Have We Lost Spacetime on the Way? Narrowing the Gap Between General Relativity and Quantum Gravity

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Abstract

Important features of space and time are taken to be missing in quantum gravity, allegedly requiring an explanation of the emergence of spacetime from non-spatio-temporal theories. In this paper, we argue that the explanatory gap between general relativity and non-spatio-temporal quantum gravity theories might significantly be reduced with two moves. First, we point out that spacetime is already partially missing in the context of general relativity when understood from a dynamical perspective. Second, we argue that most approaches to quantum gravity already start with an in-built distinction between structures to which the asymmetry between space and time can be traced back.

Contents

1 Introduction

In the recent literature, much has been written on the emergence of spacetime and spatio-temporal theories from non-spatio-temporal theories in the context of quantum gravity (cf. for instance Huggett and Wüthrich (2013), Crowther (2016)). In this essay, we discuss the extent to which this so-called emergence of spacetime is as radical as has been claimed. We will argue in favor of two claims. First, contrary to what is often said, namely that spacetime emerges from a non-spatio-temporal structure, many of these cases might be described as the emergence of *non-spatio-temporal structures* from distinct non-spatio-temporal structures because spacetime, in a substantive sense, is already missing in General Relativity (GR hereafter). Second, we argue that in many research programs on Quantum Gravity (QG from now on), a local distinction between a spatial or quasi-spatial structure on the one hand, and a temporal or quasi-temporal on the other hand, is still implemented. With the expressions "quasi-spatial" and "quasi-temporal" structures, we generically mean structures that respectively share features of space and time but do not implement all of the features usually attributed to them.

More precisely, we argue that the fundamental structure replacing spacetime in QG approaches still contains a distinction between quasi-spatial and quasi-temporal elements at the level of its most basic constituents (for instance, at the level of nodes and/or edges for a graph-like fundamental structure) and that, therefore, spacetime, in a minimal sense, is still there in QG—indeed, we take the existence of a local split between quasi-space and quasi-time to justify the existence of a minimal spacetime, associated with the existence of such a local split. Taken together, these two claims entail that spacetime may be regarded as already partially missing in GR, and as still partially present in QG, narrowing the explanatory gap between the two theories and questioning the relevance of describing the relation between GR and QG as entailing that GR spacetime emerges from a non-spatio-temporal QG structure. As a terminological convention, we will refer to this partial spacetime as "minimal spacetime", being granted that this is a matter of convention to which extent this structure should be called “spacetime” or not.

What do we mean exactly by “explanatory gap”? Following Le Bihan (2018), it is useful to introduce a distinction between *the hard problem of spacetime emergence* and the *the easy problem of spacetime emergence*. The hard problem is to understand the ontological status of the two structures at play (the *fundamental* and the *derivative* structures) and the nature of the *relation* obtaining between the two structures: Are these two structures real, one of them being more fundamental than the other, or is the derivative structure a pure illusion, an approximate description of the fundamental structure without an ontological counterpart? The easy problem consists in finding the formal derivation of the derivative theory by using mathematical tools and bridge principles between the primitive notions involved in both theories.[1] We then define the “explanatory gap” between the two theories as the conceptual discrepancy between the primitive notions involved in the two theories. For instance, admitting that the easy problem was convincingly addressed in the case of QG, one could ask how we should interpret the primitive notions of the derivative theory (GR), allegedly relying on the existence of spacetime, if these are very different from the primitive notions of the fundamental theory (QG), which are potentially non-spatio-temporal.

Note that in this essay we do not take a position on whether there *genuinely is* a hard problem of spacetime. One may indeed argue that there is no hard problem of spacetime because the derivative theory (GR) does not describe a genuinely existing structure, just as one may deny that there is a hard problem of consciousness by denying the existence of consciousness. However in this scenario one still has to explain *why* it is the case that there is no hard problem of spacetime (see e.g. Chalmers (2018) for a defense of this point in the context of the philosophy of mind). In a nutshell, if one argues that the physical system described by GR is not real in such a way that there is no hard problem of spacetime, the *ontological hard problem of spacetime* will be deflated. Nonetheless, the more general hard problem of spacetime will not be solved because we still have to understand why this approximation (the structure described by GR), rather than another one, describes the world. Compare this situation with the one we find in philosophy of mind: It is not because we solve the hard problem of consciousness by stipulating that there are no mental states that the problem is fully solved. We still have to explain why we do have the

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[1] We keep the name “easy” in analogy with the terminology in the philosophy of mind, with a touch of humor. The easy problem of spacetime relies on finding a theory of quantum gravity and relating it to GR, which arguably is one of the most difficult challenges ever met by physicists.

illusion that there are mental states, and therefore, explain why we are lured into believing that there is a hard problem of consciousness in the first place.

