Spacetime Functionalism and the Collapse Problem

Abstract

Recent work in quantum gravity (QG) suggests that spacetime is not fundamental. Rather, spacetime emerges from an underlying non-spatiotemporal reality. Spacetime functionalism has been proposed as one way to make sense of the emergence of spacetime. However, spacetime functionalism faces a 'collapse' problem. The functionalist analysis seems to force spacetime into the (more) fundamental ontology of QG, thereby conflicting with—rather than elucidating—spacetime emergence. In this paper, I show how to resolve the collapse problem. The solution is to differentiate between *physical* and *metaphysical* notions of (relative) fundamentality. With this distinction in hand, we can see that spacetime functionalism does not after all force spacetime into the (more) fundamental ontology of QG in any troubling sense. A side benefit of the paper is that it provides a sharpened characterisation of various notions of (relative) fundamentality.

1. Introduction

Recent work in quantum gravity (QG) suggests that spacetime emerges from an underlying non-spatiotemporal reality. Rather, spacetime emerges from an underlying non-spatiotemporal reality. Spacetime functionalism has been proposed as one way to make sense of the emergence of spacetime. According to the approach favoured by Lam and Wüthrich (2018), spacetime functionalism proceeds in two stages (see also Huggett and Wüthrich (2013, p. 284)):[1]

> (FR-1) The higher-level properties or entities, which are the target of the reduction, are 'functionalized', that is, they are given a functional definition in terms of their causal

[1] Knox and Wallace (ms.) call this approach 'Lewisian' functionalism, as opposed to 'Dennettian' functionalism. I set Dennettian functionalism aside, since it is not clear it faces a collapse problem as it isn't used to 'connect the levels'.

or functional role.

(FR-2) An explanation is provided of how the lower-level properties or entities can fill this functional role. (Lam and Wüthrich, 2018, p. 43)

One begins by providing a functional characterisation of spacetime. One then links spacetime to the ontology of a theory of QG by finding something within such a theory's ontology that can realise spacetime. In this way, the emergence of spacetime is explained as an instance of functional realisation. Just as neural states or patterns of neural firing give rise to pain by playing the pain role, so too do structures in a theory of QG give rise to spacetime by playing the spacetime role (see Le Bihan (2021) for discussion of the analogy).

As a number of authors have noted, however, spacetime functionalism of the above kind faces a 'collapse' problem (Baron 2020, pp. 2220–2221, Baron et al. 2022, pp. 145–147, Chalmers 2021, p. 178, Lam and Wüthrich 2021, p. S348, Yates 2021, p. 142). Functionalism appears to underwrite certain identities. For instance, functionalism about the mind typically involves identifying some underlying neural state or property with pain. Similarly, spacetime functionalism apparently identifies spacetime with something in the fundamental ontology of a theory of QG. But the fundamental ontology of such a theory is supposed to be non-spatiotemporal. On the face of it, this is difficult to square with the success of spacetime functionalism. Spacetime functionalism thus apparently conflicts with, rather than elucidates, the emergence of spacetime.

In this paper, I resolve the collapse problem. The solution to the collapse problem is to differentiate between *physical* and *metaphysical* notions of fundamentality. With this distinction in hand, we can see that spacetime functionalism does not after all force spacetime to be fundamental in any troubling sense. At worst, spacetime is physically fundamental. But this leaves open that spacetime is metaphysically non-fundamental.

Note that this is somewhat similar to the line taken by Chalmers (2021, p. 178). In his brief remarks on the problem, Chalmers also seems to deny that spacetime functionalism forces spacetime to be fundamental. However, Chalmers does not distinguish between different types of fundamentality. Differentiating between types of fundamentality is important, however. For if we have just a single notion of fundamentality then it is unclear in what sense spacetime fails to be fundamental, since it is after all part of fundamental QG ontology. The solution proposed here clarifies this issue by showing that spacetime may be a part of physically fundamental ontology, despite being a metaphysically non-fundamental item in that ontology. A side benefit of the paper is that it provides a sharpened characterisation of physical and metaphysical notions of fundamentality.

Note that while I talk of 'fundamentality' nothing I say here is committed to a notion of *absolute* fundamentality: the idea that there is something that is ontologically basic. Instead, what I say is compatible with the weaker notion of *relative* fundamentality: the claim that some things are more basic than others, which can be true even if nothing is absolutely fundamental. This is important because, as McKenzie (2011) has convincingly argued, there are reasons to reject the notion of absolute fundamentality.

The rest of the paper is structured as follows: I begin, in §2, by outlining the collapse problem in more detail. In §3, I draw a distinction between physical and metaphysical fundamentality, and show how this leads to two different versions of the collapse problem. Having disambiguated the collapse problem, I explain how both versions of the problem can be addressed in §4. In §5 I respond to four objections, before summing up in §6.

2. The Collapse Problem

One way to state the collapse problem is as a problem for *realiser* spacetime functionalism. According to realiser spacetime functionalism, spacetime functionalism is identified with whatever realises the spacetime role (where the role itself may be specified via some Ramsey sentence). Suppose, then, that through the application of the functionalist program we discover that something within the ontology of a theory of QG plays the spacetime role. Given realiser spacetime functionalism, whatever plays the spacetime role within the relevant theory just is spacetime. But, so the thought goes, the fundamental ontology of QG is supposed to be non-spatiotemporal. That, after all, is what motivates the use of spacetime functionalism in the first place: spacetime is supposed to emerge from some more fundamental structure. Thus, we seem to have a conflict: the success of spacetime functionalism implies that spacetime is part of the fundamental ontology of QG, but this is at odds with an interpretation of a theory of QG as one that does not feature spacetime fundamentally.

Lam and Wüthrich (2021) sum the problem up nicely when they write that:

> ... in this case the fundamental entities can be identified with higher-level spatiotemporal entities which were supposed to be absent. Consequently, according to Yates, the fundamental ontology is, after all, spatiotemporal. (Lam and Wüthrich, 2021, p. S348)

One could deny that there is something in the ontology that plays the spacetime role, but then spacetime functionalism fails to be an account of spacetime emergence. For then it can no-longer forge a connection between the derivative spacetime level and the more fundamental QG level. As Lam and Wüthrich put it, if one denies that there is anything in a theory of QG that plays the spacetime role then:

> ... the functional reduction sought fails to connect the non-spatiotemporal fundamental theory to higher-level spatiotemporal theories ... spacetime functionalism is impotent. (Lam and Wüthrich, 2021, p. S348)

Thus, it seems that we have a dilemma (Yates (2021)): either spacetime functionalism succeeds, or it doesn't. If it does, then the fundamental ontology is spatiotemporal after all. If it doesn't, then spacetime functionalism fails as an account of spacetime emergence.

Note that the problem has been stated as a difficulty for realiser spacetime functionalism, but it is really more general than that. The problem also applies to role spacetime functionalism. According to realiser functionalism about, say, pain, pain is identified with whatever plays the pain role. So, for instance, if what plays the pain role in humans is a particular pattern of neural firing, then pain just is identical with that pattern. A role functionalist about pain, by contrast, maintains that pain is identical with a particular higher-order property, namely the higher-order property of being in a state that plays the pain role (Bennett 2007, p. 323, Endicott 2007, p. 218, Van Gulick 2009, p. 135). Thus, if a neural system realises pain by having a particular pattern of neural firing, then it possesses the higher-order property of being in pain. This has the consequence that, as Moore (2011, p. 515) puts it "higher order properties are properties of the same object as their first order realizers."

