**Mereological Models of Spacetime Emergence**

**Abstract:** Recent work in quantum gravity has prompted a re-evaluation of the fundamental nature of spacetime. Spacetime is potentially emergent from non-spatiotemporal entities posited by a theory of quantum gravity. Recent efforts have sought to interpret the relationship between spacetime and the fundamental entities through a mereological framework. These frameworks propose that spacetime can be conceived as either having non-spatiotemporal entities as its constituents or being a constituent part of a non-spatiotemporal structure. I present a roadmap for those interested in exploring the role of composition in understanding the emergence of spacetime. I establish a taxonomy based on four crucial parameters that should be considered when constructing potential mereological models. Subsequently, I connect these models to a spectrum of perspectives found in current literature, with the aim of pinpointing areas that require further exploration. Finally, I identify three potential challenges facing mereological models of spacetime emergence, rooted in issues of mereological harmony, the distinction between continuous and discrete spacetime, and the implications of quantum superposition.

**Keywords:** Spacetime Emergence; Mereology; Mereological Models; Quantum Gravity; Dependence; Fundamentality; Parthood

1. **Introduction**

According to physics, it is expected that it is possible to derive an approximate description of spacetime as specified by the theory of general relativity (GR), from a theory of quantum gravity (QG) (Crowther, 2016, 2022; Healey, 2017; Isham & Butterfield, 1999). Approaches to QG, such as string theory, loop quantum gravity (LQG) and causal set theory (CST)—suggest that spacetime or spatiotemporal properties may not be fundamental (Huggett & Wüthrich, 2013; Wüthrich, 2018). What is fundamental, or so physics may indicate, are entities that lack spatiotemporal properties, where such entities are the primary theoretical posits of a theory of QG (Crowther, 2016, 2018; Huggett & Wüthrich, 2013, 2018). One important strand in this discussion focuses on the idea that spacetime metaphysically depends on something that is non-spatiotemporal (Wüthrich, Le Bihan, & Huggett, 2021).[[1]](#footnote-2)

Here, I am interested in the idea that spacetime *emerges* from some more fundamental non-spatiotemporal structure.[[2]](#footnote-3) I’ll treat emergence as a metaphysical relation that holds between entities *in the world* (Baron, 2019; Lam & Esfeld, 2013). I’ll also assume the following: when an entity or structure, , metaphysically emerges from an entity or structure, , is ontologically dependent on . This raises important questions—that I’ll explore here—about how spacetime emerges from a more fundamental structure and in what sense general relativistic spacetime is emergent from entities in QG.[[3]](#footnote-4)

It is worth pointing out that I am operating under the assumption of spacetime realism. Some philosophers have argued for a kind of eliminativism about spacetime: the view that spacetime does not exist (see for instance, (Baron, 2021a; Le Bihan, 2018) and to a lesser extent (Baron & Le Bihan, 2022c). Also see discussion by Ismael (2021)). In contrast, I assume that there is some real physical entity that is spacetime that is at least approximately described by our best scientific theories. Even in the case that a fundamental theory of the world is non-spatiotemporal, we can adopt spacetime realism. However, it remains open as to what exactly spacetime is like, which may well depend on developments in physics [see (Lam & Wüthrich, 2020)].

A model of spacetime emergence should explain how spacetime arises from the non-spatiotemporal: it should explain the existence of spacetime in terms of the non-spatiotemporal entities posited within a theory of QG. In this paper, my aim is to survey the landscape of possible *mereological* models of spacetime emergence.[[4]](#footnote-5) A conceptually coherent mereological model of spacetime emergence aims to explain how spacetime depends on the non-spatiotemporal by specifying the dependence in terms of the parthood relation: the relation between parts and wholes.

There has been some discussion of mereological models of dependent spacetime [for example see, (Baron & Le Bihan, 2022a, 2024; Le Bihan, 2018; Paul, 2012)], however the range of possible mereological models is yet to be fully articulated in the literature. My goal here is to address this lacuna. In the following section, I discuss some motivations for appealing to mereology as a viable explanatory strategy for spacetime emergence. In Section 3, I specify a basic mereological framework that obeys standard mereological axioms. This framework can be used to build a model in which spacetime depends on non-spatiotemporal parts. Then, in Section 4, I provide a set of questions we should aim to answer in forming possible mereological models. The questions are followed by the range of possible ways in which we might model dependent spacetime by combining the answers to these questions. In Section 5, I connect the space of models with a range of views currently defended in the literature, with an eye toward identifying gaps. Finally, I identify three possible problems for mereological models of spacetime emergence based on mereological harmony (Section 6.1), continuous vs. discrete spacetime (Section 6.2), and quantum superposition (Section 6.3).

1. **Motivations for Mereological Models of Spacetime Emergence**

Here’s one reason to think that a mereological model offers the right explanation of how spacetime emerges: parthood may be one of the fundamental properties and relations that gives rise to the structure of the world. Some have argued in favour of composition as the one true building relation on *a priori* grounds. For example, Paul (2012) claims that that the minimum requirements for a world to be built, is that the fundamental building blocks are fused together by the relation of composition and those fusions build more complex composite objects. What Paul calls the ‘composition intuition’ is our direct grasp of proper parthood.[[5]](#footnote-6) However, appeal to intuitions and *a priori* knowledge about composition seems inappropriate in the context of science where the entities and relations that are the fundamental constituents of the world should not be settled *a priori*. There is also a long-standing debate over the extent to which *a priori* methods play a substantive role in philosophy and the sciences [for an example of an argument that *a priori* reasoning has no role, see (Papineau, 2009)].