Therefore, in this essay, we try to solve the hard problem of spacetime by narrowing the conceptual discrepancy between the primitive notions of GR and the primitive notions of QG. On the one hand, if you believe that there is no hard problem of spacetime in the first place, our approach helps to explain why this is so by narrowing the conceptual discrepancy between the two sets of primitive notions. On the other hand, if you do accept that there is a hard problem of spacetime if there is a conceptual discrepancy between the two sets of primitive notions, our narrowing of this conceptual discrepancy also helps to make the problem less salient. As we will go on to explain, we may narrow the conceptual discrepancy by endorsing the "dynamical approach"to GR, which entails that the spatiotemporality of the metric field is physically contingent, *and/or* by acknowledging that the fundamental structure described by the various theories of QG already relies on a distinction between structures that maps into the spacetime split present in GR. Indeed, the two moves presented in order to narrow the explanatory gap stand independently.[2] For instance, the reader who does not accept that the dynamical approach is consistent may accept the point about quantum gravity, and vice versa.

Here is a more precise description of the two moves. First, spacetime may be construed as already partially missing in the framework of GR. In fact, according to the dynamical approach, the chronogeometric nature of the metric field (or to put it differently, its spatiotemporality) is contingent on its coupling to other matter fields, entailing that the spatiotemporality of the metric does not obtain in all possible worlds that are described by GR. This contingency of spacetime deflates in part the common concept of spacetime as a necessary structure and, as a result, spacetime can be regarded as a derivative result of, a specific and contingent configuration of the metric field. Given the dynamical approach, we (only) need to derive GR with its metric field from QG—*not the full-blown spatiotemporality of the metric field.*[3]

Second, we find that a split between space and time still obtains in the fundamental structures described by QG approaches either in the form of (representations of) the Lorentz symmetry, or along another principle playing the same role in the theory. As we will argue, if

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[2] With a small caveat, to be explained in the conclusion.

[3] We will explain later why we take the *contingency* of the spatiotemporality of the metric field—a particular consequence of the dynamical approach—to deflate partly its spatiotemporality.

one takes the local differentiation between space and time to be a minimal and essential feature of (minimal) spacetime, then *(minimal) spacetime has not been lost on the way.*

Three last introductory remarks are in order. First, we do believe that QG exhibits intriguing features, missing in GR and vice versa (see section 3.3 for a list of decisive differences in features of GR and QG: classicality vs. superposition, continuity vs. discreteness, locality vs. disordered locality/non-locality). Our point in this essay is not that there is no interesting problem of emergence of spacetime, but rather that the two theories related by a relation of emergence may be regarded as being spatio-temporal in a minimal sense.

Second, we want to situate our claim in a more general context. In order to explain the phenomenology of space and time, namely our ordinary experience of space and time, we believe that a two-step strategy is fruitful: (1) Relating the phenomenology of space and time to the ontology described by GR and, (2) filling the explanatory gap between QG and GR (by solving the easy and hard problems, or explaining why the hard problem does not appear). In this paper, we undertake the second step.

Third, it is common, when examining this issue, to jump into the philosophical literature on emergence in order to make sense of spacetime emergence. But our present goal is different since we aim at narrowing the explanatory gap between GR and QG—not at offering a philosophical analysis of the inter-theoretical relation obtaining between the two theories, or of the building relation obtaining between the non-spatio-temporal structure and GR spacetime. In fact, it might even be that there is no explanatory gap between spatio-temporal and non-spatio-temporal features left at the end of the day, in such a way that the novel features of QG with respect to GR should not be related to spacetime. To put it differently, the way we propose to narrow the gap may mean that there is no need to appeal to the notion of spacetime emergence, or alternatively, that the kind of emergence involved in spacetime emergence is weaker than is usually thought. In any case, our work is logically anterior to any analysis of emergence or spacetime emergence.