According to role spacetime functionalism, then, spacetime is identified with a particular higher-order property, namely the higher-order property of being in a state that plays the spacetime role. What this means, though, is that if a physical system realises spacetime by being in a particular state, then that system possess the higher-order property of being spatiotemporal—the very higher order property with which spacetime, on this view, is identified. Thus, role functionalism—just as much as realiser functionalism—threatens to collapse spacetime into the fundamental ontology of QG. In both cases, the fundamental ontology ends up being spatiotemporal. That's because the higher-order properties are properties of the same object as the first-order realisers. So whatever it is in the fundamental ontology of a theory of QG that plays the spacetime role *also* possesses the higher-order property of being spatiotemporal.[2]

How might the collapse problem be solved? Lam and Wüthrich (2021, p. S348–S349) provide a response:

> ... we disagree that success [of spacetime functionalism] would mean that the fundamental ontology was spatiotemporal after all, for two reasons. First, judged by their own lights, and still under the presupposition that current research programmes in QG are indicative of future ones, the fundamental theories are radically different from anything spatiotemporal ... Second, models of these theories will in general not give rise to spacetime: many of the physically possible ways in which the fundamental existents combine will not yield structures even approximately isomorphic to spacetime (e.g. 'non-geometric phases' in certain QG approaches).

The first point emphasises that the fundamental ontology of QG is, indeed, non-spatiotemporal. While this seems plausible, it is not obvious how this solves the collapse problem, since the collapse problem grants that the fundamental ontology is non-spatiotemporal and then goes on to question the capacity of spacetime functionalism to preserve this insight. The second point, by contrast, emphasises that the models of a theory of QG may not give rise to spacetime at all. This is also plausible. The trouble, however, is that we are interested in models that do give rise to spacetime. For those models, the challenge is to show how the model can have non-spatiotemporal ontology. As such, both points seem to leave the collapse problem unsolved.

Fortunately, Lam and Wüthrich (2021, pp. S348–S349) provide a further response, writing that:

[2]The problem may not arise for 'eliminative functionalism', see Le Bihan (2021) for discussion.

> ... the two horns of the dilemma are not so cleanly separated in real approaches to QG. The situation is much murkier, we should expect there sometimes to be substructures at the fundamental level which are (partially) isomorphic to salient aspects of spacetime, and always to be substructures at the fundamental level which are not isomorphic to anything resembling spacetime. This makes the sought functional reduction hard and the fundamental ontology non-spatiotemporal.

It is tempting to read Lam and Wüthrich as simply reiterating their second point noted above, namely that some models of QG are spatiotemporal while others are not. There is, however, another interpretation available. What Lam and Wüthrich may be suggesting is that within a single model of QG, something can play the spacetime role and yet there be ontological structures that are non-spatiotemporal. If this observation is correct, then it may form the basis of a solution to the collapse problem, since it would demonstrate that the success of functionalism is potentially compatible with a non-spatiotemporal, fundamental ontology after all. However, their suggestion raises an important question: how, exactly, can the ontology within a single model of QG realise spacetime and yet still be non-spatiotemporal in a deep sense?

My goal is to answer this question and thereby flesh out Lam and Wüthrich's brief remarks into a full solution to the collapse problem. Note that there is a simple answer to the question that I will mention only to set it aside. One might respond that there is nothing worrying about the ontology of a single model both realising spacetime and featuring non-spatiotemporal items, so long as these are distinct items of the ontology. Thus, the simplest approach emphasises the distinctness of the spatiotemporal and non-spatiotemporal items in the ontology of a model as a way of answering the above 'how' question.

It is not clear, however, that this straightforward answer is compatible with the particular interpretation of these theories that motivates spacetime functionalism in the first place, namely one in which "crucial spatiotemporal features (and possibly even space and time themselves) are not part of the fundamental physical ontology" (Lam and Wüthrich, 2018, p. 39). What we are looking for, then, is a way to reconcile the sense in which the ontology of QG does contain spatiotemporal features with the idea that in some more fundamental way, the ontology is not spatiotemporal. Thus, the mere distinctness of spatiotemporal and non-spatiotemporal items in the ontology of a model is not enough, since this tells us nothing about the relative fundamentality of the items. What we need, then, is to elucidate the sense in which a single model of QG may contain spatiotemporal items that are less fundamental than any non-spatiotemporal items. It is this idea that animates the discussion that follows.

From now on, when I talk about theories of QG, I will refer implicitly to QG models in which spacetime can be realised, unless otherwise stated. However, to make the discussion a bit neater I will talk just of theories or even directly of QG ontology in order to avoid cumbersome locutions such as 'the ontology of a model of a particular theory'. For similar reasons, I will also convert the collapse problem into an argument, rather than treating it as a dilemma, since this makes it a bit easier to discuss. The basic form of the argument is this:

The Collapse Argument A

1 If spacetime functionalism is true, then the fundamental ontology described by QG is spatiotemporal.

2 The fundamental ontology described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

The appeal to fundamentality may seem contentious. Perhaps there is no truly fundamental ontology or, if there is, it may not be provided by a theory of QG. However, the collapse problem can be reformulated with a notion of relative fundamentality only. A version of the collapse problem along these lines can be stated as follows:

The Collapse Argument B

1 If spacetime functionalism is true, then the **more fundamental** ontology described by QG is spatiotemporal.

2 The **more fundamental ontology** described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

Exactly how to interpret 'the more fundamental ontology described by QG' is something I return to below. For now, we can just take it to mean 'more fundamental than the ontology described by GR'.

Note that one response to the collapse argument is to give up the idea that the (more) fundamental ontology of QG is non-spatiotemporal. This is perhaps not the greatest concession, since it would still allow one to connect the ontology of QG with spacetime which, as Lam and Wüthrich (2018) discuss, is enough to address problems of empirical incoherence that arise from rejecting spacetime outright (see Huggett and Wüthrich (2013)). However, before we retreat that far it is worth considering whether we might allow that the (more) fundamental ontology of QG is non-spatiotemporal, while also accepting that spacetime is functionally realised (as Lam and Wüthrich seem to suggest, above). As I will now argue, such a position is indeed viable.

First, however, a worry: isn't the collapse problem just a general problem for functionalism? If so, shouldn't it be resolved at that more general level? Take pain. Suppose that pain is what plays the pain role, and that the pain role is played by a particular neural state. Given realiser functionalism, the relevant neural state just is pain. But now suppose that mental properties are emergent from neural states. If, according to our best neuroscience, neural states lack mental properties, then we have a collapse problem: neural states are supposed to lack mental properties, but by virtue of functionally realising mental states apparently possess them.

This version of the problem, however, is easily solved. For it is not plausible that, according to our best neuroscience, neural states lack mental properties. Granted, and to foreshadow some of the work that will be done in this paper just a bit, individual neurons lack mental properties, but neural states construed as groups of neurons, or patterns of neural firing over time, do possess mental properties. In general, there is nothing wrong with admitting as much, and thus treating the ontological description given by neuroscience as one that includes pain. By doing so, one admits that neuroscience manages to describe pains, by virtue of describing certain neural states, but it also describes more, namely the constituents of neural states, which lack mental properties.

The key to the solution is to recognise that the ontology of neuroscience admits a metaphysical distinction between, on the one hand, individual neurons that constitute neural states and, on the other hand, neural states. Neural states can functionally realise pains, and in this way possess mental properties. But this does not force individual neurons—which are the basic components of the neuroscientific ontology—to have mental states. Thus, one is able to allow (i) that there are levels of physical description at which mental properties disappear, namely the level of individual neurons; (ii) that there are levels of description at which mental properties arise, namely the level of groups of neurons and (iii) that mental properties are emergent from a level of neurons that lack mental properties, by virtue of emerging from the group behaviour of neurons.

This way of avoiding any threat of collapse is already taken for granted when thinking about functionalism in other domains. That's because it is very natural to think of the states that play a functional role as having constituents that lack the functionally realised properties. The solution presented in this paper is the same: once we recognise a distinction between the individual components that are basic to the ontology of a theory of quantum gravity, and the group behaviour of those components, we can both allow that spatiotemporal properties disappear at the individual level, but arise at the group level (where they are functionally realised). In some sense, then, all I do below is show how to extend an already present, rather general solution to collapse problems for functionalism over to the case of spacetime emergence as well.

