Geometry, Fields, and Spacetime

James Binkoski

Abstract

I present an argument against a relational theory of spacetime that regards spacetime as a 'structural quality of the field'. The argument takes the form of a trilemma. To make the argument, I focus on relativistic worlds in which there exist just two fields, an electromagnetic field and a gravitational field. Then there are three options: either spacetime is a structural quality of each field separately, both fields together, or one field but not the other. I argue that the first option founders on a problem of geometric coordination and that the second and third options collapse into substantivalism. In particular, on the third option it becomes clear that the relationalist's path to Leibniz equivalence is no simpler or more straightforward than the substantivalist's.

1 Introduction

A relational theory of spacetime is a theory according to which all claims concerning the geometric structure of spacetime have their ultimate truth conditions in terms of spatiotemporal relations among material bodies, with the nature of the bodies varying according to whether the world is built up out of particles or fields. If particles, then the relevant bodies will be the points along the particle worldlines. But if fields, then the relevant bodies will be the point-sized parts of the fields. In the latter case, standard spacetime structures can be said to inhere in the fields, with the ultimate truth conditions for claims concerning the geometry of spacetime being given in terms of facts about how the different parts of the fields are related to one another. The result, we might say, is a view according to which spacetime can be said to emerge as a 'structural quality of the field'.[1]

This view of spacetime as a structural quality of the field promises two key benefits. First, insofar as a field constitutes a plenum, the relationalist

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[1] The phrase is from (Einstein [1961], pp. 155–6). I will have something to say about Einstein's use of the phrase in section 5.

is promised an ontology robust enough to provide truth conditions for claims concerning the geometry of spacetime that might otherwise be difficult to secure—for example, the claim that spacetime has the structure of an affine space, or the claim that spacetime has the structure of a smooth manifold. Second, insofar as the view avoids having to posit the independent existence of a manifold of substantival points, the relationalist is promised to be in a position to endorse what Earman and Norton ([1987], p. 522) have termed 'Leibniz equivalence'. Consequently, the relationalist is promised to be in a position to avoid familiar modal arguments like the hole argument.

In what follows, I will argue that the view of spacetime as a structural quality of the field cannot deliver on its promises. The argument will take the form of a trilemma. On one horn, I will argue that the view founders on a problem of geometric coordination. On the other two, I will argue that the view collapses into substantivalism. In particular, I will argue that the most plausible version of the view—a version according to which spacetime is a structural quality of the gravitational field—holds absolutely no advantage over substantivalism on the issue of Leibniz equivalence.

2   Background

I want to present a problem for a relational theory of spacetime that regards spacetime as a structural quality of the field. Toward this end, let me first say a little more about what I mean by a 'relational theory of spacetime'.

2.1   Relational theories of spacetime

As above, a relational theory of spacetime is a theory according to which all claims concerning the geometric structure of spacetime have their ultimate truth conditions in terms of spatiotemporal relations among material bodies. In this respect, the relationalist aims to offer something like a 'material reduction' of spacetime. In contrast, the substantivalist claims that spacetime is a fundamental entity, an object whose existence is independent of whatever particles or fields happen to populate the world.

We can be more precise. Call a point along the worldline of a point-sized particle a 'stage point'. Then a relational theory of spacetime is a theory according to which spacetime is most faithfully represented by a set $\mathscr{R}$ of models of the form $(D, R_1, \ldots, R_n)$, where D is a set of stage points and $R_1 \ldots R_n$ are spatiotemporal (or otherwise geometric) relations on D.[2] On this approach, the

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[2]To be clear: $R_1, \ldots, R_n$ are relations of two places or more. In particular, I mean to exclude primitive, monadic spatiotemporal properties like 'being located at point p' or 'accelerating absolutely at a rate of one meter per second squared'. A theory including such properties would not count as relational by my lights.

set D comprises the theory's ontology, the list $R_1, \ldots, R_n$ comprises the theory's primitive, 'structure-making' relations, and each member of the set $\mathscr{R}$ is understood to represent a kinematic, or geometric, possibility.[3]

Our setup highlights the fact that one can generate different relational theories of spacetime by adjusting the available stock of relations. One example is Leibnizian relationalism, a theory which includes a temporal distance relation $t(p, q)$ defined for any two stage points whatsoever, plus a spatial distance relation $d(p, q)$ defined on pairs of simultaneous stage points. Another is Galilean relationalism, which aims to account for the affine structure of spacetime by adding a collinearity relation $col(p, q, r)$ (Maudlin [1993], pp. 193–4; Binkoski [2016]). A third example is Maxwellian relationalism, which replaces the Galilean's three-place collinearity relation with a four-place relation $A(p, q, r, s)$ measuring the angular difference between spatial vectors at different times (Saunders [2013]; Pooley [2013], p. 552). Turning to relativity, familiar examples include a relation $I(p, q)$ corresponding to the spacetime interval, or else a two-place relation $p < q$ determining causal connectability.

What about when the basic objects are fields rather than particles? In this case, it has been argued that the relationalist is in trouble. According to the argument, fields are distributions of properties over regions of spacetime, and so require what the substantivalist asserts and the relationalist denies, namely, the independent existence of regions of spacetime (Field [1989], pp. 181–2; Earman [1989], pp. 154–5, 158–9). But relationalists will have no truck with this notion of a field. Instead, relationalists will want to adopt a view according to which fields are themselves autonomous, self-standing physical objects. Thus, Gordon Belot writes that, 'relationalists—and others—can treat fields as they would, say, rigid bodies—as extended objects whose parts stand in determinate spatial relations to one another, and to which differing properties can be attributed' ([2000], p. 584). And along the same lines, Oliver Pooley observes that, 'According to the relationalist, ϕ [a field] does not represent an assignment of properties to space; it is an extended, material thing' ([2001], p. 4).[4]

Call this the 'material object view' of a field (which we can distinguish from the 'property distribution view'). Then having adopted the material object view, the domain of the relational model $(D, R_1, \ldots, R_n)$ will take as its elements the point-sized parts of whatever fields happen to exist, with the theory's primitive relations holding among the different parts of the fields. The result will be a view according to which spacetime structure is something inhering directly in the fields themselves; a view according to which spacetime is a 'structural quality of the field'.