In section 2, we argue that GR may be interpreted as a non-spatio-temporal theory in an interesting sense. In section 3, we argue that substantive features of space and time are still present in most approaches to QG and discuss possible counter-examples. We close in section 4 with conclusions and outlook.

2 GR as a Non-Spatiotemporal Theory

2.1 The Fundamental Spacetime Asymmetry

An essential feature of what we call "spacetime" is that there is an asymmetry between what is called "time" and what is called "space". By this asymmetry we do not mean the notion of an arrow of time, or of a flow of time. Most of our best microphysical theories are formulated with respect to space and time but do not at all favour one direction in time over the other[4], or refer to a flow. We refer to a fact even more basic. Generally, we take it that the asymmetry between space and time in relativistic worlds—whether classically or quantum mechanically described—is captured by their local Lorentzian nature.[5] To be clear, we do not take the existence of an *asymmetry in time* to be constitutive of an *asymmetry between space and time*, we rather consider the more primitive existence, locally, of an asymmetry between the three spatial dimensions and the temporal dimension, an asymmetry represented in our current best physical theories mathematically by Lorentz symmetry.

The reader might object that the split between space and time is not *necessarily* captured by Lorentz symmetry even in our best physical theories. An alternative possibility is that it is rather captured by the causal structure of these theories.[6] It is useful here to distinguish between the relativistic and the quantum gravitational cases. In the relativistic case, the local split between space and time can equivalently be seen as *encoded* either by (local) Lorentz symmetry, or by a (local) causal structure. This is because—in a relativistic context—the local lightcone structure is tantamount to locally Lorentz invariant dynamics. Which side to stress seems somewhat unimportant to us since our interest here is in the codification of the split (and not in its "true" origin). Prioritising Lorentz symmetry over the causal structure may seem to suggest that the source of Lorentz symmetry is not the causal structure of spacetime. However, we do *not* wish to imply

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[4] Arguably, the weak interaction—as part of the standard model and thus of our best microphysical theories—is not invariant under time-reversal. We would like to thank an anonymous referee for pressing us on pointing this out. Note though that (1) it is highly non-standard to consider the macroscopic arrow of time to be grounded in the weak interaction's violation of time-reversal symmetry (for discussion, see for instance Price (1997), Wallace (2013)); and that (2) the weak interaction remains invariant under CPT-transformation—a generalized notion of time-reversal.

[5] This is explicated in more detail below, including considerations of caveats.

[6] We want to thank an anonymous referee for raising this point.

that this is the case. We remain neutral on the source of the split—we simply identify the existence of spacetime, in a minimal sense, with the existence of such a split.

Regarding the quantum gravitational case, let us stress that we do not have a problem with taking (as in the case of causal set theory, see section 3.1) the split between the quasi-spatial and the quasi-temporal structures to be for instance encoded by a primitive graph structure (call it "causal"), and not by (a representation of) the Lorentz (symmetry) group. Our stress really is on the persistence of a split between quasi-spatial and quasi-temporal structures in quantum gravity, not on its needing to be realized through a representation of Lorentz symmetry (or a close-by relative for that matter).

As we see it, the claim that spacetime is not fundamental may amount to two claims: First, that operational spacetime—namely the ordering structure of the universe, as we may partly operationalize it through rods, clocks and even our perceptions—is not the rock-bottom ordering structure of the world.[7] Second, that theoretically-loaded spacetime—namely the entity posited in the standard geometrical formulation of GR in order to make sense of what we measure operationally—does not exist. What we will argue for in this section is that the (heavily) *theoretically-loaded spacetime* of the standard geometrical interpretation of GR may be regarded as already missing in GR, easing the way for the possibility to narrow the gap between GR and QG.

2.2 The Non-Fundamentality of Spacetime in GR

Spacetime in GR (and already in Special Relativity, SR hereafter) very visibly differs from space and time as we find them in Newtonian physics since there is no absolute simultaneity anymore. However, several ordinary intuitions about space and time are preserved (such as a partial ordering of spatio-temporal events), in such a way that SR and GR are not generally presented as entailing that space and time do not exist, but rather as implying that our pre-relativistic and pre-theoretic beliefs about space and time are deceptive to some extent.