3. Two Notions of Fundamentality

Fundamentality can be understood in either a *physical* or a *metaphysical* sense. While a distinction between these two notions is often tacit in discussions about fundamentality, the distinction is rarely made explicit. A fairly natural way to differentiate the two notions is as follows:

x is physically fundamental $=_{\mathrm{df}}$ x is within the ontology of a fundamental physical theory.

x is metaphysically fundamental $=_{\mathrm{df}}$ there is no y such that y grounds x.

Note that these are definitions of *absolute fundamentality*. They can, however, be straightforwardly translated into definitions of *relative* fundamentality:

x is more physically fundamental than y $=_{\mathrm{df}}$ x is within the ontology of a physical theory T that is more fundamental than any theory T' that has y within its ontology.

x is more metaphysically fundamental than y $=_{\mathrm{df}}$ x grounds y.

Note also that the notion of 'theoretical fundamentality' is essential to both the absolute and relative definitions of physical fundamentality. The notion of theoretical fundamentality can be further defined as follows:

T **is theoretically fundamental** $=_{\mathrm{df}}$ there is no theory T' from which T emerges.

T **is more theoretically fundamental than** T' $=_{\mathrm{df}}$ T' emerges from T.

The notion of 'emergence' that appears in these definitions of theoretical fundamentality signifies an *inter-theoretic* relation. It is meant to capture deduction, but also weaker notions such as approximation. Exactly how to formulate the notion of theoretical emergence at issue is controversial. For present purposes, I will assume the account developed by Butterfield (2011); Crowther (2018), which emphasises notions of novelty and autonomy. As Crowther argues, GR is likely to be theoretically emergent from an underlying approach to QG in this sense.

Metaphysical emergence is based on a notion of *grounding*. There are, broadly speaking, two ways to understand grounding. First, grounding can be understood as a primitive, generative relation, one closely analogous to causation (Schaffer (2016); Wilson (2018)). On this view, causation is typically generative across time, whereas grounding is usually generative upwards 'through the levels'. Moreover, while causation is governed by the laws of nature, grounding is supposedly governed by more general metaphysical principles, sometimes called 'metaphysical laws' (see Wilsch (2016); Wilson (2018)).

On the second conception, grounding is not a distinctive relation but, rather, the name for a cluster of more specific relations. These are sometimes called 'building' relations (see e.g., Bennett (2017)) and are named for the way in which they capture how some things are 'made' of others in a generic sense. Exactly which relations qualify as grounding relations is controversial. However, there is consensus that composition and material constitution qualify. Other relations, such as determinate/determinable relations and relations of ontological dependence have also been suggested.

The first notion of grounding is sometimes called big 'G' Grounding, and the second notion small 'g' grounding. Big 'G' grounding relations are generally more contentious than small 'g' grounding relations, and so I will focus on the latter in what follows. This is fine, since in both cases grounding relations are supposed to induce metaphysical structure of the kind that underwrites relative and absolute fundamentality.

Two observations before I move on. First, different combinations of physical and metaphysical fundamentality are allowed. What's (more) physically fundamental relates to the ontology of a theory. It may turn out that within the ontology of a specific theory, every item is metaphysically on a par. That is, none of the items within the ontology ground any of the other items. This, of course, is compatible with there being other theories, with different ontologies that are grounded in or that ground the 'flat' ontology of the first theory. The point, though, is that a theory can have a metaphysically unstructured ontology. The reverse is also true: what's (more) physically fundamental may be metaphysically structured. Which is to say that the ontology of a single physical theory may feature items that are linked by grounding relations.

Second observation: the notion of (relative) metaphysical fundamentality stated above is naturally paired with objective facts about what grounds what. This pairing may well be an oversimplification. For, as McKenzie (2017) argues, the notion of (relative) metaphysical fundamentality can be relativised again. She considers a number of different relative fundamentalities, including: relativisation to specific analyses of fundamentality, relativisation to ontological assumptions, relativisation to computational assumptions, relativisation to theory construction or presentation and relativisation to a possible world.

Relative fundamentalities are important for understanding S-duality in physics. In the case of S-dualities, we have two different mathematical approaches to quantum field theory (QFT) based on different classical limits (note that McKenzie uses 'S-duality' to mean more than just S-duality in string theory). In one presentation, it appears that certain particles, such as the soliton, are composite, while in another presentation of the same QFT, the soliton is elementary. Because composition is apparently a small 'g' grounding relation, it appears that whether the soliton is fundamental is relative to the presentation of a theory. As McKenzie points out, the relativity of fundamentality has led some physicists to deny that there is a fact of the matter as to what is more fundamental than what, leading to a style of anti-realism about metaphysical fundamentality claims.

In response, McKenzie argues that the relativity of fundamentality at issue in S-duality is relativisation to a world. She notes that this allows for both realist and anti-realist thinking about metaphysical fundamentality. On the realist side, there are some worlds in which there are facts about what is more fundamental than what, and so some worlds in which, say, the soliton is (more) fundamental. It may be that our world is one of those worlds, and so there are objective facts about metaphysical fundamentality after all. On the anti-realist side, she notes that there are also worlds in which the soliton is metaphysically on a par with other particles, and in those worlds the anti-fundamentalist claims seem justified.

Everything I say is compatible with the further relativisation of metaphysical fundamentality facts suggested by McKenzie. Thus, it may turn out that it is only relative to a specific theory of QG, or relative to specific assumptions about fundamentality that there is something that is metaphysical (more) fundamental than spacetime. This is acceptable, however, so long as this relativity of fundamentality does not inevitably lead to anti-fundamentalism. Fortunately, as McKenzie has shown, it does not.

That said, if anti-fundamentalism turns out to be warranted for a given approach to QG, then that may pose a difficulty for the solution to the collapse problem that I propose. But not necessarily. For if the kind of relative fundamentality at stake is the world-relativity of fundamentality that McKenzie argues for, then the anti-fundamentalist line is broadly compatible with actual fundamentality facts. The only real threat to what I say comes from a type of anti-fundamentalism, according to which nothing in the ontology of a theory of QG is more metaphysically fundamental than anything else either actually or in any world. For in this situation, it seems that the notion of metaphysical fundamentality falls idle. I will return to say a bit more about this eventuality later on. For now, however, I will assume that this aggressive style of anti-fundamentalism is off the table and that there are facts about (relative) metaphysical fundamentality, even if those are ultimately relativised in one or more of the ways discussed by McKenzie.

4. Addressing the Problem

I turn now to addressing the collapse argument. The distinction between physical and metaphysical fundamentality renders the collapse argument ambiguous. There are two ways to disambiguate the argument, which leads to two distinct versions of the collapse problem:

Metaphysical Collapse Argument

1 If spacetime functionalism is true, then the **metaphysically fundamental** ontology described by QG is spatiotemporal.

2 The **metaphysically fundamental** ontology described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

Physical Collapse Argument

1 If spacetime functionalism is true, then the **physically fundamental** ontology described by QG is spatiotemporal.

2 The **physically fundamental** ontology described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

A version of the collapse problem that uses relative fundamentality also admits of two disambiguations. For now, however, I will focus just on versions of the argument that use absolute fundamentality. This will make it easier to address arguments that use relative fundamentality in §4.3.

4.1. The Metaphysical Collapse Argument

Let's begin with the metaphysical collapse argument. As discussed, different combinations of physical and metaphysical fundamentality are allowed. In particular, the ontology of a single theory of QG—which might be physically fundamental—can have metaphysical structure. There can be items within that ontology that are not metaphysically basic. This is important since it shows that from the mere fact that something in the ontology of a theory of QG is identical to spacetime it does not follow that the most metaphysically basic components of that ontology are spatiotemporal.