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[3]It is an interesting question how the relationalist ought to understand this brand of modality. See (Belot [2011]) for a book-length discussion of the topic as it arises in connection with the geometry of space.

[4]See also (Malament [1982], note 11) and (Teller [1991], pp. 381–2).

2.2 Brief remarks on GR

Going forward, I want to focus on one field theory in particular, the general theory of relativity (GR). We can understand GR extensionally in terms of the set of spacetime models permitted by the theory. These will be mathematical models of the form (M, g_{ab}, T_{ab}), where M is a four-dimensional, smooth manifold, g_{ab} is a semi-Riemannian metric tensor field of Lorentz signature, and T_{ab} is a second-rank energy-momentum tensor field. Our two fields couple with one another via the Einstein field equation, and we count a model as 'permitted by the theory' just in case the Einstein equation is satisfied.

Each model (M, g_{ab}, T_{ab}) can be interpreted as representing a possible spacetime structure for the physical universe. Here, talk of 'spacetime structure' ought to be understood broadly so as to include not only the (pseudo) metric structure represented by g_{ab}, but the topological and large-scale structure of spacetime as well. Thus, with respect to topology, standard models are assumed to be connected, boundaryless, paracompact, and Hausdorff. And with respect to large-scale structure, models may be, for example, globally hyperbolic or spatially orientable or such that they contain closed timelike curves. The task for one who wants to 'take the models seriously', then, is to spell out the conditions under which the physical universe can be truthfully said to instantiate such properties.[5]

Given our discussion in the last section concerning relationalism and the material object view of a field, the question arises whether either g_{ab} or T_{ab} ought to be interpreted as representing an autonomous, self-standing physical object. With respect to the energy-momentum field, the answer is clearly 'no'. In GR, the energy-momentum field is sourced by a collection of 'matter fields'. Familiar examples include the electromagnetic field and the Dirac field. Associated with each such matter field is an energy-momentum field T_{ab}^i. For example, associated with the electromagnetic field F_{ab} is the energy-momentum field

$$T_{ab}^{EM} = F_{am}F^m{}_b + \frac{1}{4}g_{ab}F_{mn}F^{mn},$$

where the superscript on the T indicates the source of the field. These individual T_{ab}^i then sum to yield $T_{ab} = \sum_i^n T_{ab}^i$, which ought to be read as representing the total distribution of energy-momentum in spacetime. It is this total energy-momentum field that couples with the metric field in the Einstein equation and

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[5]Why 'take the models seriously'? One reason is that you would like to make straightforward sense of the predictive and explanatory power of the theory. However, another is that you would like to make straightforward sense of important theorems covering everything from the existence of black holes to the possibility of time travel. Such theorems are purely geometric: one assumes a relativistic spacetime (M, g_{ab}, T_{ab}) with geometric properties $P_1, \ldots, P_n$ before going on to prove that such a spacetime must also have geometric property X. An account of physical geometry that 'takes the models seriously' ought to specify the conditions under which the physical universe can be truthfully said to instantiate such properties.

which must satisfy the conservation condition $\nabla_a T^{ab} = 0$. (The individual T^i's which contribute to the total need not).

Now, as a matter of practical concern, when proving theorems in GR one almost always works directly with T_{ab}. But when it comes to the question of fundamental ontology, it is the matter fields that are fundamental. One way to see this is to note that the energy-momentum field asymmetrically supervenes on its matter fields. Let w and w' be any two general relativistic worlds. Suppose that w and w' agree with respect to (1) their manifold structure, (2) their metric structure, and (3) their matter fields. Then, necessarily, w and w' agree with respect to their energy-momentum fields. But the converse is false: let w and w' agree with respect to (1) and (2), and let them agree with respect to their energy-momentum fields; it simply does not follow that, necessarily, they agree with respect to their matter fields. This is just a consequence of the fact that the energy-momentum field is a sum (and, of course, different sets of terms can yield the same sum).[6] Consequently, there is a 'arrow of determination' running from the matter fields to the total energy momentum field, an arrow that simply cannot be run in the opposite direction. In this respect, the energy-momentum field in GR has roughly the same status as the center of mass (COM) of a collection of particles. Though we might gladly concede that the COM of a collection of particles exists, no one would be tempted to regard it as a fundamental object. The reason why is that if you fix the masses and locations of the particles, then you get the COM for free, as it were—though not vice versa. Likewise, in GR, fix some collection of matter fields (plus a manifold and a metric) and you get the energy-momentum field for free, as it were—though not vice versa.[7]

What about the metric field? Does it represent an autonomous, self-standing physical object? Here, things are much more complicated. On one interpretation, the metric field represents a structural property of spacetime—its shape. It does so by encoding information about spacetime distance relations. On this interpretation, the metric field does not represent a self-standing physical object. However, on another interpretation, it does. Thus, Earman and Norton

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[6]In some cases, matter fields will couple with one another, and so the terms in the sum $\sum_i^n T_{ab}^i$ may not be totally independent of one another. But not always—for example, not in the case of a neutrally charged perfect fluid and an electromagnetic field.

