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Composing Spacetime

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Abstract

According to a number of approaches in theoretical physics spacetime does not exist fundamentally. Rather, spacetime exists by depending on another, more fundamental, non-spatiotemporal structure. A prevalent opinion in the literature is that this dependence should not be analysed in terms of composition. We should not say, that is, that spacetime depends on an ontology of non-spatiotemporal entities in virtue of having them as parts. But is that really right? On the contrary, we argue that a mereological approach to dependent spacetime is not only viable, but promises to enhance our understanding of the physical situation.

1 Introduction

Various approaches in theoretical physics suggest that spacetime does not exist fundamentally. For instance, a number of approaches to quantum gravity (QG), such as string theory and loop quantum gravity are thought to deny the fundamental existence of spacetime (see e.g. Huggett and Wüthrich 2013, 2018, Crowther 2017, 2018). Although the development of such approaches is very much a work-in-progress, the fact that they point toward the disappearance of spacetime, or of spatiotemporal properties, is intriguing.

What the elimination of spacetime entails exactly varies from one research program to another. String theory, for instance, suggests that the world is made of not four, but ten or eleven dimensions. Because of the existence of certain deep symmetries (called dualities) between the solutions of distinct string theories, describing distinct spaces, some have argued that the higher-dimensional spaces apparently being posited are mere artefacts of the mathematical representation being used. These higher-dimensional spaces should therefore not be identified with our familiar space and time or even to spacetime as described by the general theory of relativity (see e.g. Huggett 2017). In a certain sense, then, space is missing at some fundamental level of description. Similarly, in loop quantum gravity—the chief alternative to string theory—the fundamental ontology seems to involve a range of entities that bear no spatiotemporal relations to one another. For there is nothing like the smooth metric structure of a manifold to be found in the standard representation of the theory (see Rovelli 2011). Rather, the entire ontology of the theory can be represented by a discrete graph-theoretic structure of nodes and links that is not, strictly speaking, geometric in nature.

Philosophers are quick to point out, however, that the loss of spacetime at some fundamental level is nonetheless compatible with the existence of spacetime. Spacetime exists, just not fundamentally; in the same way that chairs exist, despite not forming a part of the ontology of fundamental physics. When first met, this picture of spacetime 'above' and no spacetime 'below' is difficult to understand. Indeed, it can seem positively mysterious. Most contemporary metaphysical theories presuppose the fundamentality of spacetime in some sense. So how could it be that spacetime exists as a dependent entity? And even if this is broadly conceivable, how exactly is it supposed to work?

One strategy for making the dependence of spacetime more understandable is to characterise the relationship between spacetime and a more fundamental ontology in terms of composition (see, for instance, Le Bihan 2018).[1] Dependent spacetime is literally *com-*

[1]Paul (2012) and Ney (2017) make similar claims with a focus on quantum mechanics; see also Chalmers

posed of non-spatiotemporal building blocks just as, say, a gas is composed of atoms in motion. These non-spatiotemporal building blocks constitute *proper parts* of a spacetime. This picture has the *prima facie* advantage of being familiar: the relationship between spatiotemporal and non-spatiotemporal entities is just like the relationship between, say, macro and micro entities. Moreover, just as we are used to the idea that macro entities share none or very few of their properties with their micro-constituents, so too can we come around to the idea that spacetime might not share its spatiotemporal structure with the more fundamental components that make it. In this way, the mystery of how spacetime depends on a non-spatiotemporal ontology can be eased.

Recently, however, some philosophers have expressed dissatisfaction with the idea that spacetime could be mereologically composed of non-spatiotemporal parts (see for instance, Lam and Wüthrich 2018, p. 50 and Wüthrich 2019, p. 10). Baron (2019a, forthcoming) has recently fleshed out this dissatisfaction into an objection. He argues that composition undergoes a kind of 'conceptual breakdown' when it is applied beyond its usual spatiotemporal context. For him, treating the dependence of spacetime in terms of composition amounts, roughly, to a category error.

Our goal in this paper is to, first, clarify the problem with using composition to model dependent spacetime and to then see what can be done about it. The problem is sharpest when framed as the idea that composition in the case of spacetime is not like ordinary cases of composition for physical objects, and so, in fact, we can't rely on our familiarity with standard forms of composition as a way to help us understand dependent spacetime. We go on to identify two ways in which appealing to mereology to model dependent spacetime might be illuminating nonetheless. In both cases, the discontinuity between mereological models of spacetime and composition for physical objects is no bar to understanding. We concede, however, that mereological models of dependent spacetime fail to yield full understanding of the situation. But, ultimately, we trace this failure back

(forthcoming) for discussion.

to physics, not metaphysics.

2 The Challenge

Let us begin by considering why, according to some, a mereological approach to dependent spacetime is conceptually incoherent. In order to state the challenge we must work within a broad locative framework, based on a notion of exact location, $L(x, y)$:

> An entity x is exactly located at a region y if and only if x has (or has-at-y) exactly the same shape and size as y and stands (or stands-at-y) in all the same spatial or spatiotemporal relations to other entities as does y. (Gilmore, 2018)

Following Parsons (2007, p. 204), exact location is then used to define weak location:

$$\text{WKL}(x, y) =_{df} \exists z[L(x, z)\&O(z, y)]$$

Where 'O' is the standard mereological notion of overlap (defined below), and thus the definition tells us that x is weakly located at y iff x has an exact location that overlaps y.