The distinction between physical and metaphysical notions of fundamentality thus makes room for the following scenario. First, the functional reduction of spacetime is successful, resulting in spacetime being part of the ontology described by a theory of QG. This makes spacetime *physically* fundamental. Second, spacetime is not *metaphysically* fundamental, because despite spacetime being a part of the ontology, it is grounded in something else *within that very ontology*, where what grounds spacetime is not spatiotemporal. In this way, we can preserve the claim that the metaphysically fundamental ontology described by QG is not spatiotemporal, without giving up on the functional reduction of spacetime.

This shows that one can deny that the success of functionalism has implications for metaphysically fundamental ontology, which leaves space to grant that the metaphysically fundamental ontology is non-spatiotemporal. As such, one can safely reject the first premise of the metaphysical collapse argument, while granting the second premise. Being free to grant the second premise is important, as it allows one to do justice to the interpretation of QG ontology as non-spatiotemporal. For despite the physically fundamental ontology being spatiotemporal, what grounds spacetime need not be. Thus, in a deep metaphysical sense the ontology can be non-spatiotemporal.

For this solution to the metaphysical collapse argument to work, it must be plausible to draw a distinction within the ontology of QG between, on the one hand, whatever plays the spacetime role and, on the other hand, items that are metaphysically fundamental compared to whatever plays the spacetime role. But is this a plausible distinction to draw? I believe so. For what plays the spacetime role in theories of QG is typically some structured entity. To see this, it is useful to briefly consider a couple of examples.

Consider, first, loop quantum gravity (LQG). In LQG, what plays the spacetime role is a *weave state* (Lam and Wüthrich, 2018, p. 49). A weave state is a particular type of spin-network that approximates the spacetime manifold at certain scales. Rovelli (2004, p. 268) describes a weave state by analogy with a fabric: [3]

> Consider the fabric of a T-shirt as an analogy. At a distance, it is a smooth curved two-dimensional geometric surface. At a closer look, it is composed of thousands of one-dimensional linked threads. The image of space given by LQG is similar. Consider a very large spin network formed by a very large number of nodes and links, each of Planck scale. Microscopically, it is a planckian-sized lattice. But probed at a macroscopic scale, it appears as a three-dimensional continuous metric geometry. Physical space around us can therefore be described as a very fine weave. The hidden texture of reality is a weave of spins.

The description of a weave state as a planckian-size lattice captures neatly the idea that weave states are made up of quantum loops at some level, with the quantum loops being the components of the lattice structure. This idea is reflected in the description of weave states given by Ashtekar et al. (1992, p. 239):

> The basic idea is to weave the classical metric out of quantum loops so that on an average precisely one line crosses every surface element whose area ... is one Planck unit.

That weave states are made out of quantum loops suggests that a grounding relation is in play, but exactly which one cannot clearly be read off the mathematics of LQG. Rather, the mathematical description seems to leave open the metaphysical connection between a weave state and the quantum loops from which it is made. That the metaphysics is left open need not trouble us here, however. For what matters is just that weave states are made up of quantum loops in some sense,

[3]Rovelli (2004, p. 268) makes this precise by specifying a weave state as a spin-network $|\mathsf{S}\rangle$ such that:

$$\hat{\mathrm{A}}(\mathcal{S})|\mathsf{S}\rangle = (\mathsf{A}[\mathsf{g};\mathcal{S}] + \mathcal{O}(\mathsf{l}_\mathsf{P} = \mathsf{l}))|\mathsf{S}\rangle,$$
$$\hat{\mathrm{V}}(\mathcal{R})|\mathsf{S}\rangle = (\mathsf{V}[\mathsf{g};\mathcal{R}] + \mathcal{O}(\mathsf{l}_\mathsf{P} = \mathsf{l}))|\mathsf{S}\rangle$$

Where l is a scale such that $\mathsf{l} \gg$ Planck scale; $\mathcal{S}$ is a macroscopic 2-surface; $\mathcal{R}$ is a macroscopi 3-region; $\hat{\mathrm{A}}(\mathcal{S})$ and $\hat{\mathrm{V}}(\mathcal{R})$ are area and volume operators over $\mathcal{S}$ and $\mathcal{R}$ respectively; $\mathcal{O}(\mathsf{l}_\mathsf{P} = \mathsf{l})$ is a correction term where $\mathcal{O}$ specifies the order of the corrections and $\mathsf{A}[\mathsf{g};\mathcal{S}]$ and $\mathsf{V}[\mathsf{g};\mathcal{R}]$ are classical spacetime area and volume operators.

and so one reasonable interpretation of LQG is that quantum loops are more metaphysically basic than weave states in the sense that matters for the collapse problem.

Accordingly, one can accept that the ontology of LQG contains spacetime at least sometimes (whether this happens may well vary model-by-model), while maintaining that the metaphysically fundamental ontology described by the theory is not spatiotemporal. That's because one can maintain that the quantum loops that are metaphysically fundamental compared to weave states do not have spatiotemporal properties. Indeed, this seems quite plausible: the quantum loops that make up a weave state do not seem to have spatiotemporal properties. It is only when formed into weave states that the collection of loops display emergent spatiotemporal behaviour.

Similar considerations apply to causal set theory (CST). In CST, the basic structure is a discrete set of partially ordered elements (see Dowker (2013) for an overview). Some models of CST provide a basis for the functional reduction of spacetime, insofar as those models contain causal sets that are 'manifoldlike', and so constitute appropriate realisers for spacetime (Lam and Wüthrich, 2018, p. 45). However, these manifoldlike causal sets are collections of partially ordered causal set elements. In this way, causal sets appear to be made out of causal set elements and the links between them. Indeed, this seems plausible once one considers the standard dynamics—the sequential growth dynamics—in which manifoldlike causal sets are built element-by-element via a dynamical process of growth (see Sorkin and Rideout (1999)).

To be clear, the formal relationship between causal sets and their elements is set membership. However, when causal sets are interpreted as physical, the relationship between physical causal sets and their physical elements appears to be a grounding relation: the elements and links are the grounds for manifoldlike causal sets, perhaps in combination with the sequential growth dynamics. If that's right, though, then the elements, and the partial ordering relation that joins them can be considered metaphysically fundamental compared to the manifoldlike causal sets that correspond to spacetime. Importantly, neither the elements of causal sets considered individually, nor the links between causal sets considered individually seem to have any spatiotemporal properties. It is only manifoldlike causal sets considered as a whole that are spatiotemporal. Accordingly, as with LQG, one can grant that the functional reduction of spacetime to manifoldlike causal sets succeeds and so something plays the spacetime role, without thereby conceding that the metaphysically fundamental ontology of the theory has any spatiotemporal properties.

In sum, in both LQG and CST, there is a distinction implicitly drawn between a structured entity (weave states, manifoldlike causal sets) and whatever produces that structure (quantum loops, causal sets/elements/links). If we imbue this distinction with metaphysical significance—as I have suggested we should—then it is possible to view the ontology of these theories as one that features a distinction between more and less metaphysically basic items. This, in turn, provides a basis for identifying the non-fundamental items in the ontology with spacetime, in a way that preserves the non-spatiotemporal nature of any metaphysically fundamental ontology.

Now, conceivably, one might deny that weave states or manifoldlike causal sets are grounded in quantum loops or causal set elements/links. For one notion of 'grounding' this is potentially plausible. With respect to big 'G' grounding, it is indeed unclear that there are primitive relations of generation that are governed by metaphysical laws and by which weave states are produced. However, as noted, my focus here is on small 'g' grounding relations. Small 'g' grounding relations just are any relations that underwrite how one thing is 'made' from another. These relations are much less metaphysically substantive, and so in general easier to accept.

Still, one might deny that weave states are made from quantum loops, or that causal sets are made from elements/links in even this weak sense. If one does deny this, then it becomes unclear what the relationship between the two items of the ontology is supposed to be. Weave states and manifoldlike causal sets certainly seem to be made from quantum loops and elements/links *in some sense*, and so a bit more must be said to give the objection force.