[7]Here's an objection to my claim that the energy-momentum field is not fundamental: it features in a fundamental law, the Einstein field equation, and objects which feature in the fundamental laws of nature are one and all fundamental. In response, I reject the premise that objects which feature in the fundamental laws of nature are one and all fundamental. Indeed, I think that the energy-momentum field is a counterexample. But here's another counterexample. Consider a parallel argument concerning properties (rather than objects). Suppose that $F = ma$ is a fundamental law. It refers to acceleration. But acceleration is not a basic, fundamental property of a body; typically, we analyze it in terms of something else (like deviation from a tangent geodesic). See (Hicks & Schaffer [2017]) for a detailed defense.

have stressed that in GR 'the metric tensor now incorporates the gravitational field and thus, like other physical fields, carries energy and momentum. . . ' Their conclusion is that this 'forces its classification as part of the contents of spacetime' ([1987], p. 519). Along the same lines, Harvey Brown notes that while gravity may differ from other interactions, 'this doesn't mean that it is *categorically* distinct from, say, the electromagnetic field' ([2005], p. 159). He goes on to cite Carlo Rovelli, who remarks:

> A strong burst of gravitational waves could come from the sky and knock down the rock of Gibraltar, precisely as a strong burst of electromagnetic radiation could. Why is the. . . [second] 'matter' and the. . . [first] 'space'? Why should we regard the. . . [first] burst as ontologically different from the second? Clearly the distinction can now be seen as ill-founded (Rovelli [1997], p. 193; Brown [2005], p. 159).

As others have noted, the inference from 'the metric field carries energy and momentum' to 'the metric field is categorically of the same kind as other matter fields' is questionable.[8] But I do not want to enter into this debate. Instead, my strategy is going to be to grant the relationalist a reified metric field. Doing so puts the relationalist in the strongest position possible by affording her an important piece of ontology. As we will see in sections 3 and 4, without a reified metric field the project of grounding spacetime structure in the fields founders on a 'problem of geometric coordination'. With it, one can escape the problem.

3 First Horn: Geometric Coordination

Substantivalists and relationalists agree over the mathematics of GR. Neither, I will assume, demands a revision in the formal structure of the theory. And each, I will assume, aspires to be a realist about the structure represented by the theory's models. Where the two sides disagree is in their account of the physical instantiation of that structure.[9] Substantivalists claim that an adequate account of the structure of spacetime requires that one admit spacetime as a fundamental entity. With a large base set of substantival points to work with, the substantivalist is in a position to provide truth conditions for physical-geometric propositions analogous to the truth conditions for the corresponding mathematical propositions. It seems that no such option is available to the relationalist in the point-particle case—the ontology is 'too thin'. But relationalists

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[8]See especially (Hoefer [1996], [2000]) and (Pooley [2006]).

[9]My approach to the spacetime ontology debate is similar to the approach in (Belot [2011]). Belot's relationalist, like my relationalist, is a realist about structure who aspires to give relationally kosher truth conditions for propositions concerning the geometry of space or spacetime.

with fields in their ontology appear to be in equally as strong a position, for if fields are material objects then relationalists have access in their ontology to a plenum of materialized field parts, and a plenum of field parts can instantiate a geometry in precisely the same way as a manifold of substantival points can.

But if in the point particle case the relationalist's ontology is too thin, in the field theoretic case we might worry about the opposite problem: an over-abundant ontology. We might ask: which field or fields instantiate the geometry of spacetime and how? We can approach the problem by focusing on the case in which there exist just two fields, an electromagnetic field and a reified metric field—a gravitational field—each construed as an extended material object. Then there are three possibilities: either (A) each field separately instantiates a geometry, (B) both fields together instantiate a geometry, or (C) one field but not the other instantiates a geometry. We'll look at each in turn.

Start with (A), the hypothesis that each field separately instantiates a geometry. Here is one way of pursuing the idea. Let X denote the set of atomic, point-sized parts of our gravitational field and let Y denote the set of atomic, point-sized parts of our electromagnetic field. By hypothesis, each is a self-standing, physical object. Now define on X some set of relations so that X can be said to instantiate a spacetime geometry and then, separately, define on Y some set of relations so that Y can be said to instantiate a spacetime geometry. On this approach, the relational model will take the form $(X, Y, R_1, \ldots, R_n)$, where we have split the domain in an effort to capture the idea of each field separately instantiating a geometry. Then, so long as we have allowed ourselves the necessary relations, each field will instantiate its own geometry, so that the structure of X can be faithfully represented by a model (M, g_{ab}) and the structure of Y can be faithfully represented by a model (M', g'_{ab}).[10]

But now we run into the following problem. Since physical spacetime has a single geometry, we require that the geometries defined over our fields coordinate with one another. Thus, if some subset of elements of X instantiate some set of relations, then we expect that the corresponding subset of elements of Y

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[10]It is important to distinguish between the electromagnetic field qua extended, physical object and the electromagnetic field qua mathematical object, qua second-rank tensor field. If you start with the mathematical object F_{ab} and ask 'what geometry does it determine?', the answer will be 'none'. First, a single F_{ab} is compatible with different g_{ab}'s. (Here is a quick 'proof'. Start with an F_{ab} and a perfect fluid Φ. Suppose that there is no interaction between F_{ab} and Φ. Then we can vary T_{ab} by changing Φ even while holding F_{ab} fixed. Consequently, by the Einstein equation, we can vary g_{ab} even while holding F_{ab} fixed.) Second, no analysis of F_{ab} is going to yield full information about the large-scale structure of spacetime insofar as tensor fields are local objects. (Not even g_{ab} fixes the large-scale structure of spacetime; for example, g_{ab} puts rather weak constraints on M. See note 13). But the electromagnetic field qua physical object can house all of the geometry we want so long as the right relations are defined on its parts—in the same way that a point manifold can house all of the geometry we want so long as the right relations are defined on its parts. I thank an anonymous referee for pressing me on this.

will instantiate the same relations. But now one wants to know: what explains the coordination? What is there to prevent, say, X from instantiating a curved geometry and Y a flat geometry? Usually, when two systems are coordinated we expect to find some third factor, a common cause, that explains the coordination. But in this case, there is no third factor—by hypothesis, all that exists are our two fields. Call this the 'problem of geometric coordination'.