Next, we need a primitive notion of parthood, P. To this, we add the following axioms which turn P into a partial order:

1. Pxx (Reflexivity)
2. $(Pxy \wedge Pyz) \rightarrow Pxz$ (Transitivity)
3. $(Pxy \wedge Pyx) \rightarrow x = y$ (Antisymmetry)

A mereology is produced by combining the above partial order with the following definitions:

1. $Oxy =_{df} \exists z(Pzx \wedge Pzy)$ (Overlap)
2. $Uxy =_{df} \exists z(Pxz \wedge Pyz)$ (Underlap)
3. $EQxy =_{df} Pxy \wedge Pyx$ (Equality)

4. $PPxy =_{df} Pxy \wedge \neg x = y$ (Proper Parthood)

5. $PExy =_{df} Pyx \wedge \neg x = y$ (Proper Extension)

In order to state a problem for the idea that spacetime has non-spatiotemporal parts, we must go beyond this basic mereological system. The problem, as outlined by Baron (forthcoming) appeals to four further principles. Note that these principles need not be exhaustive; but we follow Baron in regarding them as, at least *prima facie*, plausible conditions that the framework must satisfy in order to be categorised as describing mereological—and no other—relations. First, we need a principle of locative inheritance. The original principle that Baron uses is drawn from work by Sider (2007, p. 25) but is sharpened as follows:

> **Downward Inheritance of Location:** For any composite object y and region z if y is exactly located at z, then for any x, if x is a part of y then x is weakly located at z.

Next, we need a principle of harmony, namely (H5) from Saucedo (2011):

> **H5:** For any x and any y, x is a part of y iff x's location is a subregion of y's location.

Third, we require a principle of 'size', which appears to be broadly analogous to another of Saucedo's principles (namely, H6) and which is conjoined to a further claim, namely that proper parts are always smaller than the wholes that they compose (a similar principle is used by Donnelly 2011):

> **Smaller Than:** For any x and y, x is smaller than y iff there is a region r at which x is exactly located that is a proper sub-region of the region $r*$ at which y is exactly located.

Finally, we need a principle of extension (spatiotemporal extension, that is, not extensionality in the sense of $PExy$ above):

The Compositionality of Extension: For any spatiotemporal object y and for any $x_1 ... x_n$, if $x_1 ... x_n$ compose y, then the spatiotemporal extent of y is a function of the spatiotemporal extensions of $x_1 ... x_n$ and the spatiotemporal relations between $x_1 ... x_n$.

According to Baron (forthcoming), these four extra principles are falsified if we suppose that spacetime is composed of non-spatiotemporal parts. This is easy enough to see. Assume that spacetime is composed of spatiotemporal regions which are, in turn, composed of non-spatiotemporal parts. Every spatiotemporal region has a spatiotemporal location. But none of its non-spatiotemporal parts do. So the downward principle of inheritance is false. More generally, it is hard to see how there could be any transmission of location between regions of spacetime and the non-spatiotemporal parts that compose them. It thus seems that there's no way to satisfy the broad idea that 'everyone accepts' according to Sider:

> The locations of a thing's parts are automatically reflected in the thing's location—more evidence of the intimate nature of the part-whole connection. Parthood is alone in this respect; my location is not tied to the locations of my relative, things I own, things I am near, and so on ... our actual usage of 'located' reflects the peculiar intimacy of parthood; we choose a meaning that matches my boundaries with my parts' locations ... Everyone accepts the inheritance principles. If they are true, then the part-whole connection is a uniquely intimate one. (Sider, 2007, p. 25)

H5, like Sider's inheritance principle, is also falsified. H5 entails that if a spatiotemporal region has non-spatiotemporal parts, then those parts must be located at a sub-region of the initial region. But the non-spatiotemporal parts are located at no spatiotemporal regions whatsoever, and so are located at no sub-regions. The 'smaller than' principle is similarly imperilled. Suppose that a spacetime region has non-spatiotemporal proper parts. The region has a particular size. But it can't be said that its proper parts are smaller in size, at least not for the same concept of size. To be smaller than a spatiotemporal region, an object has to have at least some spatiotemporal extent in the first place, but the non-spatiotemporal proper parts of spacetime regions have none. Finally, the compositionality of extension fails. The extent of a spatiotemporal region is not a function of the spatiotemporal extent of its non-spatiotemporal parts and the spatiotemporal relations between them, because those parts have no spatiotemporal extent and stand in no spatiotemporal relations.

In light of the failure of the four extra principles that Baron adduces for mereology, he concludes that whatever the relation might be between spacetime and some more fundamental collection of non-spatiotemporal entities, it is not a mereological relation. As he puts the point:

> [T]he resulting notions of 'composition' and 'part' bear little resemblance to the common-sense notions that drive our understanding of the mereology of objects. These concepts appear to break down when they are used to model the relationship between spatiotemporal and non-spatiotemporal objects. Of course, one can always stipulate a relation that satisfies the formal axioms of mereology and maintain that it holds between spatiotemporal and non-spatiotemporal objects. But the question is whether the relation so defined deserves to be called a relation of composition. And I don't see that it does. (Baron forthcoming)

To be clear, we don't think that Baron is raising a terminological point about whether we should use the word 'composition' to describe the relation between spacetime and some more fundamental entities. The problem, as he puts the point elsewhere (see Baron 2019a), is that the falsification of the four principles stated above signals a conceptual break-down of parthood. The concept of parthood is somehow misapplied when it is used to characterise the relationship between spacetime and its non-spatiotemporal parts. One could certainly posit a relation between spacetime and its non-spatiotemporal parts. And maybe that relation is a partial order. But the relation is not a composition relation because it does not possess enough of the right features to be rightly called mereological. We are simply making a conceptual mistake if we insist on appealing to mereology in this way.