I can thus see two ways of developing the objection. First, one could argue that the idea of, say, weave states being made of quantum loops brings to mind a very simple picture in which quantum loops are *parts* of weave states. Such a picture, one might continue, is too naive to be plausible. I will deal with this first objection below (see §4.2 and §4.3). For now it is enough to say that parthood is not necessary for understanding the relationship at issue. Second, one could argue that while, say, weave states are made of quantum loops, this is not a grounding relation, and so there's no basis for the claim that quantum loops are metaphysically fundamental.

The second version of the objection can be dealt with as follows: the whole point of small 'g' grounding is, in part, to capture every relation by which one thing is made from another. The thought, then, is that this relation of 'being made from' is always a grounding relation in the relevant sense. What one would need to show, then, is that 'being made of' does not always induce metaphysical structure. Perhaps this can be shown, but note that it is a substantial project, given how closely related these two notions appear to be.

Even if such a project can be completed, this does not undermine my analysis. For what really matters is that quantum loops and causal set elements are more metaphysically basic than weave states or manifoldlike causal sets. Even if one doesn't like the 'being made of' talk, one can still get behind the more general notion of a small 'g' grounding. For grounding in this sense includes building relations of all kinds, including general relations of ontological dependence. Ontological dependence is enough for my argument, since it alone can underwrite notions of absolute and relative metaphysical fundamentality.

Moreover, it is plausible that weave states and manifoldlike causal sets depend ontologically on quantum loops and causal set elements/links. One way to see this is by consideration of certain counterfactual relationships, such as the following: if the relevant quantum loops or causal set elements/links had not existed, then neither would the corresponding weave states or manifoldlike causal sets. The reverse, however, is not true. Quantum loops and causal set elements/links can exist without giving rise to any corresponding weave states or manifoldlike causal sets. Such asymmetric counterfactuals involving existence facts are usually taken to indicate ontological dependence relations.

One may remain unconvinced. But note that all my argument really needs is for there to be *some* metaphysically significant distinction between what plays the spacetime role and other items within the ontology of a theory of QG. If one denies that there is any such distinction at all, then one veers close to some version of anti-fundamentalism. I will return to this possibility below (see §4.4).

At this point, one could take a different approach. One might object that we cannot, in fact, differentiate between more and less basic entities in the manner suggested in LQG in particular. A weave state is a semi-classical state, and so we can expect it to be in a superposition (Rovelli, 2004, p. 271). If, however, a weave state is in a superposition, one might argue it is not entirely clear there are more basic states that can be individuated. If that's right, then the quantum to classical boundary may present a challenge to ordering the ontology of LQG in terms of metaphysical fundamentality.

There are two things to say here. First, it is hard to see why being in a superposition would prevent more basic entities from being individuated. If we think of a weave state as a superposition of spacetimes with a probability distribution over them, we can still individuate each spacetime in the superposition. Having done that we can then look at each spacetime and further individuate more basic states from which they're built.

Second, even if there is some problem here, it is likely one that must be addressed to make sense of the emergence of spacetime at all. That's largely because emergent spacetime appears to be classical. As Wüthrich (2017, §4) discusses, decoherence may thus play a role in explaining how an apparently classical spacetime emerges from an underlying quantum superposition of weave states. Assuming something along these lines, however, we can apply the notion of metaphysical fundamentality to the decohered weave state. For this weave state, we can say that it is a structure consisting of more basic entities—the quantum loops—and these are non-spatiotemporal.[4]

Here it is perhaps useful to lean on McKenzie's (2017) notion of relative fundamentality: what is fundamental in LQG is relative to the status of weave state decoherence. In some situations—such as when a weave state is in a superposition—we cannot apply the notion of metaphysical fundamentality to differentiate between weave states and quantum loops. But, in this situation, it is not clear that we can talk of emergent spacetime either, since we don't clearly have a classical spacetime, and so perhaps the functional role of spacetime is not played. However, in other situations—namely, when the weave state decoheres—we both have emergent spacetime and can apply the notion of metaphysical fundamentality. Thus, either spacetime is not functionally realised, in which case there is no metaphysical collapse problem, or it is and the collapse problem can be addressed. Either way the threat of collapse is avoided.

4.2. The Physical Collapse Argument

I turn now to the physical collapse argument. We start by granting the first premise, according to which if spacetime functionalism is true, then the physically fundamental ontology described by QG is spatiotemporal. We then note an ambiguity in the second premise:

[2a] Every item in the physically fundamental ontology described by QG is not spatiotemporal.

[4]This approach to decoherence is still in development. See Huggett and Wüthrich (2024) for discussion.

[2b] Some items in the physically fundamental ontology described by QG are not spatiotemporal.

If we read the second premise as [2b] then the physical collapse argument is invalid. For one can accept both the first premise, and the second premise while still rejecting the conclusion. That's because the first premise does not commit one to the claim that everything in the physically fundamental ontology described by QG is spatiotemporal. It only commits one to the view that something in that ontology is spatiotemporal. Given this, the success of the functional reduction does not conflict with the idea that some items in the ontology described by a theory of QG are not spatiotemporal. Because accepting the second premise does not amount to rejecting the first, the conclusion doesn't follow.

One might respond that granting the second premise under its [2b] interpretation is to give up on treating QG as non-spatiotemporal in a deep sense. As we've already seen, however, that's not the case. For one can grant that the less metaphysically fundamental ontology of QG is spatiotemporal, while accepting that the more metaphysically fundamental ontology is not spatiotemporal. Thus, one can grant [2b] while still maintaining that the ontology is non-spatiotemporal in a manner that is important: namely, the metaphysically fundamental ontology of the theory does not feature spacetime or have spatiotemporal properties.

For this response to the physical collapse argument to work, the [2a] reading of the second premise must be rejected in favour of the [2b] reading. There are two points that speak in favour of the [2b] reading over the [2a] reading. First, the [2a] reading appears to be question-begging in the current context. For this reading to be plausible, one must assume that spacetime functionalism is false, and thus that nothing in the ontology of QG plays the spacetime role. That's because the only way for every item in the physically fundamental ontology described by QG to be non-spatiotemporal is if the functional reduction of spacetime fails. Thus, if one adopts the [2a] reading, then one is assuming, in the premises, what one sets out to prove: namely, that spacetime functionalism does not succeed.

The second reason for rejecting [2a] in favour of [2b] relates to recent work by Le Bihan and Linnemann (2019). Le Bihan and Linnemann (2019) argue that for many approaches to quantum gravity, a minimal notion of spacetime remains. They defend this claim for a number of theories on the grounds that such theories still obey Lorentz symmetries. For other theories, a ‘split’ between space and time is identified in a different way. For instance, in the case of CST, the ‘split’ correlates to the distinction between chains and anti-chains in the partial order that structures causal sets. If Le Bihan and Linnemann (2019) are correct, and I think they are, then the [2a] reading of the second premise is too strong.

One might reply that far from supporting spacetime functionalism, Le Bihan and Linnemann’s (2019) analysis undermines it. For one could interpret their argument as showing that spacetime functionalism is unnecessary for connecting QG and GR, because the ontology of QG is already spatiotemporal. There is, however, no deep conflict between spacetime functionalism and Le Bihan and Linnemann’s (2019) analysis. For a functionalist can ultimately argue that what Le Bihan and Linnemann (2019) have provided is evidence that the functional role for spacetime is played within the theories of QG that they consider. Thus, from a functionalist perspective, their result is to be expected.

Of course, it may turn out that, in the final theory of QG, the entire ontology of that theory is non-spatiotemporal. In that situation, the [2a] reading will be inescapable. For now, all we can really do is consider the approaches currently available and see whether, for those approaches, it is plausible to suppose that the entire ontology is non-spatiotemporal. The answer seems to be ‘no’, and so the physical collapse argument can be resisted for those approaches to QG. What’s more, the demonstration provides a template for evaluating the physical collapse argument for any future theories of QG, namely: check to see if the entire ontology is spatiotemporal using something like Le Bihan and Linnemann’s (2019) analysis, and if it is not, then reject the [2a] reading of the second premise.