If spacetime is substantival, then there is no problem of coordination. If substantivalism is true, then the geometry of spacetime is instantiated by a manifold of substantival points and the spatiotemporal relations holding among some configuration of events are determined by the spatiotemporal relations holding among the regions of spacetime those events occupy. It follows that if two configurations occupy the same regions of spacetime, then they will instantiate the same set of spatiotemporal relations—they will be geometrically coordinated. Relationalists who go for (A) have no access to such an explanation.

One response to the problem would be to give up the assumption that spacetime has a single geometry and simply let each field instantiate its own structure. But if what we are looking for is an interpretation of GR, then this won't work. General relativistic models suggest a physical world with a single geometry. We need a response that will preserve this feature of the theory.

So give up on (A): it founders on the problem of geometric coordination. The remainder of the paper will be spent dealing with the consequences of this.

Before moving on, it's worth pausing to note a similarity between the problem of geometric coordination and another problem of coordination that has received attention over the past couple of years. Harvey Brown ([2005]) has argued for an approach to physical geometry according to which the geometry of spacetime, in some theories, is grounded in the dynamical laws of nature. In particular, in the case of the special theory of relativity, Brown has argued that the Minkowski structure of spacetime is grounded in the Lorentz covariance of the fundamental laws of nature; in his words, Minkowski's geometry 'is no more than the Kleinian geometry associated with the symmetry group of the quantum physics of the non-gravitational interactions in the theory of matter' (Brown [2005], p. 9). But this raises a question: what explains the fact that the laws of nature are one and all Lorentz covariant? From whence the coordination? According to Brown, the coordination is just a brute fact ([2005], p. 143). But others see here the makings of a 'common origin explanation', with the symmetries of spacetime explaining the symmetries of the laws (Janssen [2003]; Norton [2008]).

The problem of geometric coordination is structurally similar to this problem of dynamic coordination. In both cases we have structural coordination among some set of distinct objects—fields in the one case, laws in the other.

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In both cases, substantival spacetime presents itself as an origin for the coordination. But the problems are aimed at very different targets. The problem of dynamic coordination is a problem for those hoping to find a dynamic foundation for physical geometry. Traditional relationalists have no special interest in this project. Instead, traditional relationalists work from a stock of primitive spatiotemporal relations and regard spacetime structure as emerging not from the laws but from the pattern of instantiation of those relations. The problem of geometric coordination is a problem for this latter sort of project.[11]

4   Second Horn: Problems of Coincidence

In the previous section, I listed three possibilities: either (A) each field separately instantiates a geometry, (B) both fields together instantiate a geometry, or (C) one field but not the other instantiates a geometry. The first option founders on the problem of geometric coordination. You can avoid that problem by adopting either the second or third option. The question will be whether there is a way of executing either (B) or (C) so that the resulting view can still be considered a relational theory of spacetime.

First, consider (B), the hypothesis that both fields together instantiate the geometry of spacetime. Here is one way of developing the idea. As in the previous section, let X denote the set of atomic, point-sized parts of the gravitational field and let Y denote the set of atomic, point-sized parts of an electromagnetic field. Then let D, the domain of the relational model $(D, R_1, \ldots, R_n)$, be the union $X \cup Y$. The idea here is to gather everything that exists into a single set and then put a single structure on that one set. The problem is that it is difficult to see that this strategy can work. Since our two fields occupy the same spacetime, they overlap one another: for every $p \in X$ there exists a $q \in Y$ such that p and q are coincident, and vice versa. Because of this, $X \cup Y$ cannot instantiate many of the standard structures of GR. For example, physical spacetime cannot be Hausdorff. A space is Hausdorff if for all p and q in the base set, there exist open sets U and V such that $p \in U$, $q \in V$, and $U \cap V$ is empty. No open set structure on the base set $X \cup Y$ can satisfy this condition: coincident elements will force a violation. But to surrender the Hausdorff condition would be to surrender a great deal. As Earman points out in a different context, the Hausdorff condition 'is implicitly assumed in so many standard results in [GR] that dropping it would require a major rewriting of textbooks' (Earman [2008],

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[11]That said, the problem of geometric coordination may pose a problem for the dynamic foundationalist as well. Brown is happy to admit that *some* prior geometry is needed in order to formulate the laws—at the very least, one will need some level of topological structure. But then so long as that prior geometry is claimed to inhere in the fields, the dynamic foundationalist will face the problem of geometric coordination and the trilemma of which it is part.

p. 199).

Nor can physical space have the structure of a metric space. Consider a model of GR admitting a global time function so that it makes sense to talk about space at a time. The spacetime metric field of such a model will induce a metric structure on space. But if the structure of physical spacetime is instantiated by $X \cup Y$ then no such structure is possible. Metric spaces are such that for all p and q in the space, $dist(p, q) = 0$ iff $p = q$. The base set $X \cup Y$ cannot satisfy this condition: again, coincident elements will force a violation. But as with the Hausdorff condition, one should be loath to surrender the metric structure of space. Indeed, Belot ([2011], pp. 8–14) goes so far as to assert (albeit with some hedging) that metricity is an essential property of all spaces!

Now, there is an obvious and natural solution to these problems. The solution is to form equivalence classes of coincident field parts, gather these equivalence classes into a set Z, and then let Z instantiate the geometry of physical spacetime by having $R_1, \ldots, R_n$ take elements of Z. On this approach, all spatiotemporal relations are relations first and foremost among classes of coincident field parts with the parts themselves entering into such relations in an indirect way in virtue of membership in a class. That will solve the problem of coincident parts. But the problem now is that the resulting view violates a central tenet of relationalism, namely, the tenet that spatiotemporal relations among material objects be 'direct'. This is the proposition that Earman codifies as R2 in his discussion of relationalism in (Earman [1989], p. 12).[12] So the upshot is that relationalists adopting this strategy will have to give up on R2. But if there is an 'acid test' for relationalism, then R2 is it. Relationalists will do better to look elsewhere.

