime parts', which contains spacetime regions as a proper subset.

[28] On this view, even what physicists call empty Minkowski spacetime (or indeed any 'vacuum solution' of General Relativity) would count as one giant material object, by fiat.

[29] If I had to choose among only different variants of the identity view rather than also being allowed to choose from (what I think are) more attractive variants of super-substantivalism, I would choose a variant where only spacetime regions that possess mass-energy are identified with material objects. The reason is that, I think, there are strong reasons to regard mass-energy as an essential (or, if you want, necessary) property of matter, as argued in Lehmkuhl (2011).

[30] Thomas (2013b, chapter 3), attributes this version of super-substantivalism to the early Newton, expressed in his *De Gravitatione*.

[31] If the identity and the composition relationship are concluded *not* to be identical, in particular if the composition relationship is taken to imply that that which is composing is ontologically prior to that which is composed, then the composition view is an extension of the MESC (familiy of) positions.

[32] A gas has a temperature even if the particles it's made of do not, and a spacetime manifold has the property of being 'connected' (in a technical sense) even if no point by itself has that property; more on this and the connection to the debate between reductionism and emergentism below.

[33] For Newton in *De Grav*, matter, being composed of space, is a substance, whereas space itself is not. This means that Newton is not so easily categorized as a substantivalist as is often done; however, it is clear that Newton (in *De Grav*) thought of space as ontolologically prior to matter. Thus, even though classifying him as a straightforward substantivalist is tricky, it is clear that he believed in the 'super-' of super-substantivalism.

[34] For similar reasons, *supervenience* is unlikely sufficient for ontological priority, if one takes the supervenience relation to be reflexive and not asymmetrical.

[35] See Thomas (2013a) for details.

[36] It is debatable whether the relationship is also irreflexive, i.e. whether it is true that the existence of spacetime (structure) is not ontologically prior to itself. The answer to the question depends on what exactly we take the referent of 'spacetime (structure)' to be. Metric structure needs manifold structure to be in place but not vice versa; affine structure (that allows to distinguish between straight and non-straight lines) was originally thought to depend on metric structure but was then found to be definable independently of the metric (see Levi-Civita (1917), Weyl (1918)). The only way to make the relationship in question irreflexive is to take 'spacetime (structure)' to mean '*all of* spacetime (structure)'; then the hierarchy of spacetime structures just hinted at can actually serve as an argument for the claim that 'all of spacetime structure' is not ontologically prior to 'all of spacetime structure'.

[37] See Anderson (1999), Brown (2009, 2007) and Rovelli (2004) for the latter view, and Maudlin (1993, 1989), Hoefer (1996) and Pooley (2013, forthcoming) for the former view.

[38] This is true even for manifold substantivalists, i.e. substantivalists who take only the manifold M as representing physical spacetime (rather than, say, the pair $(M, g_{\mu\nu})$). For, even if one regards the metric field $g_{\mu\nu}$ as analogous in almost every respect to the other fields defined on M, it is still the case that $g_{\mu\nu}$ encodes paradigmatically spatiotemporal properties, that it endows the manifold M with

a geometry, or—put more neutrally—that it allows for a geometrical interpretation which other fields lack.

[39] Of course, which category a given field should be put in depends on which theory of physics one takes as a basis of one's metaphysical deliberations. If the theory in question is GR, then the metric field arguably belongs in the 'offers itself to be interpreted as a property of spacetime' category, while the electromagnetic field belongs in the '*can* be interpreted as a property of spacetime' category. If the theory in question is, say, Kaluza's original five-dimensional unified field theory of gravitation and electromagnetism (see Kaluza (1921)), then both the 4-dimensional metric field and the electromagnetic field arise from projection of the metric field of 5-dimensional spacetime, and are thus equally 'spacetimy'.

[40] One way of approaching this challenge would be to give an argument for why the distinction between geometric and non-geometric properties or fields just is not an important or enduring distinction. Indeed, in Lehmkuhl (2014) I argued that Einstein himself took the distinction between geometric and non-geometric fields as a purely linguistic distinction, and argued that the metric field $g_{\mu\nu}$ is neither more nor less geometric, even according to GR, than the Farday tensor $F_{\mu\nu}$ representing the electromagnetic field. He did admit, though, that it was easier to give a geometric interpretation to $g_{\mu\nu}$; he just considered this choice a "private matter" rather than something that tells us anything about the world.

[41] Wheeler (1962a, p.361).

[42] Wheeler solved the Einstein-Maxwell equations for the electromagnetic field tensor $F_{\mu\nu}$, pointing out that Rainich and Misner had shown that this is possible only if the curvature tensor fulfils the two properties

$$R = 0 \tag{1}$$

and

$$R_\alpha{}^\beta R_\beta{}^\gamma = \delta_\alpha{}^\gamma \left(\frac{1}{4} R_{\sigma\tau} R^{\sigma\tau} \right) \tag{2}$$

The result is then put into Maxwell's equations, and thus the Einstein-Maxwell equations are formulated in terms of $R_{\mu\nu\sigma}{}^\omega$ alone rather than $R_{\mu\nu\sigma}{}^\omega$ and $F_{\mu\nu}$. With the definition

$$W_\tau := (-g)^{\frac{1}{2}} \epsilon_{\tau\lambda\mu\nu} \frac{(\nabla_\mu R^{\lambda\beta}) R_\beta{}^\nu}{R_{\gamma\delta} R^{\gamma\delta}} \tag{3}$$

the Maxwell equations then become

$$\nabla_\eta W_\tau - \nabla_\tau W_\eta = 0, \tag{4}$$

which are equations of fourth order in the metric. See Wheeler (1962b, pp.250–253).

[43] Einstein (1919), unbeknownst to Wheeler, had tried out a mathematically similar approach, interestingly without radically super-substantivalist motivations.

[44] See Stachel (1972), Graves (1972), Earman (1972), Misner (1972) for details of the reasons.

[45] Giulini (forthcoming) discusses the extent to which research in general relativity showed that the ideals of geometrodynamics were fulfilled to a much larger extent by results in canonical GR (a formulation of GR with which geometrodynamics had started out with) than Wheeler and Misner had antipicated when they abandoned the approach.

[46] Relating electric charge to the topology of a multiply connected four-dimensional spacetime was actually part of Wheeler's programme; the other two options named here have not, to my knowledge, been pursued yet.

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