4.3. Relative Fundamentality

So much, then, for versions of the collapse argument that appeal to absolute fundamentality. As noted, the collapse argument can also be formulated using relative fundamentality. Using the distinction between metaphysical and physical notions of relative fundamentality we can disambiguate two versions of the collapse argument:

Metaphysical Collapse Argument

1 If spacetime functionalism is true, then the **more metaphysically fundamental** ontology described by QG is spatiotemporal.

2 The **more metaphysically fundamental** ontology described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

Physical Collapse Argument

1 If spacetime functionalism is true, then the **more physically fundamental** ontology described by QG is spatiotemporal.

2 The **more physically fundamental** ontology described by QG is not spatiotemporal.

Therefore,

3 Spacetime functionalism is false.

These arguments now admit of straightforward solutions. For, presumably, the ‘more physically fundamental ontology described by QG’ is more physically fundamental relative to anything that is described by GR; and the ‘more metaphysically fundamental described by QG’ is more metaphysically fundamental than anything described by GR. Understood this way, however, the first premise in both arguments is false. For what GR describes is spacetime. However, spacetime functionalism does not imply that anything that grounds spacetime is spatiotemporal and nor does it imply that anything that is more physically fundamental than spacetime is spatiotemporal. All that spacetime functionalism implies is that something in the ontology of a theory of QG is spatiotemporal. Whatever that is, however, need not be physically or metaphysically more fundamental than something in the ontology of GR. Indeed, it can be the very same thing.

Moreover, as we’ve seen, whatever grounds spacetime in the ontology of a theory of QG can be non-spatiotemporal in a manner that is compatible with the functional realisation of spacetime by items in that ontology. Thus, we can safely reject the first premise of each argument, while nonetheless accepting both that spacetime is functionally realised and that the more metaphysically fundamental ontology of QG—namely, whatever does ground spacetime—is non-spatiotemporal. In this way, we seem to get everything we want.

5. Objections

This concludes my response to the collapse problem. The solution builds on Lam and Wüthrich's (2021) response by clarifying the way in which the ontology of QG is non-spatiotemporal. It is the (more) metaphysically fundamental ontology of QG that is not spatiotemporal. This is compatible with the ontology containing spacetime. Moreover, the fact that the spacetime is less metaphysically fundamental compared to any non-spatiotemporal features of the ontology licenses a non-spatiotemporal interpretation of these theories. I anticipate four objections.

5.1. Objection One

Here's the first: my solution to the collapse problem undermines, rather than vindicates, spacetime functionalism. In order to account for the emergence of spacetime, we need to explain how it is that spacetime emerges from non-spatiotemporal features. One might argue, however, that on the account I have proposed all of the work is being done by the small 'g' grounding relations that connect spacetime to a more fundamental, non-spatiotemporal ontology. If that's right, though, then we can dispense with functionalism entirely. So, by solving the collapse problem I have inadvertently shown that spacetime functionalism fails as an account of spacetime emergence.

In order for this objection to work, it must be the case that if we dispense with functionalism and just use small 'g' grounding relations we are left with a complete story of spacetime emergence. But that is not the case. For example, suppose we have a range of non-spatiotemporal entities related via the small 'g' grounding relation of composition. It is compatible with there being non-spatiotemporal entities related in this way that spacetime does not arise. That's because, in the theories of QG considered above (e.g., LQG, CST), there are collections that can be formed via composition that *don't* manage to compose a spacetime. One way to see this is to note that many of the models of these theories do not have a continuum approximation. In these models, however, we can still talk about how quantum loops or causal set elements compose larger entities, but there is no sense in which these mereological wholes correspond to spacetime.

Thus, in addition to having non-spatiotemporal entities and a composition relation, we also need an account of the conditions under which the non-spatiotemporal entities compose spacetime in particular. In other words, we need to answer the spatiotemporal composition question:

> **Spatiotemporal Composition Question:** When does a group of non-spatiotemporal entities compose a spatiotemporal entity?

The composition relation alone gives us no insight into this question. All it tells us is that if there is something that is a spatiotemporal entity, and that thing is a collection of sorts, we can specify how that collection relates to the members of the collection. What we don't get is a story concerning what it is about certain collections built via composition such that they count as spacetime.

Crucially, spacetime functionalism provides an answer to the the spatiotemporal composition question. A group of non-spatiotemporal entities compose a spatiotemporal entity just when the group so composed plays the spacetime role. Thus, not just any way of composing non-spatiotemporal entities delivers spacetime. Rather, the entities must compose a specific whole in such a manner that the whole can then perform certain functions. When that happens, we get spacetime emergence.

Note that while I have used parthood to make the point, nothing hangs on this. The spatiotemporal composition question is an instance of a more general 'grounding' question:

> **Spatiotemporal Grounding Question:** When does a group of non-spatiotemporal entities ground a spatiotemporal entity?

Again, merely specifying that there is some entity E that is connected to more metaphysically fundamental entities $\mathsf{e}_1 ... \mathsf{e}_n$ via a small 'g' grounding relation does nothing to answer this question. For it is compatible with there being an E that is connected to the e_i in this way that E is not spatiotemporal. As before, evidence of this can be found in models of QG in which spacetime does not emerge, but in which we can find E's that are connected to e_i's via some small 'g' grounding relation.

To answer the spatiotemporal grounding question, we need a set of conditions under which the e_i being related to some E via a small 'g' grounding relation produces spacetime. Spacetime functionalism provides one, compelling answer to this question. When the e_i are related to some E via a small 'g' grounding relation in such a manner that E then satisfies the right functional specification, then and only then do the e_i manage to ground spacetime.

Thus, my solution to the collapse problem proposed above does not render spacetime functionalism idle. The solution involves finding some small 'g' grounding relation by which the physically fundamental ontology of a theory of QG can be metaphysically structured. However, having found such a relation spacetime functionalism is then needed to specify the conditions under which the non-spatiotemporal components come together via such a relation to form spacetime, and when they do not. Without some story along these lines we simply do not have a complete picture of spacetime emergence.

5.2. Objection Two

Here's the second objection: everything in the physically fundamental QG ontology is non-spatiotemporal, despite what I have said. Why? Because the whole ontology is, apparently, describable in non-spatiotemporal terms, without the use of spatiotemporal concepts. It is then a non-trivial project to try and 'recover' spacetime from the theory, in the theoretical sense of emergence described in §2. For instance, in the case of LQG the conceptual machinery is that of spin-networks (or spin-foams, in the covariant formulation, see Rovelli and Vidotto (2014)). Similarly, in the case of CST, the conceptual machinery is the notion of a bare element plus a partial order, interpreted to be a causal order. In neither case does it seem that spatiotemporal concepts are in use, so it's just implausible to suppose that the ontology is ever spatiotemporal.

Note, however, that there's a distinction to be drawn between a theory (or model), on the one hand, and its ontology, on the other. Just because a theory does not feature spatiotemporal concepts, or conceptual machinery that we recognise from explicitly spatiotemporal theories like GR, it does not follow that the ontology of the theory cannot be spatiotemporal. For it is at least conceivable that the same ontological features that are described using conceptual machinery associated with spacetime are described in a completely different way, using different conceptual machinery, in a different theory.

Indeed, something like this appears to be going on in more familiar cases. Consider, for instance, theories in psychology versus theories in neuroscience. Psychological theories use the conceptual machinery of mental states, whereas theories in neuroscience don't, using instead the conceptual machinery of neural states. Despite this difference, it seems entirely possible—and, indeed, for the materialist, plausible—that the two theoretical systems are describing exactly the same ontological items. Indeed, this is in some sense what functional reduction is designed to show: that items in the ontologies of two very different theories, using quite different conceptual machinery, can nonetheless be identical.