5 Third Horn: GR and Gauge

So give up on (B): it cannot support standard structures in a relationally kosher fashion. Turn instead to (C), the hypothesis that one field and not the other instantiates the geometry of spacetime. The obvious candidate here is the gravitational field. Indeed, there are profound reasons for assigning special status to the gravitational field, chief among them being the fact that the gravitational field is the only field that can claim 'universality' insofar as it is the only field

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[12]Here is what Earman's R2 says: 'Spatiotemporal relations among bodies and events are direct; that is, they are not parasitic on relations among a substratum of space points that underlie bodies or spacetime points that underlie events' ([1989], p. 12). Of course, in our case the 'underlying substratum' is one consisting not of spacetime points but of classes of coincident field parts. But this just looks like another version of substantivalism, with the membership relation replacing the occupation relation. In both cases, the important point is that spatiotemporal relations among material bodies are indirect, being parasitic on relations between other things, where those other things are the primary bearers of the relations.

that interacts with every other field. Thus, Carlo Rovelli has advocated for the view that 'spacetime geometry is nothing but the manifestation of a particular field, the gravitational field' (Rovelli [1997], pp. 183–4). Here, Rovelli looks to be echoing Einstein, who at one point endorsed a similar view:

> If we imagine the gravitational field, i.e., the functions g_{ik}, to be removed, there does not remain a space of type (1) [Minkowski spacetime], but absolutely *nothing*, and also no "topological space." For the functions g_{ik} describe not only the field, but at the same time also the topological and metrical properties of the manifold...There is no such thing as empty space, i.e., a space without field. Spacetime does not claim an existence of its own, but only as a structural quality of the field (Einstein [1961], pp. 155–6).

Einstein contends that if one were to remove the gravitational field, then there would remain behind absolutely nothing—no metric facts, no topological facts, no facts whatsoever concerning the structure of spacetime.[13] I read this as an endorsement of a view according to which (1) what exist, fundamentally, are just 'matter fields', that (2) included among these fields is the gravitational field, and that (3) it is the gravitational field which is responsible for instantiating the geometry of spacetime, so that spacetime structure, rather than inhering in something that exists over and above the gravitational field, is something inhering in the gravitational field itself. (This reading makes the most sense of the conditional in the first sentence of the quote).

For us, the attraction of this view is that it solves the problem of geometric coordination: with only one field instantiating the geometry of spacetime, there are no worries about coordination. Instead, the worry is that we have once again collapsed into substantivalism. Oliver Pooley sums it up:

> What, then, is at stake between the metric-reifying relationalist and the traditional substantivalist? Both parties accept the existence of a substantival entity, whose structural properties are characterised mathematically by a pseudo-Riemannian metric field...It is hard

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[13]Einstein talks about removing 'the functions g_{ik}'. This makes it seem as if he intends to make a mathematical point. But if that's the case, then what Einstein says is false. First, if you remove the functions g_{ik} from a mathematical model of spacetime, then, contrary to what Einstein says, there *does* remain a topological space, namely, the point manifold M. Second, a metric tensor field (qua mathematical object) puts rather weak constraints on its underlying manifold so that, contrary to what Einstein says, the functions g_{ik} do *not* describe the topological properties of the manifold. To cite a familiar example, the fact that spacetime carries a flat, Minkowski metric tensor field η_{ab} fails to determine whether spacetime is topologically R^4 or $R^3 \times S^1$. Instead, we should read Einstein as advancing an ontological claim, and so, correspondingly, we should read his reference to 'the functions g_{ik}' as an intended reference to the gravitational field (or to a reified metric field).

to resist the suspicion that this corner of the debate is becoming merely terminological. At least this much that can be said for the choice of substantivalist language: it underlines an important continuity between the "absolute" spacetime structures that feature in pre-generally relativistic physics and the entity that all sides of the current dispute admit is a fundamental element of reality (Pooley [2013], p. 579).[14]

I will discuss this worry in the next section. For now, the fact that we are sailing so close to substantivalism might prompt interest in other options. I'll discuss two. First, I have been supposing the existence of an electromagnetic field and a gravitational field. But consider a relationalist who denies that the gravitational field is a self-standing, physical object and who interprets g_{ab} as the substantivalist is inclined to, as a mathematical representation of the shape of spacetime. In other words, consider a relationalist who says this:

All that exists is the electromagnetic field, period. The electromagnetic field has energy-momentum content, represented mathematically by T_{ab}. Moreover, the electromagnetic field has a shape, represented mathematically by g_{ab}. And finally, the shape of the field and its energy-momentum content are coupled with one another via the Einstein equation. Since on this approach all that exists is a single electromagnetic field, there is no problem of geometric coordination. And since there is no reification of the metric field, there is no worry about sailing too close to substantivalism.

This is an attractive view. But it cannot sustain a comprehensive, relational interpretation of GR. In the imagined case, the energy-momentum field has a single source, an electromagnetic field. But in any realistic model, there will exist more than one matter field. So while the view described does indeed avoid the problem of geometric coordination, the solution is of limited interest. The moment we add even the slightest bit of complexity, the problem returns.

Another option along the same lines would be to replace the role of the electromagnetic field in the above speech with the energy-momentum field.[15] On this approach, all that exists is the energy-momentum field, period. Spatiotemporal relations are then defined on parts of the energy-momentum field. Here, too, there exists just one field, and so the problem of geometric coordination never arises. But I do not think that this represents a plausible ontology for GR.