An alternative argument for the use of parthood to model spacetime emergence appeals to inductive considerations, rather than *a priori* knowledge. Note, in the first instance, that composition is useful in many cases of scientific explanation. For example, composition is used in the philosophy of biology (Brenner, 2018; Brogaard, 2004; Calosi & Graziani, 2014; Casetta & Vecchi, 2019; Hull, 1978); in biomedical contexts (Schulz, Kumar, & Bittner, 2006); and in social science (Copp, 1984; Hawley, 2017; Schmidt, 2020; Strohmaier, 2018).[[6]](#footnote-7) Recently, in the philosophy of physics, mereology has featured in discussions of wave function or configuration space realism.[[7]](#footnote-8) Wave function realists endorse the view that there is one fundamental entity—the quantum wave function (or, the configuration space in which the wave function lives). A number of philosophers argue that we can specify the relation between ordinary three-dimensional objects and the fundamental ontology in quantum mechanics as a mereological relation. For instance, according to Le Bihan (2018), spatiotemporal objects like spacetime regions just are the scattered proper parts of the configuration space. Similarly, Ney (2020) has claimed that parthood is the natural starting point for specifying the relation between macroscopic particles and the wave function.[[8]](#footnote-9)

Moreover, there are many systems that demonstrate emergent behaviour where parthood is appealed to for at least a partial explanation of that emergence. For example, it is used to in the explanation of emergent characteristics of social behaviour (Abdou & Gilbert, 2009; Epstein, 2002; Schelling, 1971); economic behaviour (Chen & Yeh, 2002; Dosi & Roventini, 2019); behaviours of biological systems (Vicsek, Czirók, Ben-Jacob, Cohen, & Shochet, 1995; Winfree, 1967); and artificial neural networks, such as machine learning algorithms like Deep Learning (Baron, 2023; Gupta & Jayannavar, 2021).

The use of composition in scientific accounts of emergence gives us a modest inductive argument for mereological models of spacetime emergence: because composition is useful in so many scientific domains for explaining emergence in particular, we can expect it to be useful in the case of spacetime emergence as well. The strength of this kind of argument depends on the strength of the inductive base. However, there is reason to suppose that in physics, at least, the inductive base is not very strong. Healey (2013), for instance, argues that light, matter, and quanta associated with various quantum fields do not straightforwardly decompose into spatiotemporal parts. He argues that decomposition is perhaps then not the only explanatory and predictive strategy used in physics in accounting for the behaviour of a physical system.

Baron and Le Bihan (2022a) offer a third motivation for pursuing a mereological approach to spacetime emergence. According to them, mereological models offer a source of ‘how possibly’ explanations (HPE) for how spacetime could be possibly emergent. HPEs are useful in giving explanations for how spacetime is possible as they show that we can develop a model of spacetime in terms of composition that is conceptually coherent. Further, HPEs can provide a possible explanation for the existence of spacetime itself, given that spacetime exists derivatively according to theories of QG. Explaining the existence of spacetime largely requires input from physics, but mereology may be used in developing a possible explanatory strategy to be filled out later on (Baron & Le Bihan, 2022a). Even if mereological models are not successful for spacetime in the full course of time, offering HPEs in mereological terms may reassure sceptics that it is possible that spacetime can in fact emerge from non-spatiotemporal entities.

Baron and Le Bihan (2022a) mention a further motivation for mereological models of spacetime emergence. Mereological models of spacetime emergence may allow for continuity in explanation with ordinary composite objects. This means that offering explanations in mereological terms for spacetime emergence allows us to carry over what we know about parthood and ordinary objects to the case of spacetime emergence as well. Accordingly, by starting with the hypothesis that the dependence relation between spacetime and the non-spatiotemporal is a mereological relation, we gain potential benefit from the familiarity that we have with using mereology in our explanations of ordinary physical objects.[[9]](#footnote-10)

1. **Principles for Parthood and Mereology**

To build a mereological model of spacetime emergence, we require a primitive two-place notion of parthood, . Following Cotnoir and Varzi (2021) I introduce below, the minimal requirements for General Extensional Mereology. The following ordering axioms impose a partial order on the parthood relation:

(A.1) (Reflexivity)

(A.2) (Transitivity)

(A.3) (Antisymmetry)

I’ll adopt the following standard mereological definitions:

(D.1) (Overlap)

(D.2) (Proper Parthood)

(D.3) (Fusion)

Finally, I take to obey one decomposition axiom and the axiom schema for unrestricted composition, to complete our mereological vocabulary:

(A.4) (Strong Supplementation)

(A.5) (Unrestricted Fusion)

General extensional mereology is, arguably, the standard mereological system discussed in metaphysics. There are, however, some philosophers who seek to strengthen mereology with principles of mereological harmony (Leonard, 2016; Parsons, 2007; Schaffer, 2009; Uzquiano, 2011; Varzi, 2007). Roughly, mereological harmony is the view that there is at least some mirroring between the mereological structure of material objects and the mereological structure of the regions at which they are located. Consider that it may be impossible for my left leg to be a part of my body without the location of my left leg being a part of my body’s location. So too does it seem impossible for the location of my left leg to be a part of the location of my body unless my left leg is a part of my body.

Mereological Harmony consists in a cluster of principles.[[10]](#footnote-11) For present purposes, however, it is enough to consider the following core principle from Saucedo (2011)[[11]](#footnote-12):

**Harmony**  *is a part of iff 's location is a subregion of 's location.*

What this principle tells us is that the parts and their locations should not misalign with wholes and their locations.[[12]](#footnote-13) For a part, , of an object, , where is located at region , ’s location must be a subregion of . One very natural thought is that subregions relate to regions in terms of a relation that is mereological: When is located at , any part of will be located at a part of . Note that only entities with locations will non-trivially satisfy Harmony since can only be a part of , if and both have a unique location.

On the face of it, Harmony seems flatly inconsistent with the emergence of spacetime from non-spatiotemporal entities since non-spatiotemporal entities will lack the property of being spatiotemporally located. I’ll return to this issue in section 6.1.

1. **Possible Mereological Models of Dependent Spacetime**

Mereological models of dependent spacetime vary depending on what kind of object spacetime is, what kind of spatiotemporal entities are composed, what the non-spatiotemporal parts of spacetime might be, and whether spacetime emergence is a matter of composition or decomposition. These dimensions of difference constitute four parameters for specifying a space of models.

Note I will not include questions that physics should answer, as the basis for the space of models I carve out. My aim is to categorize the possible *metaphysical* models of spacetime emergence in terms of composition. The taxonomy I develop here will thus be neutral with respect to physics. That said, I will return to considerations of physics toward the end.

1. *What kind of entity is spacetime?*

I will consider two main options for what spacetime might be in the models that I present here: substantivalism and relationalism. Spacetime substantivalism takes spacetime to be a structure that exists independently of the material content of spacetime. That is, spacetime is a real *object* that can, in consistency with the laws of nature, exist independently of material things (Hoefer, 1996). In contrast, the relationalist views spacetime as a structure produced by the spatiotemporal *relations* that hold between material objects (Lam & Wüthrich, 2020).