There's no problem here unless one thinks that the very same thing cannot be described in two, radically different ways. But there is little reason to accept that line of thought, for it is hard to see why any particular ontological feature might be 'conceptually locked' to just one way of describing it. Or, at least, some argument is needed to show that this is plausible, particularly in the face of a successful functional reduction which seems to show the opposite.

5.3. Objection Three

Third objection: my argument relies heavily on the notion of metaphysical fundamentality. This notion, in turn, relies on the notion of grounding. But grounding, one might object, is not naturalistically acceptable. As a consequence, it can play no role in saving spacetime functionalism from the collapse problem, at least not in a way that leaves the naturalistic credentials of spacetime functionalism intact.

Is grounding naturalistically suspect? This might be true for large 'G' grounding relations. Recall that grounding in this sense is supposed to be a metaphysically primitive relation that is not governed by the laws of nature. This does sound fairly non-naturalistic, and so perhaps the objection framed this way has merit (see Miller and Norton (2017) for discussion).

Note, however, that this is not the only way to interpret grounding. As noted, small 'g' grounding is just the name for a cluster of more specific relations. It is plausible that there is some such relation that is naturalistically acceptable and that can underwrite the notion of metaphysical fundamentality outlined above. In particular, *parthood* seems to be a good bet. Parthood is thought to be a grounding relation, and so is thought by many to induce the kind of metaphysical structure described here, which includes notions of relative and absolute fundamentality.

Moreover, parthood appears to play a role in science. For instance, some versions of supersubstantivalism attributable to Newton appeal to parthood relations, which shows that parthood may be important for understanding spacetime (Lehmkuhl (2016)). In a similar vein, Healey (2013), although ultimately critical of the role of parthood in physics, identifies a range of historical examples in which parthood plays a role (particularly in thinking about particles, prior to the development of field theories). The notion of S-duality discussed by McKenzie in string theory and QFT also seems to rely on parthood. Indeed, what S-duality seems to show is that parthood facts are relative to the presentation of a theory. Parthood may also be important for quantum mechanics (Bailey and Brenner (2020), Ismael and Schaffer (2020) and Calosi and Tarozzi (2014)). For example, separability can be analysed in terms of composition (see, e.g., Ismael and Schaffer (2020, p. 4145)). Other examples include the use of parthood relations in engineering, computer science, thermodynamics and chemistry (see Bjorner (2014); Llored and Harré (2014); te Vrugt (2021)).

Note, also, that parthood may be particularly important for understanding the relationship between collections of entities in certain approaches to quantum gravity, and the members of those collections. For instance, Baron and Le Bihan (2023) have argued that parthood can be used to interpret the relationship between manifoldlike causal sets in CST, and the elements and links that appear to 'make up' these causal sets. Parthood can thus be used to explain the relationship between what plays the spacetime role, and the more metaphysically fundamental, non-spatiotemporal entities within a CST ontology. A similar story may work for LQG as well, where it is tempting to suppose that weave states are literally composed of quantum loops which, arguably, is within the spirit of Rovelli's fabric analogy.

It is also important to keep in mind that we are certainly not forced to use parthood, for there may be some *other* notion of grounding that we can apply to the case of QG. I've already mentioned one: ontological dependence. Another option is just the relation between a group and its members. This relation does seem to have some role to play in science as, for instance, when we differentiate the effects of natural selection at the individual level versus the group level. Moreover, it seems plausible that the members of a group are more metaphysically fundamental than the group itself.

Of course, the group membership relation that we use to describe organisms cannot literally be the relation that we use in the case of QG, since there we are not talking about groups of organisms. Note, however, that the notion of a group has application beyond organisms, as when we talk of a group of numbers, or a group of sets that obey certain conditions. Here too it seems the relation is not parthood, and here too it seems that some notion of metaphysical fundamentality may be induced. If that's right though, then there may be a very general metaphysical relation that connects groups of all kinds to their members that could be used to describe how, say, collections of quantum loops relate to weave states, or collections of causal set elements relate to causal sets.

Another option entirely is to focus on the distinction between systems and sub-systems. This is a distinction that appears to be important throughout science, particularly in physics. Moreover, the distinction between systems and their sub-systems seems to carry some metaphysical weight. It is plausible to suppose that systems are sometimes 'made up' of sub-systems, where this means that sub-systems are the more metaphysically basic components. That being so, the relation between systems and sub-systems could potentially play the role of grounding in the definition of metaphysical fundamentality offered here. Of course, some will be inclined to view this very relation as a relation of parthood. However, as Healey (2013) argues, the system/sub-system distinction is not plausibly analysed in terms of parthood for QFT, where there may be no natural way to specify the parts of a quantum system (at least, for any ordinary notion of part). It is perhaps for this reason that Calosi and Morganti (2021) interpret something close to the system/sub-system relation in quantum mechanics as a non-mereological relation of ontological dependence.

I recognise that the group case and the system/sub-system case are controversial. As such, I don't want to put too much weight on them. Instead, I want to use the discussion of these cases to draw out a general moral. Instead of picking some small 'g' grounding relation off the shelf of metaphysical practice we may allow that developments in physics suggest new small 'g' grounding relations. Whatever these relations might be, we can then use them to resolve the collapse problem in the manner described.

5.4. Objection Four

Fourth objection: I have assumed throughout that metaphysical fundamentality is in good standing. In particular, I have assumed that the ontology of various approaches to QG is metaphysically structured, in the sense that there are facts about what is more fundamental than what with respect to that ontology. As discussed in §2, however, metaphysical fundamentality may be highly relativised. As also noted, the relativisation of metaphysical fundamentality may lead to anti-fundamentalism: the view that there are no facts about metaphysical fundamentality. If anti-fundamentalism is true, then the solution to the collapse problem I've proposed is in trouble. For the solution crucially relies on being able to say that there are items in the ontology of a theory of QG that are (i) non-spatiotemporal and (ii) metaphysically fundamental compared to spacetime.

This is a serious challenge. Resolving the collapse problem in the above manner does indeed presuppose that anti-fundamentalism is false for those approaches to QG in which something plays the spacetime role. So far as I know, the presupposition is reasonable for at least LQG and CST. In those cases, we don't have anything like the kind of situation that motivates anti-fundamentalism in the cases that McKenzie discusses. For instance, in the case of LQG, we don't have two alternative presentations of the theory such that, in one, weave states are more metaphysically fundamental than quantum loops while, in the other, the reverse is true. Similarly, in the case of CST, the only formulation of the theory available appears to be one in which manifoldlike causal sets are structured out of more fundamental features.

The case of string theory is perhaps a bit harder, since there we do apparently have dualities in which spatial features vary. Specifically, in T-duality the compactification radii of strings differ across dual string theories (these are distinct to the S-dualities McKenzie focuses on, see Huggett (2017) and Huggett and Wüthrich (2013, p. 281)). So here we might find that an item of the ontology with certain spatial or spatiotemporal features is fundamental relative to the rest of the ontology with respect to one presentation of the theory, but not with respect to another.

To some extent, we can address this issue by drawing on McKenzie's analysis of relativised fundamentality for S-duality. Recall that, for her, S-duality is indicative of fundamentality relative to a world. Perhaps this can be extended to all string theory dualities. If so, then the anti-fundamentalism potentially supported by T-duality is made less threatening. For it remains open that in the model that corresponds to our world, there remain facts about whether spatiotemporal or spatial features are fundamental.

Nonetheless, it remains open that anti-fundamentalism is just true in general for one or more theories of QG, and thus that the solution to the collapse problem proposed here fails. Then there are two options: either find a new solution to the problem or simply concede the problem outright, and give up on the idea that theories of QG are spatiotemporal in a deep sense. Of these options, the second seems best. For if it were to turn out that, on the one hand, theories of QG have spacetime in their ontology and, on the other hand, there is no sense in which something non-spatiotemporal is more metaphysically basic than spacetime, then I expect this really would cast doubt on the idea that such theories are non-spatiotemporal.