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[14]The argument in this last sentence stressing continuity with earlier theories is the same as the argument in (Hoefer [1996]). We should note that the thesis that the debate collapses is not the thesis, defended by (Rynasiewicz [1996]), that the debate is outmoded. For a response to Rynasiewicz, see (Hoefer [1998]).

[15]I thank an anonymous referee for asking about this option.

I have already argued (in section 2.2) that the matter fields at a world w fail to supervene on the energy-momentum field at w. Consequently, taking T_{ab} as basic, there is simply no hope of recovering the matter fields in one's ontology. In my view, that's a steep cost.

(It may be useful to contrast this last option with the following. It is common to think of the charge current density field J^b as the 'source' of the electromagnetic field F_{ab}. On this approach, the current density field is construed as the ontologically more basic of the two. But one can just as well run things the other way around: one can take F_{ab} as basic and then recover J^b as an emergent object via the Maxwell equation $J^b = \nabla_a F^{ab}$. In contrast, the relation between the energy-momentum field and its source matter fields cannot be similarly inverted.)

5.1 Preventing collapse

The only option that I see for avoiding the problem of geometric coordination is to reify the metric field and to assign it a privileged role in instantiating the various different geometric structures and properties that we are inclined to think of as physically real. The worry, as I noted in the last section, is that the resulting view is just a kind of substantivalism. In response, those attracted to the view usually stress that there remains an important difference between an ontology that grounds spacetime in the fields and one that regards it as a substantival entity. The difference is a modal difference. Thus, if spacetime is substantival, then there will be many different ways to position a collection of fields in spacetime. Choose a placement at random—if spacetime is substantival, then it will be possible to smoothly reposition the collection with respect to the underlying spacetime in such a way that the resulting arrangement is ontologically distinct though qualitatively indiscernible from the original. The reified metric field relationalist, on the other hand, seems to face no such embarrassment. Because she denies that spacetime is something separate from the gravitational field, she looks to be in a position to identify such repositioned possibilities.

There is a way to make this rigorous. It is a formal property of the general theory of relativity that its models are invariant under the group of diffeomorphisms, a diffeomorphism being a smooth map $\phi : M \to M$ with smooth inverse. Thus, if (M, g_{ab}, T_{ab}) is a model of GR and ϕ is a diffeomorphism, then $(M, \phi_* g_{ab}, \phi_* T_{ab})$ is also a model of GR, where ϕ_* is the push-forward of ϕ. Moreover, it is a formal property of ϕ_* that $(\phi_* g_{ab})_{|\phi(p)}(\eta^a \xi^b)_{|\phi(p)} = (g_{ab})_{|p}(\phi^* \eta^a \phi^* \xi^b)_{|p}$ and likewise for T_{ab}, so that pairs of models related by a diffeomorphism will differ only over how the fields are positioned with respect to the underlying manifold.[16] So, to connect back up to what we said concerning

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[16]The equation in this sentence says that the pushed-forward metric $\phi_* g_{ab}$ at the image

repositioned fields: if substantivalists are committed to counting repositioned field placements as ontologically distinct ways for the world to be, and if we wanted to represent such a pair of repositioned possibilities with a pair of space-time models, then these would be models (M, g_{ab}, T_{ab}) and $(M, \phi_* g_{ab}, \phi_* T_{ab})$ for some appropriately chosen ϕ. Relationalists, on the other hand—including those who reify the metric field—will want to count these two mathematical models as equivalent representations of the same physically possible state of affairs. And more generally, they will want to interpret the invariance of relativistic models under the group of diffeomorphisms as capturing a kind of 'descriptive freedom' in the theory analogous to the freedom accompanying the choice of where to center a coordinate system.

So one way to keep the debate from collapsing is to maintain that though reified metric field relationalism may look like substantivalism, the views nonetheless disagree over how to understand a formal property of the general theory of relativity, namely, the invariance of its models under the group of diffeomorphisms. Following Earman and Norton ([1987], p. 522), let 'Leibniz equivalence' name the proposition that diffeomorphic models represent the same physical possibility. Then our two ontologies are supposed to differ with respect to Leibniz equivalence. The traditional assumption is that substantivalists must deny it and that relationalists—including those who reify the metric field—are in a position to accept it.[17]

Following the publication of (Earman & Norton [1987]), there has developed a large and familiar body of work on Leibniz equivalence and the commitments that come with adopting a substantival conception of spacetime. In particular, sophisticated substantivalists have made a compelling case for the claim that, so long as you get your metaphysics right, there does indeed exist a path to Leibniz equivalence through substantivalism.[18] But the committed relationalist will not be moved. Some—the 'strongly committed'—will deny the viability of a sophisticated substantivalism altogether. Others—the 'weakly committed'—will acknowledge the viability of a sophisticated substantivalism but maintain that the relationalist's path to Leibniz equivalence is the simpler of the two.[19]

The argument in the next section is aimed at the committed relationalist. I

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point $\phi(p)$ acts on vectors η^a and ξ^b at $\phi(p)$ in the same way that the original metric g_{ab} at the point p acts on vectors $\phi^* \eta^a$ and $\phi^* \xi^b$, where $\phi^* \eta^a$ and $\phi^* \xi^b$ are the vectors η^a and ξ^b pulled back from $\phi(p)$ to p. For details, see (Malament [2012], pp. 35–42).

[17]Of course, denial of Leibniz equivalence is supposed to carry with it a commitment to the conclusion that GR is an indeterministic theory. This is the famous hole argument.

[18]See, for example, (Butterfield [1989]), (Hoefer [1996]), (Maudlin [1990]), and (Pooley [2006]).