Whether the problem is compelling depends a bit on background views that are optional. Note first that none of the core aspects of the parthood relation stated above—the three axioms and the five definitions—are violated by the claim that spacetime has non-spatiotemporal parts. It is only the four *further* principles that Baron adds which cause trouble. So one might respond that the relation is mereological well-enough, it just isn't constrained by these extra principles.

More generally, there are a number of philosophers who take mereology to be topic neutral, in this sense: it is not about any particular type of object, but instead constitutes a neutral framework for describing mereological relationships between, well, anything (see Johnston 2006, p. 655, Varzi 2008 and Donnelly 2011, p. 239-240 for a view along these lines). The four principles that Baron identifies are quite plausibly principles that are specific to only certain kinds of objects: namely, spatiotemporally located objects (and, we hazard to suggest, material objects at that).[2] If mereology truly is topic neutral, then the principles that Baron identifies are unlikely to be essential features of mereological relations more generally. Indeed, Baron's argument is an example of damage done to the topic neutrality of mereology by such principles.

Given the topic neutrality of mereology, any relation that obeys only the core axioms of the basic mereological system defined above counts as a genuine parthood relation. Furthermore, any relation that obeys only these axioms can be used to consistently model a situation in which spacetime has non-spatiotemporal parts. The divide between the

[2]Not everyone agrees that spatiotemporal located objects obey the four principles. Koslicki (2008) for instance denies the smaller than principle.

spatiotemporal and the non-spatiotemporal presents no barrier to the application of core mereology, since core mereology is insensitive to such a distinction. There is therefore little reason to suppose that mereological models in which spacetime has non-spatiotemporal parts will be conceptually incoherent in general.

Now, perhaps Baron can grant that, in some sense, mereology can be used to describe all kinds of relations, some of which don't obey his four principles. He might argue, however, that with respect to *physical* entities and the *physical* mereological relations between them, it is extremely intuitive to suppose the principles in question. Intuitive to the point of essentiality: it is an essential feature of the mereology of physical objects in particular that H5 holds, or that location is downwardly inherited. Since the mereology that is needed for spacetime is one for physical entities, it is physical mereology that breaks down when applied to spacetime and its non-spatiotemporal parts.

An important question arises at this point: namely, how do we know what the mereology of physical objects is like? We can detect two quite different attitudes toward the epistemology of mereology, both of which are identified by Donnelly (2011) and Hovda (2014, p. 141). On the one hand, one might argue that the nature of mereological relations is something that should be yielded by metaphysical or even empirical investigation. Thus, we shouldn't come to metaphysics, or physics for that matter, with rigid views about the nature of mereology. We should, rather, let our views about the nature of mereology be pushed around by what we discover about the world. Thus, while a principle like H5 might seem intuitively plausible and may even serve us well for the most part, we should be open to the revision of that principle (or at least the truncation of its scope) as we find out more about reality. The second attitude takes intuitions as sacred. We start with intuitions about mereology and keep them as a fixed point in our metaphysical and physical theorising. We thus use them as a basis for guiding physical and metaphysical investigation, rather than as an output of that investigation.

Baron's four principles do seem to be very intuitive for the mereology of physical objects. Thus, if we take an intuition-first approach to the mereology of physical objects, then perhaps Baron's objection works. In our opinion, however, the intuition-first approach is problematic. To begin with, the relevance of intuitions for metaphysical disputes is questionable (see e.g. Benovsky 2015). But even if intuitions play a reasonable evidential role in metaphysics, it seems risky to assert that the facts corresponding to these intuitions are beyond revision. To illustrate, consider for instance folk intuitions about time. If intuitions about the universality of time had been considered as fixed points constraining our theories about the world, it would have been difficult to develop relativistic physics.

If, therefore, we take an approach to the mereology of physical objects that is guided by what we discover about the world rather than by intuition, then it is less clear that Baron's objection succeeds. Unless we have some strong physical or metaphysical reason to think that the mereology of physical objects must, in every case, obey his four principles, reasons that go beyond mere intuition, it is hard to see why we should rule out mereological models of spacetime. Moreover, precisely what's at stake in the current context is how we should think about spacetime in light of developments in both physics and metaphysics. These developments could well force us to concede that spacetime has non-spatiotemporal parts. And so it seems quite risky to rule out mereological models of spacetime in advance of any specific discovery about the world. We therefore don't see why we should accept that physical mereology is necessarily constrained by the kinds of principles that Baron identifies, and so we don't think he has shown that mereological models of spacetime are conceptually incoherent.