Note that if spacetime is a network of relations, this will not commit us to anti-realism about spacetime. The relationist can still take the network of relations to exist such that they are committed to the reality of spacetime [see, for example, (Bain, 2006; Esfeld & Lam, 2008; Le Bihan, 2016)].[[13]](#footnote-14)

1. *What are the spatiotemporal entities that are composed of non-spatiotemporal parts?*

Consider dividing spacetime into its most minimal portions. We can think of the minimal portions of spacetime as that which is built from non-spatiotemporal parts. The minimal portions of spacetime are then used to construct spacetime regions according to one’s preferred view of what spacetime is (see the options discussed in question 1). I’ll present two candidates for what these minimal portions might be: points or individual relations.

Substantivalism assumes that there are such entities as spacetime regions. I’ll adopt a set-theoretic understanding of spacetime, according to which spacetime is built out of a set of points where any non-empty set of points is a region of spacetime (Gilmore, 2013).[[14]](#footnote-15) Spatial points are thought to be mereologically simple and unextended.[[15]](#footnote-16)

According to general relativity, spacetime is a continuum: space and time are tightly woven together into a smooth four-dimensional fabric. If spacetime is continuous and a substance, then the ‘smooth’ texture of unified space and time is typically partitioned into uncountably many points.[[16]](#footnote-17) But a smooth spacetime structure of points does not necessarily have to be one in which there are uncountably many. So, while substantival spacetime might be—on one view—divided into points, it may also be a discrete structure, partitioned into countably many points.[[17]](#footnote-18)

Here's the second option for what the minimal portions of spacetime might be: individual relations. Relationists will construct spacetime from relations, from which they then build spacetime regions.[[18]](#footnote-19)

I won’t distinguish between substantival or relational spacetime as either continuous or discrete in the table below. I assume, for now, that the spacetime of GR is a continuous structure of points or relations. With that said, I think that it is left open that some approach to QG may successfully interpret GR spacetime as a discrete structure. Several approaches to QG attempt to do so. Thus, the discretization of GR spacetime may be relevant in the context of QG which leads me to discuss the continuous/discrete distinction further in section 6.2. For the purposes of the space of models, however, let’s assume that whatever the minimal portions of substantival spacetime are—and whether they are continuous or discrete—they will be generated via composition in much the same way.

1. *What are the non-spatiotemporal ‘parts’ that compose spacetime?*

One possible answer to this third question is that spacetime is composed of non-spatiotemporal *entities.* Here, I’ll refer to ‘entities’ as any ontological posits other than properties. Alternatively, the non-spatiotemporal parts may be *properties* that are instantiated by the non-spatiotemporal structure or system. ‘Entities’ and ‘properties’ will be the two responses to this question in our taxonomy. I take entities and properties to be distinct. To some, this might be an unorthodox convention, but I doubt it will cause much trouble here.[[19]](#footnote-20) Moreover, to say that spacetime is composed by non-spatiotemporal parts that are more specific than ‘entities’ or ‘properties’ likely requires input from physics since different theories of quantum gravity commit to different ontological posits at the fundamental level.[[20]](#footnote-21)

We should also differentiate between the question of *what* kind of non-spatiotemporal parts might compose spacetime, from the question of *how* spacetime may be composed of the non-spatiotemporal. Non-spatiotemporal entities or properties might compose spacetime in several ways. They may be parts of the minimal portions of spacetime via a one-one correspondence, individually composing each point or relation. Or they may compose spacetime by their collective behaviour (i.e., they might be a bundle or fusion). Some might even be inclined to fuse entities and properties to construct spacetime.

This question of *how* spacetime may be composed of the non-spatiotemporal does not feature in our taxonomy here since we would want to defer to physics for its answer. For example, consider that in LQG, at some level, spacetime is a very fine non-spatiotemporal weave of spins but at a higher level we observe the continuous metric geometry. Physics will need to explain how spacetime is ‘woven out’ of these quantum loops (Rovelli, 2007).

1. *Is spacetime the result of composition or decomposition?*

Lastly, we can consider whether spacetime is composed of non-spatiotemporal parts, or whether spacetime is the result of something decomposing. If spacetime is composed, then spacetime is the whole, built from non-spatiotemporal parts; if spacetime is a matter of decomposition, then a non-spatiotemporal whole will decompose into spatiotemporal parts.

Many will expect the answer to this fourth question to be tied to a question about whether spacetime is ontologically prior to the non-spatiotemporal, or vice versa. That’s because it is commonly assumed that facts about the direction of composition are tracked by facts about relative fundamentality.[[21]](#footnote-22) But it remains open that this may not be the case.[[22]](#footnote-23) Since this matter is not central to our taxonomy, I set ontological priority aside for the time being.

Table 1 captures the range of possible mereological models of spacetime emergence that can be formulated based on combining different answers to the above set of questions.

*Table 1: Possible models of spacetime (ST) emergence from the non-spatiotemporal (NST)*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Spacetime emerges by.. | | | | | |
|  |  | **Composition** | | **Decomposition** | |
| **Spacetime is…** | *Substantival* | *Relational* | *Substantival* | *Relational* |
| **Smallest parts of ST are…** | Points | Individual relations | Points | Individual relations |
| The NST parts of spacetime are… | Entities | 1) ST points composed of NST entities | 2) ST relations composed of NST entities | 3) NST entities decompose into ST points | 4) NST entities decompose into ST relations |
| Properties | 5) ST points composed of NST properties | 6) ST relations composed of NST properties | 7) NST properties decompose into ST points | 8) NST properties decompose into ST relations |

In what follows, I will present three mereological models of dependent spacetime that are available to us in the literature from Paul (2012), Le Bihan (2017, 2018) and, Baron and Le Bihan (2022a) and situate them in the space of models outlined in Table 1. As we’ll see, not all the models in the above taxonomy have been explicitly defended in the literature and so the taxonomy reveals interesting opportunities to develop novel mereological models of spacetime emergence.

1. **Basic Mereological Models of Spacetime Emergence in the Literature**
   1. **Paul’s Mereological Bundle Theory**

Paul’s answer to question 1 is this: spacetime is just a collection of properties. More precisely, spacetime, according to Paul, is a fusion of qualitative properties, locational properties, and relational properties. Since properties can be interpreted as 1-adic relations, I’ll classify Paul as a relationalist here. For question 2, Paul maintains that the most minimal portions of spacetime are individual relational properties.