[19]For example, Belot makes the point that substantivalists who adopt Leibniz equivalence are 'helping themselves to a position *most naturally* associated with relationalism' ([2000], p. 27; my emphasis). Similarly, Brown writes of the indeterminism that accompanies a denial of Leibniz equivalence that 'the *simplest* (and to my mind the best) conclusion…is that the space-time manifold is a non-entity' ([2005], p. 156; my emphasis).

will argue that on the question of Leibniz equivalence, there is complete and total parity between the substantivalist and the metric field relationalist. If sound, then the weakly committed are in trouble: it will be seen that the nature of the parity is such that the metric field relationalist's path to Leibniz equivalence is in no way simpler than the substantivalist's. And if the weakly committed are in trouble, then so too are the strongly committed: with parity in place, it will be seen that there is no way for the metric field relationalist to pin a denial of Leibniz equivalence on the substantivalist without pinning the same on herself.

5.2   The revised shift argument

I want to challenge the thought that the metric field relationalist's path to Leibniz equivalence is any simpler than the substantivalist's. To make the argument, forget about diffeomorphisms for a minute and consider a simpler operation: a spatial shift one foot to the right, at each time.[20] The traditional assumption is that substantivalists are committed to counting shifts to the right as representing ontologically distinct ways for the world to be. And traditionally this has been seen as a problem. For the result of such a shift will be a state of affairs ontologically distinct though qualitatively indiscernible from the original—a state of affairs differing from the original only in some non-qualitative respect. But, it is assumed, it is impossible for things to differ in only some non-qualitative respect. The conclusion is supposed to follow that spacetime cannot be substantival.

Relationalists are thought to avoid this 'shift argument' because they refuse to reify spatiotemporal locations. But relationalists who countenance fields construed as self-standing physical objects are subject to a very similar argument. Here it is. Suppose that a field is a self-standing physical object, each part of which instantiates some set of qualitative properties. Then it is possible to shift each set of properties one foot to the right, at each time, so that each set of properties comes to be instantiated by some other part of the field. But then things would be just as they are, qualitatively, differing only in some non-qualitative respect. Since, as above, this is not possible, fields cannot be physical objects.

In the original shift argument, shifting results in a systematic reconfiguration of location relations. In the original spacetime, material object x is located at spacetime point p, while in the shifted copy x is located at q, where q is one foot to the right of p. In our modification of the standard argument, shifting

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[20]The argument requires some structural assumptions. We assume a spacetime with a global time function so that it makes sense to talk about spaces at a time. We also assume that space is isotropic and homogeneous so that no matter where you shift from or to, the geometry is the same. The same assumptions will be in force when we turn to the 'revised' shift argument. Ultimately, when we transition back to the general group of diffeomorphisms, these assumptions can be dropped (since diffeomorphisms shift geometric structures as well).

results in a systematic reconfiguration of instantiation relations. In the original spacetime, property F is instantiated by field part a, while in the shifted copy F is instantiated by b, where b is one foot to the right of a.

Call this the 'revised shift argument'. Those familiar with the literature on modal arguments in the philosophy of space and time will have no trouble coming up with strategies for responding to the argument. The problem, however, is that all of the same strategies are available to the substantivalist. Consequently, so long as uniform metaphysical assumptions are applied across both arguments (uniform assumptions concerning issues of identity, substance, property, and structure), the original and revised shift arguments stand or fall together. A quick survey of some of the options available will make the point. Since this is familiar ground, I will keep the discussion brief.

First response: reject the possibility of a shift. One of the premises in the revised shift argument is the claim that if fields were physical objects, then it would be possible to shift properties one foot to the right. Consequently, one can disarm the argument by rejecting the possibility of a shift. Three options come to mind:

- **Invoke Essentialism**. Relationalists can reject the possibility of a shift by imposing a sufficiently strong constraint on the *de re* modal properties of field parts. One option would be to adopt the thesis that field parts have their field-strength values essentially. In this case, a shift would fail to represent a genuine possibility insofar as it would, generally speaking, represent parts as lacking properties that are essential to their identity.

- **Invoke Counterpart Theory**. The revised shift argument requires, for each part of our field, that we be able to identify that part in some counterfactual situation—in some other possible world. One can argue that (1) these kind of cross-world comparisons are best done via a qualitative counterpart relation in the sense of (Lewis [1986]), and that (2) in the context of evaluating a shift counterfactual, the right counterpart relation is the one picked out by the shift operation itself. But then the proposition 'possibly, each property is shifted one foot to the right' is false.

- **Invoke Structuralism**. According to the moderate structural realist, the identity of an object is grounded in the network of external relations within which it sits—grounded, that is, in its place 'within a structure'. Since a uniform shift one foot to the right at each time preserves external relations, we get that shifts are impossible insofar as pre- and post-shift models represent one and the same physical possibility.

Each of the above will offer an exit from the revised shift argument. However, in each case the same move is available to the substantivalist. Indeed, each

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move has its advocate: (Maudlin [1990]) argues that spacetime points have their metric properties essentially so that at most one of a set of diffeomorphic models represents a genuine physical possibility; (Butterfield [1989]) advocates on behalf of a counterpart theoretic response to modal arguments like the shift argument; and (Pooley [2006]) invokes a moderate brand of structuralism. In each case, if the response will work for the relationalist in response to the revised shift argument, then it will work equally well for the substantivalist in response to the original shift argument.

Second response: reject substance-property dualism. With respect to the original shift argument, the troublemaker is region-object dualism. Relationalists avoid that argument because they deny that regions are ontologically autonomous things. Similarly, with respect to the revised shift argument, the troublemaker is substance-property dualism. A natural response then would be to get rid of substances as ontologically autonomous things.