That being said, we think that Baron's objection inspires a nearby challenge that is harder to address. While we don't think that the four principles Baron identifies are conceptual constraints on physical mereology, we admit that those principles do at least *seem* to be satisfied in a wide range of cases, for many physical objects. And yet, for the reasons Baron outlines, these principles cannot apply to the mereological connection between spacetime and non-spatiotemporal objects. Because of this apparent difference between spacetime and other objects, we cannot clearly use our familiarity with the mereology of ordinary physical objects to inform our understanding of dependent spacetime. But then the *prima facie* advantage of appealing to mereology to understand dependent spacetime—namely that it is a familiar style of dependence for physical objects—seems to be lost. While we can certainly appeal to a general notion of parthood to produce models in which spacetime has non-spatiotemporal parts, these models, one might urge, fail to shed any light on the dependence of spacetime on non-spatiotemporal objects because of their alienation from ordinary physical cases.

Thus, while mereology doesn't conceptually break down when it is used to account for the relationship between spacetime and more fundamental non-spatiotemporal entities, it does potentially become rather unlike the mereology of other objects. There is therefore a question concerning how valuable it is to say that the relationship between spacetime and a range of non-spatiotemporal entities is a mereological one, given that it behaves differently from the mereological relations operative in the rest of the physical realm.

3 Three Types of Explanation

Our goal in what remains is to argue that it is, indeed, valuable to think about the dependence relationship between spacetime and a range of non-spatiotemporal entities in mereological terms. This is distinct from our goal in the first section, which was only to argue, against Baron, that it is conceptually coherent for spacetime to possess non-spatiotemporal parts. Thus, we now ask: assuming that such models are coherent, are they valuable?

In order to make our case that such models are useful, it is helpful to introduce the notion of a *how-possibly explanation* (HPE). How-possibly explanations come in at least two distinct forms. The first goes back to the work of Dray (1957) in the philosophy of history. On Dray's view, an HPE for some x is an explanation of how it is that x is possible, where possibility is understood to be epistemic possibility: a way for the actual world to be. Call this a Type 1 HPE. The second form of HPE is based on Brandon's (1990) work in the philosophy of biology. On Brandon's view, an HPE for some x is a possible explanation of x. Call this a Type 2 HPE.

One immediate way to see the difference between Type 1 and Type 2 HPEs is to consider that they have different kinds of explananda. In a Type 1 HPE the explanandum can be represented as $\diamond x$, i.e. the fact that x is possible. In a Type 2 HPE, by contrast, the explanandum can be represented as just x; i.e., without embedding x under a possibility operator.

A further difference between Type 1 and Type 2 HPEs concerns how they relate to a third type of explanation: how-actually explanation. A how-actually explanation (HAE) is an explanation of how something actually occurs. Type 2 HPEs are potential HAEs. Thus, a given Type 2 HPE may turn out to be an HAE if it ends up being supported by the evidence. Type 1 HPEs, by contrast, are not, in general, potential HAEs. HAEs are only explanations for how things actually are. A Type 1 HPE for x is a complete explanation of $\diamond x$.

HPEs of both types, unlike HAEs, can be quite speculative. They can draw on a range of facts for which we lack evidential support. Type 2 HPEs can also serve as Type 1 HPEs in some situations. For instance, suppose that one takes some x to be impossible because x requires explanation and one cannot see how x could be explained. In this situation, producing a possible explanation for x (a Type 2 HPE) can also help to explain how x is possible (a Type 1 HPE).

Our view is that taking a mereological approach to the relationship between spacetime and a range of non-spatiotemporal entities is useful because doing so allows us to formulate both Type 1 and Type 2 HPEs. We will show this in two stages. First, by using mereology to formulate Type 1 HPEs and, second, by using mereology as an explanatory strategy for producing Type 2 HPEs.

Note that in what follows we talk of the *existence* of spacetime. In doing this, we aim to bracket the debate between relationism and substantivalism. We thus take a commitment to the existence of spacetime to be a commitment to the existence of spatiotemporal structure in some sense. That commitment can, however, take the form of a commitment to a substance or a network of relations. This is important since some relationists who take themselves to deny the existence of spacetime in some sense, will still be committed to the existence of spacetime in the minimal sense at issue here.

4 Mereology and Type 1 HPEs

A Type 1 HPE shows how it is possible for spacetime to depend for its existence on a range of non-spatiotemporal entities. Different HPEs are called for depending on the sense in which this is thought to be impossible in the first place. If we set aside physics for the time being (which we discuss in the next section in the context of Type 2 HPEs), we can discern two ways in which dependent spacetime might be thought impossible: it might be deemed conceptually incoherent, or it might be ruled out by what we know concerning the metaphysics of the actual world.

Let's start with the conceptual option. Here a Type 1 HPE takes the form of a conceptually coherent model of dependent spacetime. Mereology can be used to produce such a model. Mereological relations are generally considered to be dependence relations. Given this, any conceptually coherent mereological model of spacetime in which spacetime has non-spatiotemporal parts is also a model that shows us how it could be that spacetime is a dependent entity.