Paul’s answer to question 3, is that spacetime is composed of properties, including n-adic relations that do not have spatiotemporal locations. Paul’s answer to our fourth question is that spacetime is generated via composition. We can locate this answer to question 4 in Paul’s view given that she thinks that spacetime is solely constructed from properties, which are the fundamental category of the world. At the fundamental level, non-spatiotemporal properties are fused together to build, for instance, fields, particles, spaces, molecules and cells (Paul, 2012).

Since Paul thinks that the minimal portions of spacetime are relations, the non-spatiotemporal entities are properties, and spacetime is composed from non-spatiotemporal properties, Paul’s view fits with model (6) in table 1.

It is worth noting that Paul uses a qualitative mereology which is a mereology of properties and relations. A qualitative mereology has broader applications than just the case of spacetime emergence. A qualitative mereology does not define composition as a relation between ‘propertied and related’ spacetime regions, but rather as a relation between constituents that need not occupy four-dimensional regions of space. Paul uses a qualitative mereology to construct a theory of spacetime in which she draws on a fundamental mereology of properties. This theory is her mereological bundle theory. On this theory, all that is needed to construct the world is one fundamental category and one fundamental building relation. So, she advocates for collapsing the categories of particular and property, in favour of a single fundamental category of properties (Paul, 2017). On her view, composition is the relation used to fuse primitive properties and thus, build the spacetime manifold. The manifold has its spatiotemporal structure because it has fundamental location properties and relations as part of its fusion (Paul, 2002).

* 1. **Le Bihan’s Mereological View of Space**

Ultimately, Le Bihan is neutral with respect to the categorical nature of spacetime (Le Bihan, 2018).[[23]](#footnote-24) He argues that spacetime may be relational, substantival, or, it may be a real entity—a substance—that is identical to a system of relations. So, his answer to question 1 is that spacetime could be either relational or substantival, or in some sense, both. For question 2, he states that in the context of recovering GR, composite spatiotemporal entities are identified with spatiotemporal relations. He thinks that relations are available to both the substantivalist and the relationalist as the most minimal portions of spacetime (Le Bihan, 2018).

On questions 3 and 4, Le Bihan offers more than one possible answer. For question 3, Le Bihan (2018) does not privilege any particular categorical nature of the mereologically fundamental constituents. Le Bihan interprets logical mereology broadly as to allow for *cross-categorical composition*. This means that parthood relations can hold between things of distinct metaphysical categories. For instance, properties might compose events. Unlike Paul, Le Bihan argues that the fundamental entities need not necessarily be properties. He leaves this open on the grounds that further input from physics is required to establish what categories the non-spatiotemporal parts belong to. Thus, Le Bihan claims that it remains unsettled as to whether the mereologically fundamental parts might be polyadic properties, points, relations, objects, or elements of another category. Le Bihan suggests that there may be a range of non-spatiotemporal things that compose spacetime; however, I will simplify the options he offers into both entities and properties, in line with our taxonomy here.

In total, Le Bihan’s theory can be interpreted as offering four possible models. In the first two he argues that spacetime can be built by composition. With one answer to question 4 available, here is one way in which Le Bihan’s view can be categorised: Spacetime relations are composed of non-spatiotemporal entities. This first interpretation fits with model (2) in the table. Since he can also answer question 3 with the claim that the non-spatiotemporal parts of spacetime are properties, a second interpretation fits with model (6): Spacetime relations are composed of non-spatiotemporal properties.

He also offers two models where spacetime is a result of decomposition. This is because Le Bihan also responds to question 4 by claiming that the non-spatiotemporal whole decomposes into its proper parts—spatiotemporal relations (Le Bihan, 2017). Recall that he thinks that the non-spatiotemporal may be either entities or properties, in response to question 3, so his view can also be categorised as fitting with models (4) and (8): Either non-spatiotemporal entities or properties decompose into spacetime relations.

Overall, and like Paul (2012), Le Bihan assumes that spacetime is a *mereological* *bundle.* For Le Bihan spacetime is a fusion of individual spatiotemporal relations; whereas for Paul, it is a fusion of relational properties. According to Le Bihan, spacetime relations are mereologically related to something in QG by either being part of it or by being composed of it (Le Bihan, 2018).

Note that Le Bihan is explicit that his answer to our fourth question will not commit him to any order of relative fundamentality between spacetime and the non-spatiotemporal. Le Bihan (2018) argues that a model where spacetime is a bundle of relations composed of something non-spatiotemporal does not entail that non-spatiotemporal parts are more fundamental, or that spatiotemporal wholes (networks of spatial relations) are less fundamental. He states that ‘Space is, in some non-spatial sense, *within* the fundamental structure’ (2018: 83) by being identical to it. Here, he eliminates both the idea of an emergent and fundamental level since he takes composition to be the relation of identity.

The Composition is Identity principle (CII) simply states that the parts of things are identical to their fusion.[[24]](#footnote-25) CII applied to spacetime says that each spatiotemporal relation that is the fusion of non-spatiotemporal properties or entities, is identical to those non-spatiotemporal properties or entities. Le Bihan proposes a bundle theory that treats spacetime as identical to the fusion of its parts. He argues that composition interpreted as the relation of identity, provides a theoretical primitive that explains the shift from the non-spatiotemporal to the spatiotemporal without moving from the fundamental to the derivative (Le Bihan, 2018). This aspect of Le Bihan’s view is controversial. For there are a range of objections to CII.[[25]](#footnote-26) It is worth noting that there might be views in the neighbourhood of Le Bihan’s that avoid this controversy, but that do everything Le Bihan wants. One example is Lewis’s view that composition is *like* identity (Lewis, 1991). Such a view might preserve the insight that composition detaches from fundamentality, but without forcing one to address the difficulties that CII faces.