If that's right, though, then we can detect the potential for anti-fundamentalism to interact in an interesting way with how we think about the status of spacetime in QG. This interaction suggests not only that my solution to the collapse problem stands or falls with the status of anti-fundamentalism but so too, perhaps, does the interpretation of theories of QG as ones that are non-spatiotemporal in a deep sense. In a way, then, I'm not too worried by the potential for anti-fundamentalism to be vindicated, since that would likely remove the pressure to resolve the collapse problem in the first place. For one could just grant that it is indeed not clear that the ontology of QG is non-spatiotemporal, and take spacetime functionalism to be a demonstration of this fact.

6. Conclusion

I have provided a response to the collapse problem for spacetime functionalism. The problem arises because the fundamental ontology associated with a theory of QG is supposed to be non-spatiotemporal and yet spacetime functionalism seems to require that the ontology is spatiotemporal. The solution is to recognise that the physically fundamental QG ontology can be spatiotemporal and yet, in a metaphysically fundamental sense, non-spatiotemporal. This requires taking grounding seriously, but there are naturalistically acceptable ways to do so. The solution won't work if anti-fundamentalism is true. But in this case, perhaps we should revise our interpretations of QG anyway.

References

Ashtekar, A., C. Rovelli, and L. Smolin (1992), "Weaving a classical metric with quantum threads." *Phys. Rev. Lett.*, 69, 237.

Bailey, Andrew M. and Andrew Brenner (2020), "Why composition matters." *Canadian Journal of Philosophy*, 50, 934–949.

Baron, Sam (2020), "The curious case of spacetime emergence." *Philosophical Studies*, 177, 2207–2226.

Baron, Sam and Baptiste Le Bihan (2023), "Causal theories of spacetime." *Noûs*.

Baron, Sam, Kristie Miller, and Jonathan Tallant (2022), *Out of Time: A Philosophical Study of Timelessness*. Oxford University Press, Oxford.

Bennett, Karen (2007), "Mental causation." *Philosophy Compass*, 2, 316–337.

Bennett, Karen (2017), *Making Things Up*. Oxford University Press, Oxford.

Bjorner, Dines (2014), “A role for mereology in domain science and engineering: To every mereology there corresponds a λ-expression.” In *Mereology and the Sciences* (Claudio Calosi and Pierluigi Graziani, eds.), 323–358, Springer.

Butterfield, Jeremy (2011), “Less is different: Emergence and reduction reconciled.” *Foundations of Physics*, 41, 1065–1135.

Calosi, Claudio and Matteo Morganti (2021), “Interpreting quantum entanglement: Steps towards coherentist quantum mechanics.” *British Journal for the Philosophy of Science*, 72, 865–911.

Calosi, Claudio and Gino Tarozzi (2014), “Parthood and composition in quantum mechanics.” In *Mereology and the Sciences* (Claudio Calosi and Pierluigi Graziani, eds.), 53–85, Springer, Dordrecht.

Chalmers, David J. (2021), “Finding space in a nonspatial world.” In *Philosophy Beyond Spacetime: Implications from Quantum Gravity* (Christian Wüthrich, Baptiste Le Bihan, and Nick Huggett, eds.), 154–181, Oxford University Press.

Crowther, Karen (2018), “Inter-theory relations in quantum gravity: correspondence, reduction, and emergence.” *Studies in History and Philosophy of Modern Physics*, 63, 74–85.

Dowker, Faye (2013), “Introduction to causal sets and their phenomenology.” *General Relativity and Gravitation*, 45, 1651–1667.

Endicott, Ronald P. (2007), “Nomic-role nonreductionism: Identifying properties by total nomic roles.” *Philosophical Topics*, 1/2.

Healey, Richard (2013), “Physical composition.” *Studies in the History and Philosophy of Modern Physics*, 44, 48–62.

Huggett, Nick (2017), “Target space ≠ space.” *Studies in History and Philosophy of Modern Physics*, 59, 81–88.

Huggett, Nick and Christian Wüthrich (2013), “Emergent spacetime and empirical (in)coherence.” *Studies in History and Philosophy of Modern Physics*, 44, 276–285.

Huggett, Nick and Christian Wüthrich (2024), *Out of Nowhere: The Emegerence of Spacetime in Quantum Gravity*. Oxford University Press.

Ismael, Jennan and Jonathan Schaffer (2020), “Quantum holism: Nonseperability as common ground.” *Synthese*, 197, 4131–4160.

Lam, Vincent and Christian Wüthrich (2018), “Spacetime is as spacetime does.” *Studies in History and Philosophy of Modern Physics*, 64, 39–51.

Lam, Vincent and Christian Wüthrich (2021), “Spacetime functionalism from a realist perspective.” *Synthese*, 199, 335–353.

Le Bihan, Baptiste (2021), “Spacetime emergence in quantum gravity: Functionalism and the hard problem.” *Synthese*, 199, 371–393.

Le Bihan, Baptiste and Niels Linnemann (2019), “Have we lost spacetime on the way? narrowing the gap between general relativity and quantum gravity.” *Studies in the History and Philosophy of Modern Physics*, 65, 112–121.

Lehmkuhl, Dennis (2016), “The metaphysics of super-substantivalism.” *Noûs*, 52, 2.

Llored, Jean-Pierre and Rom Harré (2014), “Developing the mereology of chemistry.” In *Mereology and the Sciences*

(Claudio Calosi and Pierluigi Graziani, eds.), 189–216, Springer.

McKenzie, Kerry (2011), "Arguing against fundamentality." *Studies in History and Philosophy of Modern Physics*, 42, 244–255.

McKenzie, Kerry (2017), "Relativities of fundamentality." *Studies in History and Philosophy of Modern Physics*, 59, 89–99.

Miller, Kristie and James Norton (2017), "Grounding: it's (probably) all in the head." *Philosophical Studies*, 174, 3059–3081.

Moore, Dwayne (2011), "Role functionalism and epiphenomenalism." *Philosophia*, 39, 511–525.

Oriti, Daniele (2014), "Disappearance and emergence of space and time in quantum gravity." *Studies in History and Philosophy of Modern Physics*, 46, 186–199.

Rovelli, Carlo (2004), *Quantum Gravity*. Cambridge University Press, Cambridge.

Rovelli, Carlo and Francesca Vidotto (2014), *Covariant Loop Quantum Gravity: An Elementary Introduction to Quantum Gravity and Spinfoam Theory*. Cambridge University Press.

Schaffer, Jonathan (2016), "Grounding in the image of causation." *Philosophical Studies*, 173, 49–100.

Sorkin, Rafael and David Rideout (1999), "A classical sequential growth dynamics for causal sets." *Phys. Rev. D*, 61, 024002.

te Vrugt, Michael (2021), "The mereology of thermal equilibrium." *Synthese*, 199, 12891–12921.

Van Gulick, David (2009), "Functionalism." In *The Oxford Handbook of Philosophy of Mind* (A. Beckermann, ed.), 128–151, Oxford University Press.

Wilsch, Tobias (2016), "The deductive-nomological account of metaphysical explanation." *Australasian Journal of Philosophy*, 94, 1–23.

Wilson, Alastair (2018), "Metaphysical causation." *Noûs*, 52, 723–751.

Wüthrich, Christian (2017), "Raiders of the lost spacetime." In *Towards a Theory of Spacetime Theories* (D. Lehmkuhl, G. Schiemann, and E. Scholz, eds.), 297–335, Birkhäuser, Basal.

Yates, David (2021), "Thinking about spacetime." In *Philosophy Beyond Spacetime: Implications from Quantum Gravity* (Christian Wüthrich, Baptiste Le Bihan, and Nick Huggett, eds.), 129–153, Oxford University Press, Oxford.