As discussed in §2, a basic mereological framework that obeys standard mereological axioms, but that does not include any of the principles Baron identifies can be used to provide a model in which spacetime has non-spatiotemporal parts. There are at least two such models already available: one produced by Paul (2002, 2012) and another by Le Bihan (2018). In both cases, spacetime is constructed from non-spatiotemporally located parts. In Paul's model, entities are constructed from more fundamental properties, including primitive location properties, which are bundled to form both material objects and the spacetime manifold (see e.g. Paul 2012, p. 245). Spacetime itself thus has (at least some) non-spatiotemporal parts, in the form of properties, which lack a specific spatiotemporal location. Le Bihan takes a different approach and proposes to build spatiotemporal relations directly. Thus, he suggests a model in which spatiotemporal relations are mereologically composed of non-spatiotemporal entities.

Both models are consistent mereological models, and so both models provide conceptual Type 1 HPEs for dependent spacetime. This is useful because it may not be obvious how to conceive of spacetime as a non-fundamental entity in the first instance. To be clear, we are not simply restating the point made against Baron: namely, that mereological models in which spacetime has non-spatiotemporal parts are conceptually coherent. Rather, we are assuming that such models are conceptually coherent (based on what we said in §2) and are drawing a more general moral, namely that the conceptual coherence of these models helps us to conceive of dependent spacetime.

Now, one might object that these models are conceptually incoherent, and so fail to demonstrate the conceptual possibility of dependent spacetime. There are two main concepts in play that might be used to make this claim: the concept of parthood, and the concept of spacetime. In order to make the case using the concept of parthood, one would need to run an argument along the lines of the first objection described in §2; the one offered by Baron. We have, however, already provided a response to this kind of objection.

What then of the spacetime concept? Whether the concept of spacetime rules it out that spacetime is made of non-spatiotemporal parts depends very much on what that concept might be. A popular approach to the concept of spacetime, however, analyses it in functionalist terms: what it is to be spacetime is just to play the spacetime role.[3] The exact nature of the spacetime role remains controversial. So far as we know, however, there is no existing analysis of the spacetime role that rules out the mereological models outlined above. It thus remains conceivable that whatever plays the spacetime role (and thus whatever just is spacetime on one way of understanding functionalism) is, in turn, composed of parts that lack the same functional properties. Indeed, functionalism in the philosophy of mind provides a precedent for this kind of case. What plays the functional role of pain—a specific neural state, say—may nonetheless be composed of specific neurons that, individually, fail to functionally realise pain.

Of course, there might be some other way to understand the spacetime concept, we cannot rule that out. But in the absence of a further conceptual analysis of what it is to be spacetime, we find no basis for the view that Le Bihan's and Paul's models are conceptually incoherent. Given this, we see no reason to doubt the status of these models as Type 1 HPEs for dependent spacetime.

Even if dependent spacetime is conceptually coherent, however, one might still be of the view that it is ruled out on metaphysical grounds. This presumption can be defeated in much the same way as above: by providing a mereological model. The conceptual viability of those models, however, will only take us so far. In addition, these models should not conflict with what we know concerning the metaphysics of the actual world. Now, it is something of a conceit that there is an agreed-upon metaphysics of the actual world. But, if anything, this plays in our favour, as it is then unclear how confident we should be that mereological models of spacetime conflict with actual metaphysics. That being said, in so far as we have a grasp on the metaphysics of spacetime, and of parthood, there doesn't seem to be a reason to rule out the models at issue.

For one thing, spacetime can clearly have parts in some sense. The easiest way to

[3] See e.g. Lam and Wüthrich (2018, 2020); Knox (2019); Baron (2019b); Le Bihan (2019); Linnemann (2020); Chalmers (forthcoming) and Yates (forthcoming).

see this is just to suppose that spacetime is composed of regions, and these regions are themselves spatiotemporal. Of course, one might grant that spacetime can have parts in this sense, but maintain that spacetime's parts must have exactly the same properties as spacetime. But there is no requirement on parts in general that they share the properties of the wholes they compose. Indeed, there are clear counterexamples. A diamond is hard even though 'hardness' is not a property of any of the molecules that compose it. The properties of the whole may be completely novel or 'emergent' compared to the properties of the parts.

Given that there is no requirement in general for wholes to possess all of the same properties as their parts, there is no general reason to demand this in the case of spacetime. Furthermore, we know that in the framework of general relativity some properties of spacetime are 'global', i.e. cannot be defined locally: this is for instance the case for event horizons, which can only be defined as global properties of spacetime (see e.g. Lam 2006, Manchak 2013 and Curiel 2020, section 3.1 for discussion). As it is impossible to reduce some global properties of spacetime to local properties of its spatiotemporal parts, this shows that it would be unreasonable to require, as a matter of principle, the properties of spacetime to always be the same as the properties of its parts. This, of course, is not to say that the parts of spacetime cannot share *any* properties with spacetime; any more than we need to say that the (molecular) parts of a diamond share no properties with the diamond.

Of course, one might grant that spacetime may have parts and that it may have different properties to its parts, but nonetheless maintain that the parts of spacetime must be of the same type as spacetime. As before, however, there is no general metaphysical requirement that parts must be of the same type as wholes. Types, like properties, are often emergent. Given this, there doesn't seem to be any general metaphysical requirement for spacetime to be of the same type as its parts.