* 1. **Baron and Le Bihan’s Causal-mereological Model**

Having looked at Paul’s (2012) and Le Bihan’s (2017, 2018) mereological models, I now turn to a causal-mereological model offered by Baron and Le Bihan (2024). On question 1, Baron and Le Bihan (2024) claim that spacetime is a system of relations. On question 2, they claim that the minimal portions of spacetime that are built, are individual spacetime relations. Question 3, recall, asks what the non-spatiotemporal entities are, that build spacetime. For Baron and Le Bihan, they are events. Some of these non-spatiotemporal events are causally related to one another via fundamental causal relations. Causal relations, however, are not parts of spatiotemporal relations; only events are parts of spatiotemporal relations on their view. The answer to question 4 on Baron and Le Bihan’s model is that spatiotemporal relations are composed of non-spatiotemporal events embedded within the fundamental causal structure. Like Paul (2012) and Le Bihan (2018), Baron and Le Bihan extend mereology to properties and relations such that properties and relations have parts.

Just like the framework from Paul (2012) and some of those available from Le Bihan (2016, 2018), Baron and Le Bihanclaim that spatiotemporal relations are composed by non-spatiotemporal entities. But Baron and Le Bihan differ from Paul and Le Bihan by stipulating a causal-mereological model of dependent spacetime. Baron and Le Bihan broadly take the fundamental causal relations between events as the grounds for spacetime relations. On their view, the grounding relation is best understood as the relation of parthood. Thus, our taxonomy categorises Baron and Le Bihan’s view as one that fits with model (2) in the table.

This concludes my presentation of models of spacetime emergence found in the literature. It is notable that many of the options in the taxonomy are not currently defended in detail. Note that the positions that are occupied, are those in which spacetime is a system of relations.[[26]](#footnote-27) In what follows I consider three possible problems for mereological approaches to spacetime emergence.

1. **Problems for Mereological Models of Spacetime Emergence**
   1. **Mereological Harmony**

The first problem has been raised by Baron (2019, 2021b), Baron and Le Bihan (2022a) and Baron, Miller and Tallant (2022). The problem is this: A mereological model of spacetime emergence does not seem to comply with the principle of Harmony specified in Section 3. In discussing this problem, I will talk about ‘regions’ as portions of spacetime and ‘subregions’ as parts of spacetime regions, but I will remain neutral on whether those regions are ultimately points or relations.

Harmony principles claim that the location of an object’s parts should be a subregion of the region at which the whole is located. So, if a spacetime region has parts, according to Harmony, the parts should be located at a subregion of the initial spacetime region. Non-spatiotemporal parts of spacetime, however, will not be located at any subregions of spacetime regions since they do not have spatiotemporal locations. This will violate the left to right direction of Harmony: *x is a part of* 𝑦 *if* 𝑥*'s location is a subregion of* 𝑦*'s location.* If spacetime is composed of something non-spatiotemporal at some level, the location of the non-spatiotemporal parts will not to be a subregion of the spatiotemporal location. We might worry then that dependent spacetime is not suitably analysed in mereological terms because its parts cannot be located at any subregion of a spacetime region. Baron, Miller and Tallant (2022) call this the argument from ‘intimacy’, as it relies on the idea that there is an intimate relation between location and parthood, one that is captured via the Harmony principles.

One solution is to give up Harmony. Harmony principles may in fact by falsified if we suppose that spacetime is composed of non-spatiotemporal parts, which may support the wider rejection of the harmonic modification of mereology. Baron and Le Bihan (2022a) suggest the possibility that Harmony principles may not be true for the mereology of all objects. Mereology itself may be topic neutral such that any relation that satisfies its core axioms (see section 3) will qualify as mereological. Perhaps harmony principles are only relevant for those objects that are spatiotemporally located. The mereology of abstract or social objects, for instance, may not require considerations regarding the mereological structure of their locations. In such cases, we can expect that mereology will still be useful without harmony.

With that said, ordinary objects that are spatiotemporally located do satisfy Harmony; dependent spacetime appears to be an exception.[[27]](#footnote-28) By violating Harmony, the dependence of spacetime is not much like ordinary cases of parthood which tend to be spatiotemporal. Yet, as previously noted (see section 2), we were partly relying on there being similarity between composed ordinary objects and composed spacetime, to *explain* how spacetime emerges. If what it is to be a part in ordinary cases requires that the Harmony principles hold then—given that harmony is violated—we cannot carry what we know about parthood over to the unfamiliar case of spacetime emergence. If we do give up Harmony, we may not be able to rely on the general notion of parthood to construct models of spacetime in which spacetime has parts. Or at least such models may not be illuminating with regards to explaining the dependence relation between spacetime and the non-spatiotemporal.

For Harmony to hold between spacetime and its parts, we perhaps need a more general notion of location that leaves open the nature of spaces of regions and the nature of what occupies them [for example, (Correia, 2022)]. Alternatively Baron, Calosi, and Mariani (ms) suggest that we can evade the harmony problem entirely by rejecting the claim that spacetime regions are located at all.

* 1. **Discrete vs. Continuous Spacetime**

Suppose that we expect to recover the continuous metric field of GR from a theory of QG. The challenge here is how we might recover—i.e. compose—the continuum from a discrete set of entities in QG. For any mereological model of dependent spacetime that, on the one hand, posits discreteness at the fundamental level and, on the other hand, posits a continuous manifold at the level of derivative spacetime, it is not clear that there will be enough non-spatiotemporal parts to compose a continuum of spacetime points or relations.

While this problem has been in the background of the existing discussion of possible mereological models of spacetime emergence[[28]](#footnote-29), it is yet to be sharpened. Here, I provide a sharpened version of the problem in terms of what I will refer to as the ‘cardinality gap’ for spacetime emergence. Bridging this cardinality gap with mereology—if at all possible—will depend on how we interpret the quantum system as a discrete structure. Here are some ways to interpret this structure.

First, we might make the distinction between the continuous and discrete structures in terms of *countability*. The continuous structure of spacetime, is analogous to the continuum of real numbers. The real numbers are uncountable and thus, infinite. So, the number of points or relations that make up spacetime has a cardinality equal to the cardinality of the real numbers. The discrete structure could be one that is countable. If the discrete structure is countable then it is either finite or its cardinality is equal to the cardinality of the set of natural numbers (). Let’s say that the discrete quantum structure has cardinality . On the face of it, it doesn’t look as though there can be a one-to-one mapping from *all* the ‘parts’ in the discrete structure, to the ‘wholes’ in the continuum. Since there is not even one part per whole, it doesn’t seem as though we can compose the spacetime of GR out of the set of discrete entities or properties in QG.