One way to do this would be to get rid of objects all together. Those who go for this option tend to favor of a more radical brand of structuralism than the moderate structuralism mentioned above. But this seems like unnecessarily strong medicine.[21] A more plausible option would be to keep objects in one's ontology but deny that they are ontologically autonomous. The standard way to do so is to adopt a bundle theory of substance.[22] According to the bundle theory, objects are bundles of properties. Contrast this with the more familiar substratum theory, according to which objects and properties are ontologically distinct, objects being thin particulars which combine with properties to produce states of affairs. The bundle theorist attempts to do without thin particulars, maintaining that properties can directly bundle with one another to produce states of affairs. Let's use angled brackets to distinguish a mere list of properties $F_1, F_2, \ldots, F_n$ from a bundle of properties $\langle F_1, F_2, \ldots, F_n \rangle$. Then whereas on a substance-property metaphysic the world is ultimately describable in terms of facts of the form Fa and Rab, the bundle theorist says that the world is ultimately describable in terms of facts of the form $a = \langle \ldots, F, \ldots \rangle$ and $R \langle \ldots, F, \ldots \rangle \langle \ldots, G, \ldots \rangle$, where $a = \langle \ldots, F, \ldots \rangle$ should be read as implying a reduction of a to the bundle $\langle \ldots, F, \ldots \rangle$.

What are these bundled properties? Are they tropes or universals? We had better say tropes. To see why, suppose that properties are universals and consider field parts $a = \langle F_1, \ldots, F_n \rangle$ and $b = \langle F_1, \ldots, F_n \rangle$ with all of the same universals. Then $a = b$. This follows from the fact that universals are wholly present wherever they happen to be instantiated, so that each F_i in a is nu-

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[21] See especially (Pooley [2006]). For a recent, brief overview of arguments against radical ontic structural realism, see section 2 of (Wüthrich & Lam [2016]).

[22] Both (Pooley [2006]) and (Wüthrich & Lam [2016]) suggest the bundle theory as an option for the radical ontic structural realist.

merically identical to the corresponding F_i in b, together with the fact that bundles with identical members are themselves identical. But this will create problems in the case of any field having certain nice symmetries. For example, since electric fields are spherically symmetric, we get that any two parts some fixed distance d from the source charge Q are identical. Thus, instead of there being an infinite number of field parts d units from Q, strictly speaking there's just one.[23] On the other hand, if the bundled properties are tropes, then the numerical distinctness of each part is maintained, even if those parts happen to instantiate all of the same properties.

But now we have a problem: a trope bundle theory implies the possibility of qualitatively indiscernible yet ontological distinct objects. Thus, consider objects $\langle F, G \rangle$ and $\langle F', G' \rangle$ where F and F' are exactly similar, and likewise for G and G'. Then $\langle F, G \rangle$ and $\langle F', G' \rangle$ are qualitatively indiscernible though ontologically distinct, differing in some merely non-qualitative way. Consequently, any relationalist turning to the bundle theory in an effort to disarm the revised shift argument will disarm the original shift argument as well.

Third response: stress the difference between instantiation and location. Perhaps there is something about location relations such that shifting them (as in the original shift argument) is problematic, whereas shifting instantiation relations (as in the revised shift argument) is not. But this third response won't get us very far. Substantivalists tend to endorse the property distribution view according to which a field is a distribution of properties over points of spacetime. In this case, the relation between a spacetime point and its field-strength property is not so much the location relation as the instantiation relation. Consequently, if there is something about instantiation such that it upsets the possibility of a shift, then the original shift argument is upset as well.

Each response surveyed is such that if it will work for the relationalist in response to the revised shift argument, then it will work for the substantivalist in response to the original shift argument. So my conclusion is that the revised shift argument is just as troublesome for the relationalist as the original shift argument is for the substantivalist.

It only remains to note that the revised shift argument generalizes. There is, of course, nothing special about shifts to the right. So long as fields are self-standing physical objects it will be possible to smoothly reposition properties and relations in such a way that the resulting arrangement is ontologically distinct though qualitatively indiscernible from the original. If one wanted to represent such possibilities mathematically, then diffeomorphic mappings would

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[23]See (Wüthrich [2009]) for a similar argument directed against a structuralist interpretation of spacetime.

be the tools to use. Assuming a reified and privileged gravitational field, the M in the model (M, g_{ab}, T_{ab}) would represent the manifold structure of the gravitational field, $\phi : M \to M$ would be a function on the atomic, point-sized parts of the gravitational field, $\phi_* g_{ab}$ would represent a smooth drag of the properties of the gravitational field with respect to its base M of substantive parts, and $\phi_* T_{ab}$ would represent a smooth drag of the energy-momentum field (or its source matter fields) with respect to M.

6   Conclusion

I have presented a problem for a relational theory of spacetime according to which spacetime is a structural quality of the field. I have argued that on one way of setting things up, the view founders on a problem of geometric coordination. The only viable option for avoiding the problem is to adopt a reified and privileged metric field. But then, I have argued, the view collapses into substantivalism.

The best option for preventing collapse was to find a modal difference between the views. Sophisticated substantivalists have denied the viability of this sort of approach, arguing that substantivalists, too, can endorse Leibniz equivalence. But the revised shift argument puts things into an even clearer light. Once we see that relationalists who countenance fields are subject to their own shift argument, we see that (1) the relationalist's path to Leibniz equivalence is in no way simpler than the substantivalist's, so that (2) there is no way for the relationalist to pin a denial of Leibniz equivalence on the substantivalist without pinning the same on herself.

I do not believe that the problem of geometric coordination is easily avoided. Assuming GR in its standard formalism, the problem is driven by just two assumptions: first, that the relationalist would like to countenance the notion of a field, and second, that the relationalist would like to be a realist about the kinds of geometric properties that are part of the theory's models. The first assumption drives us toward a material object view of a field according to which fields are autonomous, self-standing physical objects, while the second prompts the need for an account of the physical instantiation of such properties. Once one adopts these assumptions and begins putting fields to work housing geometric properties, one is confronted with the trilemma discussed above.

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James Binkoski
Dartmouth College
Philosophy Department
Hanover, NH, USA
james.p.binkoski@dartmouth.edu

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