Given that neither the actual metaphysics of spacetime nor of parthood seems to yield a prohibition against spacetime having non-spatiotemporal parts, it is difficult to discern a firm metaphysical basis for ruling out such mereological models of spacetime. Such models thus show how it could be that spacetime is a dependent entity against a metaphysical presumption to the contrary. This is notable given that, as noted in §1, the fundamentality of spacetime is a common assumption within metaphysics. It is, for instance, assumed by Lewis (1986) as a way to define and distinguish concrete worlds in the framework of this modal realism;[4] by Armstrong (2004) to define his naturalism according to which all there is the spacetime world;[5] and by Schaffer (2009) as the basis for his supersubstantivalism—the view that the only fundamental (super)substance is spacetime itself. Mereological models of spacetime, construed as Type 1 HPEs, provide a way to resist this trend in metaphysics.

5 Mereology and Type 2 HPEs

This brings us to Type 2 HPEs. In considering Type 2 HPEs we will move away from conceptual and metaphysical territory to focus on physical models. As noted briefly in §1, the idea that spacetime might depend, for its existence, on a range of non-spatiotemporal entities has come to the fore in recent discussions of QG. A number of theories of QG appear to imply that spacetime is not a fundamental feature of reality. It is compatible with this, however, that spacetime exists but as a dependent entity. Call such an approach to QG: *dependent spacetime realism*.[6] Dependent spacetime realism is not the only approach

[4]As Wüthrich (2019) points out, Lewis' criterion conflicts with the claim found in QG that the actual world might not be fundamentally spatiotemporal.

[5]See e.g.: "I am looking, for a metaphysics compatible with the view that the world of space-time is all that there is" (Armstrong, 2004, p. 101).

[6]In line with our stated neutrality in §3, we regard both substantivalism and relationism as two sorts of realism. In the context of spacetime emergence, one might be a substantivalist or a relationist regarding either the fundamental or the dependent structure—although the very idea of a dependent substantial spacetime might be less appealing than the alternative options. Spacetime eliminativism involves denying more than just

available, but there are strong reasons to favour it (cf. for instance Wüthrich 2017, 298 and Le Bihan 2018, 79-80). Chief among these is that the existence of spacetime in some sense appears to be a necessary precondition for empirical confirmation to occur. Without the existence of spacetime it is unclear that the approaches to QG at issue—which seem to deny that spacetime exists—are empirically viable theories (this is the so-called problem of empirical confirmation in quantum gravity, see Huggett and Wüthrich 2013).

A central task for the spacetime realist is to provide an explanation of how spacetime exists. By this we don't mean: an explanation of why spacetime takes one form rather than another (say, as a substance versus as a system of relations). Rather what we mean is: an explanation of how spacetime exists at all given that, from the perspective of the fundamental physical picture described by certain approaches to QG, only non-spatiotemporal entities exist. Such an explanation would describe how it is that spacetime emerges at certain physical scales, and what its relationship might be to non-spatiotemporal entities.

Now, one might try to answer this explanatory question in mathematical terms. It is, after all, thought that a viable approach to QG should include a derivation of the relevant sector of general relativity: the models consistent with actual data. What this means is that one ought to be able to derive the mathematical structure of spacetime—such as the metric tensor field—either completely or to a sufficiently close approximation, in order to explain the extraordinary predictive success of general relativity. By now, mathematical procedures of this kind have been identified for a range of different approaches to QG. One might argue, then, that such mathematical results tell us all there is to know about how spacetime exists in QG, and so provide a full answer to the explanatory question posed above.

It is far from clear, however, that the mathematical results alone are up to the ex-

the substantial categorial nature of spacetime (for instance one must, in addition, deny its metric or similar). It states that there is no spacetime at all—were it be to be defined as fundamental or dependent, relationist or substantivalist.

planatory task. This is because the explanatory question is not just the question of how we recover one theory or piece of mathematical structure from another. The question is really seeking an understandable physical picture of how it is that non-spatiotemporal entities and properties conspire to produce spatiotemporal ones. What we want is a minimal specification of the ontology that accompanies the mathematical results at issue, and that helps us to better grasp the dependent spacetime realist approach.

Ultimately, we must await developments in physics to find out whether the dependent spacetime realist approach is correct and, if it is, what the actual explanation for the existence of spacetime might be. In the meantime, we can provide some possible explanations. These Type 2 HPEs are valuable for two reasons. First, Type 2 HPEs of how spacetime exists are the source material for HAEs. This is true in the obvious sense that HAEs begin their lives as Type 2 HPEs, and so producing a range of Type 2 HPEs is a necessary step along the road toward finding an HAE. In addition, however, Type 2 HPEs also provide the necessary source material for producing other Type 2 HPEs through correction and modification, and thus help us produce an HAE in the end.

Second, as discussed in §3, Type 2 HPEs can be transformed into Type 1 HPEs in some situations, namely when explanation is at issue. This is useful because one reason for thinking that dependent spacetime is impossible that we haven't considered yet, relates to explanation. If spacetime depends for its existence on non-spatiotemporal entities, then its existence must be explained in terms of those entities. But, one might argue, it is a necessary condition on y depending on x that x explains y. However, one might continue, there appears to be an explanatory gap between non-spatiotemporal entities and spatiotemporal ones.[7] It is just not possible to explain spatiotemporal entities in terms of non-spatiotemporal ones given the actual physical structure of the world. A Type 2 HPE for dependent spacetime provides a possible explanation and thereby serves

[7]This suggests viewing the task of explaining how spacetime exists as involving a problem similar to the hard problem of consciousness. See Le Bihan (2019) and Chalmers (forthcoming).

as a Type 1 HPE as well, closing the explanatory gap. This is potentially valuable since at least some of the resistance to the notion of dependent spacetime in physics expressed by philosophers like Maudlin (2007, 3157) could be based on the idea that there is an explanatory gap of the relevant kind.