A second way to approach building continuous spacetime from the discrete structure in QG, is by mereologically fusing the fundamental entities or properties—our non-spatiotemporal mereological ‘atoms’. We need a suitable pair of mereological atoms to have a mereological fusion. To determine how many fusions are available from the set of fundamental entities or properties, we can assume all such possible fusions are the mereological equals of power sets.[[29]](#footnote-30) The power set of the set of fundamental entities or properties, will generate all the possible ways to select two mereological atoms from the original set of entities: all possible subsets. Thus, we can determine whether each possible fusion can be placed in a one-to-one mapping with the spacetime points or relations.

Let’s continue to assume that the discrete structure is countable in so far as it has cardinality —it is infinite. Now consider the power set of the set, , of the non-spatiotemporal entities or properties as the number of possible fusions of these mereological atoms. If the number of fundamental entities or properties in QG is , assuming is countably infinite and given unrestricted fusion, n will generate all the possible ways to select and fuse those entities or properties—all possible subsets of .[[30]](#footnote-31) It is well known thanks to Cantor that the power set of the set of natural numbers in fact has the same cardinality as the set of the real numbers.[[31]](#footnote-32) If the discrete entities in QG are countably infinite, their power set will produce enough fusions of our mereological atoms to stand in a one-to-one mapping with the points or relations in the spacetime continuum.

Interestingly, extensional mereology usually dispenses with the null individual,[[32]](#footnote-33) which is equivalent to the empty set. So, on a mereological picture of spacetime, the number of possible fusions from the set of fundamental non-spatiotemporal entities may instead be equal to . Perhaps then, mereology will depart from set theory in so far as the power set of a countably infinite set of mereological atoms will not produce enough instances of composition that can be placed in a one-to-one mapping with all spacetime points or relations.

A third option: suppose the discrete quantum structure is countable such that it is finite. Now, assuming is finite and given unrestricted fusion, the power set of the fundamental entities or properties will only generate a finite number of ways of selecting members from that set (Colyvan, 2012). So, there is no way that a mereological relation can generate infinitely many things from a finite set. It is not certain that this result should lead us to think that the cardinality gap cannot be bridged by any building relation at all; although it is not obvious that any building relation fit for spacetime will possess the recursive structure to produce a spacetime continuum from a discrete structure.

One option for solving the cardinality gap problem is to assume that spacetime is in fact, a discrete structure. Or at least, in the first instance, we might think it is unsettled as to whether spacetime is continuous or discrete since it is possible that some empirical confirmation from physics may show that spacetime is a discrete structure. This may leave open that the true nature of spacetime is discrete. If spacetime is discrete then there is no gap between spacetime and the fundamental structure: the fundamentals can be put in a one to one mapping with the minimal portions of spacetime.

Another option is to expect that a more fundamental structure in QG will only provide an *approximate description* of the continuous metric tensor field in GR (Huggett and Wüthrich (2013)). This means that the structure that is recovered from QG will merely be something *like* GR spacetime (Wüthrich et al., 2021). Because the metric structure of GR spacetime is continuous, spacetime is only expected to be approximated by an underlying fundamental discrete structure. This is true for a standard interpretation of LQG where the fundamental structure—spinfoams—are discrete, and yet are thought to approximate GR spacetime (Rovelli & Vidotto, 2014). For causal set theory, Baron and Le Bihan (2024) note that there are many more spacetime points than causal set elements. They propose to ground spacetime points up to a certain scale factor—such as the plank scale—whereby spacetime appears to be a discrete structure. Beyond this scale factor, they assume that there is excess mathematical structure in the metric field of GR i.e. the continuum. That extra structure no longer corresponds to any physical spatiotemporal distance relation.

We might worry that dispensing with the full structure of the continuum will not leave enough structure that is sufficient for empirical observations. This is a worry because we need empirical observations to justify believing in our theories. The existence of spacetime seems to be necessary for empirical observations. So too might the existence of spatiotemporally located entities. So, a theory of QG that approximates GR spacetime needs to offer enough spacetime-like structure to recover both a spatiotemporal notion of location and a spatiotemporally located entity [see (Baron, 2019b; Bell, 1987; Huggett & Wüthrich, 2013)]. Otherwise, we risk losing our basis for empirically confirming the fundamental theory that was supposed to underwrite them. Some philosophers have argued that many theories of QG do exhibit enough structure (Huggett & Wüthrich, 2013). However, if it is the case that we need to recover the full continuum from a theory of QG, then the cardinality gap persists.

* 1. **Quantum Superposition**

One final issue: there may be a conflict between the mereological approach and the quantum aspect of QG. The conflict is once again tied to the challenge of relating the fundamental non-spatiotemporal structure given by theories of QG to relativistic spacetime. This problem has been raised by Baron (2019b, 2022) in relation to functionalist models of spacetime. I’ll extend the problem to mereological approaches.[[33]](#footnote-34)

One particular theory that illuminates the worry is LQG, where spacetime is approximated by a weave state. A weave state is a large spin network of quantum loops formed by a collection of nodes and links that exhibits classical behaviour at large scales. When the spin network is viewed at the macroscopic level, spacetime is a very fine weave state (Rovelli, 2007; Rovelli, 2008). A mereological approach to spacetime, would then apply to weave states and the quantum loops that compose them. But a weave state is not a fixed structure; it is a multitude of quantum states that each, at the macroscopic level, resemble classical spacetime geometry. The generic quantum state that resembles spacetime is not a single weave state; it is a quantum superposition of weave states (Rovelli, 2007; Rovelli & Vidotto, 2014). So, there is no definite weave state that is the generic quantum state that resembles spacetime.

In general, it is not clear how to approach modelling an object that is in a superposition in mereological terms. Mereology seems to require that a system is in a definite state, one that can then be decomposed into further, definite states. If weave states are in a superposition, then it is not clear that they are in the right kind of state for mereology to apply. In short, the classical/quantum divide imposes a challenge in reconciling the mereological approach to spacetime with any potential quantum properties.

One possible solution, *decoherence*, has been proposed to minimise the appearance of interference effects in quantum systems (Bacciagaluppi, 2003). Interference effects are exhibited in quantum systems when the properties of quantum systems are indeterminate—when there can be no fact about what properties are had by the system. Decoherence is a way in which this indeterminacy is made to appear negligible and can be ignored as part of the nature of the quantum state (Glick & Le Bihan, 2024). Once the state has decohered, interference effects are ‘washed out’ of the effective description of the state such that the state appears to consist of quasi-classical states that take on classical probability distributions. Decoherence is a high-level dynamical process that allows us to disregard the additional information from the effects of interference to get an approximate determinate result (Wallace, 2011).

Decoherence may apply to weave states. If so, then the superposition of weave states may decohere into a single classical spacetime. Decoherence effects may leave room for a mereological approach to spacetime despite quantum superposition, as the classical state can then have determinate parts once the system no longer *appears* indeterminate. However, decoherence only suppresses interference approximately. While the system might appear to be a collection of quasi-classical sates, it might not actually have the ontological structure of quasi-classical states. Thus, it seems that the deeper metaphysical problem of quantum indeterminacy for mereological models of spacetime may not be solved by decoherence.

1. **Conclusion**

I have presented a framework for identifying possible mereological models of dependent spacetime. I have shown a range of ways in which we might specify the dependence of spacetime on the non-spatiotemporal, in terms of the parthood relation. Three such models have been presented in the literature already, and many of the models remain underdeveloped.

Some of the problems for mereological models that I have raised here—particularly relating to principles of parthood and locations—may be behind the lacking interest in appealing to parthood in the case of spacetime emergence. However, identifying these problems does raise some interesting questions that are worthy of further exploration: Should we reconsider the role of Harmony as a broad criterion for parthood given the case of spacetime emergence? Is there a theory of location that may accommodate some notion of Harmony for spatiotemporal objects built from non-spatiotemporal parts? Can we only approximate continuous spacetime via the interactions of discrete non-spatiotemporal parts? Does quantum superposition pose an intractable problem for specifying the parts of spacetime at the fundamental level, or does decoherence preserve a role for mereology? These questions suggest that there is more work to be done in developing mereological models of spacetime emergence. I have provided a roadmap of possible models for those who are open to the idea that there may be a role for composition in explaining the emergence of spacetime.

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1. Note that there is a discussion at the intersection of metaphysical dependence, emergence, and fundamentality. Not all conceptions of fundamentality in this debate render emergent entities as non-fundamental. For example, Barnes (2012) claims that is ontologically emergent iff is fundamental and dependent. [↑](#footnote-ref-2)
2. I will not be employing a notion of theoretical emergence:

   Theoretical Emergence: is emergent from when can be derived from or otherwise produced from using mathematical techniques of approximation.

   There is some disagreement about exactly how to specify different notions of emergence, in particular, for versions of theoretical emergence, see Isham and Butterfield 1999, and Crowther 2020. [↑](#footnote-ref-3)
3. For more substantive work on metaphysical emergence see Wilson 2021. [↑](#footnote-ref-4)
4. Appealing to mereology is only one strategy for understanding the dependence between spacetime and the fundamental non-spatiotemporal, but it is the strategy I am concerned with here. [↑](#footnote-ref-5)
5. According to Wang (1998) even in the words of Kurt Gödel we find a claim about the significance of parthood as ‘most fundamental in our conceptual system’. [↑](#footnote-ref-6)
6. Not all reference to ‘parts’ and ‘composition’ in the biological and social sciences indicate true mereological relations, however. Still, the point remains that we appeal to notions of parts and wholes in a wide range of scientific contexts. [↑](#footnote-ref-7)
7. See discussions by Calosi (2018, forthcoming), Le Bihan (2018), Ney (2020, 2021). [↑](#footnote-ref-8)
8. Although she notes there may be ‘some awkwardness’ in using mereology for parts and wholes that are not located in a common spatial framework. [↑](#footnote-ref-9)
9. Of course, one might be inclined to expect discontinuity between ordinary spatiotemporal objects and those entities beyond spacetime exactly because non-spatiotemporal entities are not in a sense ‘beyond’ spacetime. Mereology may only be evident in spacetime; however, we can at least use mereology to provide a HPE while assuming there will be some continuity. [↑](#footnote-ref-10)
10. Saucedo (2011) defines Harmony as the following 8 principles:

    (H.1) *x* is mereologically simple iff *x*'s location is mereologically simple.

    (H.2) *x* is mereologically complex iff *x*'s location is mereologically complex.

    (H.3) *x* has exactly *n* parts iff *x*'s location has exactly *n* parts.

    (H.4) *x* is gunky iff *x*'s location is gunky.

    (H.5) *x* is a part of *y* iff *x*'s location is a subregion of *y*'s location.

    (H.6) *x* is a proper part of *y* iff *x*'s location is a proper part of *y*'s location.

    (H.7) *x* and *y* overlap iff *x*'s location and *y*'s location overlap.

    (H.8) The *x*s compose *y* iff the locations of the *x*s compose *y*'s location. [↑](#footnote-ref-11)
11. The following principle is labelled as (H.5) in Saucedo 2011. [↑](#footnote-ref-12)
12. One reason to think this is that the relata in parthood relations seem to be ‘intimately’ related in a way that the relata in other relations are not. For instance, as Sider (2007) claims, ‘parthood has a unique status as an especially intimate relation… The whole is nothing over and above the parts… A part is just some of a whole’ (54). Cameron (2014) also notes that parthood is ‘peculiarly intimate’—differing from relations like parenthood, ownership, or marriage—in so far as wholes inherit their properties from their parts, are spatially located where their parts are, and are no added ontological commitment over their parts. The relevant harmony principle here (H.5), rests on the assumption that wholes inherit the locations of their parts because of this intimate connection: If *x* is part of *y*, then *y* is located wherever *x* is located (Sider 2007: 70). Baron (2021) has also noted that the inheritance of location may be formulated in the opposite direction:

    *Downwards Inheritance of Location*: For any composite object and region if is exactly located at , then for any , if is a part of then is weakly located at . (Where for to be weakly located at is for to be not completely free of .)