Now, we are not in a position to provide a complete Type 2 HPE for dependent spacetime. That, in no small part, is a matter for physics. Instead, what we aim to show is that mereology forms the basis for an explanatory strategy: a recipe for producing Type 2 HPEs in the context of specific approaches to QG. The recipe, in brief, is this: first, take a given approach to QG and reinterpret its ontology in mereological terms. Second, use mereological notions in combination with the physical structure of the theory to provide a possible explanation of the existence of spacetime.

In what remains, we will demonstrate this explanatory strategy on one approach to QG in particular: *causal set theory* (CST).[8] CST attempts to formulate a quantum theory of gravity by positing an ontology of sets. These sets are discrete and partially ordered into a maximal set via a primitive relation of causal precedence. This primitive relation of causation is metric-free. The central idea behind CST is that a structure of sets combined via metric-free ordering relations suffices to recover, to a good approximation, the rich structure of relativistic spacetime. As Wüthrich and Huggett (2020a, p. 1) describe the view:

> [CST] extracts the causal structure that it takes to be essential for relativistic spacetimes, posits it as fundamental, imposes discreteness, and tries to establish that these spacetimes generically arise from the resulting structures in the continuum limit.

The central motivation behind CST is a set of results establishing that it is possible to recover the metric structure of spacetime from spacetime's causal structure alone

[8]See e.g. Bombelli et al. (1987); Dowker (2006); Rideout and Wallden (2009) and for philosophical discussion see Wüthrich (2012); Huggett (2014); Wüthrich and Huggett (2020a,b).

(Wüthrich and Huggett, 2020a, section 1.3). CST thus draws on these results to try and quantize spacetime by reconstructing it in purely causal terms, via a relation of causal precedence between discrete elements.

The kinematics of CST can be represented as a causal set, or *causet* for short:

$$< C, \preceq >$$

where C is a set of elements and $\preceq$ is a relation defined on C: the so-called *relation of causal precedence*. CST obeys three axioms. First, $\preceq$ is reflexive, anti-symmetric and transitive and thus forms a partial order over C. Second, causal sets are locally finite:

$$\forall x, z \in C, |\{y \in C \mid x \preceq y \preceq z\}| < \aleph_0,$$

where $\aleph_0$ is the cardinality of natural integers and $|X|$ stands for the cardinality of X. Third, C is countable (i.e., there exists an injective function from the set of elements to the natural numbers).

The kinematics of CST is typically supplemented with a dynamics. A popular proposal due to Rideout and Sorkin (1999) is a *law of sequential growth.* According to this proposal, the causet grows as new elements and relations of causal precedence come into existence via a stochastic, Markov process.[9]

Now, as Huggett and Wüthrich (2013) have argued, the fundamental structure described by CST does not appear to be spatiotemporal in all respects. Suppose, nonetheless, that we take this situation to be consistent with the existence of spacetime, at least at some level of description. How might we then explain the existence of spacetime using the resources available in CST? As with many theories of QG there are some (in this case preliminary) mathematical results that suggest the derivability of some models of general relativity. However, those preliminary mathematical derivations hardly suffice to yield a full understanding of the existence of spacetime. We need conceptual resources to link

[9] A Markov process is a sequence of elements in which the probability of each element depends only on the immediately preceding element.

the ontology of CST to general relativity. To use the decidedly metaphysical language of Bennett (2017), it would be very helpful if we could specify a *building relation* that relates the CST world to the spacetime world.

The set-theoretic membership relation is a natural candidate for a building relation in the framework of CST (since it 'builds up' elements into maximal sets). However, set theory is generally regarded as better suited to abstract entities. Viewing the core building relation of CST instead as mereological offers a promising alternative, given that mereology is better suited to concrete entities. Consequently, recasting causal set theory in mereological terms, gives the theory new explanatory resources to explain the existence of spacetime.

Note that we cannot simply interpret $\preceq$ as a mereological relation. Despite both mereological relations and $\preceq$ being partial orders, the elements that are pairwise related by the primitive causal precedence relation are generally assumed to be simple, indivisible entities in CST. If we just identify $\preceq$ with a mereological relation then its relata, regarded as *simple*, and partially ordered by $\preceq$, will be such that *one is part of the other*—a manifest contradiction. Instead, what we recommend is adding a mereological relation as additional structure.[10] We can then add *fusions* to the theory. Fusions can be any group of causal set elements that are related by a second partial order, P, which is a primitive notion of parthood.[11]

To accommodate the added mereological structure we can reformulate the basic struc-

[10] An alternative would be to replace the full set-theoretic framework with mereological notions alone. This would require adding axioms to the list of mereological axioms listed above that would permit the formulation of the axioms of CST, currently formulated in set-theoretic terms. For instance, $\aleph_0$, involved in the second kinematic axiom, is a set-theoretic notion; rephrasing it in mereological terms would require some substantial work. But for our present aim, we don't need to settle in favor of a hybrid or purely mereological approach.

[11] Presumably, however, only specific fusions will correspond to spacetime (namely, groups of elements with the right causal structure). But in order for the theory to be as general as possible, we have allowed for a much larger range of fusions than just the ones that correspond to spacetime.

ture of CST as a quadruple consisting of elements, C, a causal ordering relation, $\preceq$, fusions, F, and a parthood relation P:[12]

$$< C, \preceq, F, P >.$$

The quadruple satisfies both the basic axioms of mereology laid down in §2 and the kinematic axioms of CST.

Call these mereological causal 'sets': *causal sums* or *causums*. The dynamics of the theory can then be understood in the usual way, as a growth in the elements in C that are related by $\preceq$, but with one addendum: as new elements are added to the structure, new fusions are added as well, thereby generating new causums.

The existence of spacetime in CST can now be at least partially explained in terms of causums. Recall the motivation behind CST, namely the existence of results suggesting that spatiotemporal structure can be reduced to causal structure. These mathematical results do not solve the problem of explaining how spacetime exists. While causets have causal structure, they don't *generally* have the causal structure that is needed for spacetime, otherwise we could straightforwardly find a metric connection between causal set elements. This can't be done, however, since the primitive 'causal' relation in CST is not the relativistic notion of causal connectedness, but only corresponds to it in certain special cases.

These mathematical results do, however, reduce the problem of explaining how spacetime exists to the problem of explaining how causal structure of a certain kind exists. This is advantageous because, if we look to mereology, there are many existing examples in which wholes have emergent causal properties: causal properties that are entirely novel and distinct to the causal properties of any parts. The part-whole relation is already

[12]We include both F and P because parthood, on its own, may not ensure that there are fusions. That's because the parthood relation on a model can be well-defined, and yet fail to connect any elements. If a restriction is placed on P such that it must always connect at least two elements, then F is redundant. We have chosen to specify the theory in its most general form, however, and so we don't restrict P in this way.

implicated, to a certain extent, in the emergence of unique causal features.

What the mereological interpretation of CST does, then, is turn the explanatory question of how spacetime exists into a very familiar question of how it is that a whole might come to have very different causal properties to its parts. We can thus use more standard cases of causal emergence as a template for providing a possible explanation of the existence of spacetime.

For instance, a diamond has various causal properties that are not possessed by any of its (molecular) parts. The diamond's causal properties arise because of the way its (molecular) parts are arranged, and because of the causal properties of those parts working together to produce emergent causation. By the same token, we may say that the causal relations of elements in a causum, when arranged in a certain way, form a mereological whole that is imbued with new causal properties. Those causal properties just are the causal properties associated with spacetime. Spacetime thus exists because causal properties emerge via the mereological arrangement and binding of causum elements.

This, of course, is not a complete Type 2 HPE for how it is that spacetime exists. What we are missing, in particular, is an account of the kind of arrangement of causum elements that yields the right emergent causal properties, and an account of how these causal properties arise from the causal structure of the underlying causums. To see that something is missing, consider that a diamond has the causal power to cut almost anything (within reason). That causal power is to be explained in terms of the tight bonding between carbon molecules. What we need in the case of CST is a similar story: a story about how it is that the specific causal properties of spacetime can be explained in terms of more fundamental properties. Moreover, it is unclear that these fundamental properties are causal properties in any usual sense, since the usual notion of 'cause' seems to be a spatiotemporal notion, and causums (like causets) lack spatiotemporal structure. In this way, the picture of causal emergence at issue is unusual, in so far as properties that are causal in a spatiotemporal sense are likely to be emergent from properties that are not. To better understand this picture, we require a better understanding of the fundamental properties of CST. For this reason, progress on producing a complete Type 2 HPE for CST is unlikely to come from metaphysics or philosophy alone. What we need is a better understanding of CST itself, and especially of its ontology.

Still, without mereology, we wouldn't have the same resources to formulate an explanation that mimics more ordinary cases of causal emergence in the first place. Recasting CST in mereological terms thus gives us a way to think about how we might explain the existence of spacetime within the context of this theory. We can also carry over our understanding of the fact that wholes often have entirely new properties compared to their parts. This helps us to see how spatiotemporal properties might emerge from something that is not spatiotemporal, at least in principle. A mereological approach to CST also goes some way toward providing a Type 1 HPE of how it could be that spacetime is a dependent entity. For we now have a better sense of how this could possibly be, because we have a better sense of what a possible explanation of this fact might look like, even if we currently lack the full story.

6 Conclusion

It is fair to say that we have not provided a full-blown defence of mereological models of dependent spacetime. What we have shown, however, is that we should not doubt such models because the mereology fails to satisfy intuitively compelling principles. We have also argued that mereological models are useful for explaining how it could be possible for spacetime to be dependent. This is important work. If we can't even imagine how it could be that spacetime is a dependent entity then it is rather tempting to dismiss any approach to physics that treats spacetime as non-fundamental.

Of course, whether mereological models are viable accounts of dependent spacetime is another matter. Even here, however, the models may serve a purpose in giving us a possible explanation for the existence of spacetime. This understanding may turn out to be a purely heuristic device, oversimplifying the complex nature of the physical world. Or, alternatively, it might turn out that mereology was a first step in our understanding of how spacetime depends on a non-spatiotemporal structure after all. Ultimately, we can't know until we get a more satisfying understanding of the ontology of fundamental physics via progress made in QG itself.

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