    (Note that the principles given by Sider and Baron here are not equivalent to (H.5).) [↑](#footnote-ref-13)
13. The relationist may just reject the existence of spacetime qua substance in line with metaphor of viewing spacetime as a kind of container inside which things take place or exist (see Knox 2019). Note that here I am only introducing one version of relationalism: non-eliminativist of relationism. I only introduce this version since we are interested in exploring emergent dependent systems that exist, not those that can be eliminated. [↑](#footnote-ref-14)
14. On this view, regions have subregions. There are two popular views on how subregions relate to regions: Subregions may be parts of regions; or they may be subsets of regions but not parts. [↑](#footnote-ref-15)
15. There are a number of ways in which we might define an unextended region. Here’s one: an unextended region does not have any proper subregions. This characterisation is drawn from Eagle’s (2014) definition of what it is to be extended: ‘a region is mereologically extended iff it has a proper subregion’ (167). This type of characterization has been scrutinized in relation to what has been raised as the *geometric correspondence principle*: any spatially extended object has parts that correspond to parts of the region that it occupies (see Simons 2004; Braddon-Mitchell and Miller 2006). If this principle is true, it rules out extended simples. That’s because extended simples do not have further proper parts located at parts or subregions, of the region it occupies. Now, the characterization from Eagle looks inconsistent with a mereological view of spacetime defended by Baron and Le Bihan (2022a) whereby spacetime is composed of extended simples. Note however that some non-mereological notions of extension have been developed. Pickup (2016) for instance, claims that something may also be unextended by having no location in space whatsoever; and Calosi (2023) provides an alternative measure theoretic notion of extension. Perhaps one of these non-mereological notions of extension is better suited in the context of applying a non-spatiotemporal mereology. Ultimately, I remain neutral on how to characterize the notion of an unextended region since nothing much hangs on it here. [↑](#footnote-ref-16)
16. Spacetime might be thought of as ‘infinitely divisible’ in this regard such that between any two points, we find another point (see Rogers 1968). There are two ways to consider the notion of infinite divisibility here. On the one hand, each point of spacetime might be, mereologically speaking, an atom. An atom of space will have no proper parts. On the other hand, one could interpret the infinite divisibility of spacetime as meaning that spacetime is ‘gunky’. If spacetime is gunky then each point of spacetime will itself, divide into further smaller proper parts. However, uncountable structures may also be indivisible, so it remains unsettled as to whether continuous spacetime is constructed out of uncountably many mereological atoms or is infinitely divisible into either atoms or gunk. [↑](#footnote-ref-17)
17. Here’s another choice one might make regarding the ontology of substantial spacetime. Substantival spacetime can also be divided into non-overlapping ‘tiles’ imagined as primitive minimal distance relations between points (Baker, 2014; Huggett & Wüthrich, 2013). One mereological version of this view is presented by Baron and Le Bihan (2022b) who argue that substantival spacetime is a discrete structure of *extended* simples. I acknowledge that this view is available, but I won’t discuss it in detail here. [↑](#footnote-ref-18)
18. Note that on certain views, substantival spacetime is identical to a set of relations (Le Bihan, 2016) —the metric field relations—thus, the view that spacetime exists and is a set of relations could be categorized as either relationalist or substantival. I won’t take a stand on this debate here. [↑](#footnote-ref-19)
19. If one is not inclined to adopt this distinction, one might prefer to divide these options as ‘properties’ and ‘property bearers’ instead. I take the outcome to be the same. [↑](#footnote-ref-20)
20. According to a standard interpretation of LQG, spin networks at the quantum level are formed of nodes and relations between them (Rovelli 2008). On another view, string theory proposes that the fundamental entities are one-dimensional and higher-dimensional objects—branes—that vibrate in up to eleven dimensions. At low energy levels, branes behave like various kinds of particles depending on their level of vibration, topological properties, or other properties (Le Bihan, ms). [↑](#footnote-ref-21)
21. The relevant distinction here is between *absolute* and *relative* fundamentality. Absolute fundamentality is often defined in terms of the notion of absolute ontological independence ( is independent if and only if does not depend on anything), however for my purposes I do not need to supply any particular theory of absolute fundamentality. We can adopt the plausible view that relative fundamentality and absolute fundamentality relate to one another in the following way: If is fundamental, and y is derivative, then is less fundamental than . Plausibly, this is true no matter how one defines absolute fundamentality. Then, define relative fundamentality as:

    Relative Fundamentality: is relatively fundamental to if and only if is more fundamental than, or ontologically prior to, .

    There is a large amount of discussion on this distinction—and on relative fundamentality in particular—in the literature, for example, see Fine 2001, 2012; Schaffer 2009; Rosen 2010; Wilson 2012, 2016; Zylstra 2014; Koslicki 2015; Bennett 2017; ch. 5-6; deRosset 2017. [↑](#footnote-ref-22)
22. One reason why this remains unsettled here is that it may be possible that the relations of emergence and composition will not track the very same notions of dependence and fundamentality. [↑](#footnote-ref-23)
23. In earlier work, Le Bihan (2016) argues for the dismissal of objects in spatiotemporal ontology. In that work, he prefers the relationalist view of spacetime. For our purposes here, we’ll take into account his later work that focuses on spacetime emergence and leaves open the categorial nature of spacetime. [↑](#footnote-ref-24)
24. This presentation is from Calosi (2016) but is traced back to the formulation given in Lewis 1991. [↑](#footnote-ref-25)
25. For example see (Baker, 1997; McDaniel, 2008) and a range of related essays in (Cotnoir & Baxter, 2014). [↑](#footnote-ref-26)
26. On the face of it, substantivalism might be more compatible than relational spacetime with GR—in the case that the metric field cannot be reduced to the matter fields. However, some might take spacetime to be identical to the metric field relations, in which case relational spacetime would be compatible with GR in much the same way as substantivalism. [↑](#footnote-ref-27)
27. Although note there are other cases where harmony might be violated: extended simples, unextended complexes, quantum systems in entangled states. [↑](#footnote-ref-28)
28. See for instance Baron 2022; Baron and Le Bihan 2024. [↑](#footnote-ref-29)
29. Cantor’s theorem tells us that the cardinality of the power set of a set is strictly greater than the cardinality of the original set. So, it is expected that the fusion operation will generate a higher number of composite objects than the number of available constituents (an expectation that hangs on the assumption that it is right to think of the fusion operation as the mereological counterpart of the power set operation). [↑](#footnote-ref-30)
30. See Steinhart 2009: 14-15. [↑](#footnote-ref-31)
31. See Smullyan 1996; Colyvan 2012. [↑](#footnote-ref-32)
32. See Cotnoir and Varzi 2020: ch. 2 and 4. [↑](#footnote-ref-33)
33. Baron does mention this problem for the mereological case in *Spacetime functionalism and the collapse problem* (ms). [↑](#footnote-ref-34)