GR is a specific spacetime theory based on a 4-dimensional differentiable manifold, which has fields on top, namely a symmetric rank-two tensor, the metric g of Lorentzian signature[8], and other fields $T_1, ..., T_n$

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[7] See Menon (forthcoming) for a similar notion.

[8] As a matter of convention, the signature is either $(3,1)$ or $(1,3)$. Note that requiring the metric signature to be Lorentzian amounts to requiring g to be locally Poincaré invariant, and vice versa, as both correspond to the fact that—at each point—g can be brought

(usually called matter fields—provided that they contribute to the so-called energy momentum tensor T; see for instance Lehmkuhl (2011)). The g field is subject to the so-called Einstein field equation, which amounts to equating the Einstein field tensor $G_{ab} := R_{ab} - \frac{1}{2}Rg_{ab}$ to the energy momentum tensor such that $G_{ab} = 8\pi T_{ab}$. The fields themselves are subject to dynamical equations, which are formulated by means of derivatives defined via g_{ab}.

As Read (2017a) points out, this does not define GR as it is often implicitly presented, though: in the set-up, the matter fields do not have to be (locally) Poincaré covariant. This is however necessary—albeit not sufficient—to obtain the often desired behaviour of matter as looking *locally Minkowskian* in at least some minimal sense. In this spirit, the strong equivalence principle à la Brown, Read and Lehmkuhl—$\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$ from now on—demands that the dynamical equations of the matter fields are locally invariant under (passive) Poincaré transformation.[9,10] In other words, without further qualification on the matter fields (such as $\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$), the dynamical equations of certain matters fields in GR might for instance be locally Galilean invariant (and not Lorentz invariant). The dynamical approach, however, embraces such a broad conception of GR where certain matter field types are not excluded on purely *a priori grounds*.[11]

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into the form of the Minkowskian metric. (Note that the derivatives and higher derivatives of g at this point will generically not vanish.) In the following, we will thus accept that the claim that spacetime is Lorentzian—in having Lorentzian signature—is (extensionally) equivalent to the claim that g is locally Poincaré invariant. Furthermore, whenever a spacetime is locally Poincaré invariant/Lorentzian, it will also be locally Lorentz invariant.

[9] See Read et al. (2018, p. 6), for a detailed explication.

[10] Note, though, that the stronger demand that matter "behaves" locally like in Minkowski spacetime in the sense that the matter equations locally take the same form as in Minkowski spacetime (also referred to as a strong equivalence principle by Brown (2005)) cannot be satisfied, at least in the standard conception: This has recently been stressed by Read et al. (2018) as second order dynamical equations (such as the Maxwell wave equations in curved spacetime) do not even, at a point, take the same form as in flat spacetime. Such a strong equivalence principle should not serve as a postulate of GR as it would generally not even hold *at a point* for quite familiar matter theories such as electromagnetism. We can thus conclude—as for instance Knox (2013) or Read et al. (2018) do—that this form of strong equivalence principle can generally only hold approximately, when curvature effects are negligible.

[11] Note that even if the $\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$ does not hold, the same space-time split could arguably still be implemented by matter fields whose equations of motion are locally invariant under (passive) Galilean symmetry. Matter fields with rather abnormal local symmetry properties (without any symmetry properties) might however give rise to a split incompatible with that of a Lorentzian metric and locally Lorentz invariant matter fields (might not implement a split at all).

As above, the theory of GR is usually depicted in textbooks in its manifest geometric description (after all, differential geometry is the language of relativity). However, this is not the only presentation of GR; one should for instance take note of the particle physicist's approach to GR, originally going back to Arnowitt et al. (1962) and Deser (1970), but also quite prominently put forward by Feynman and Weinberg (sometimes called the "massless spin-2 approach").[12] The classical[13] spin-2 view featuring the (classical) linearized metric field in a Minkowski background space reproduces GR without any import from quantum physics. The story is simple (albeit not fully uncontroversial—see the debate between Padmanabhan (2008) and Pitts and Schieve (2007) which we take to have been decided for Pitts eventually and thus in favour of the classical spin-2 view): Due to the self-coupling properties of the linearized field the linearized field will eventually give rise to a new field—the metric field g familiar from GR and subject to the Einstein field equation. It is interesting to wonder about the status of the Minkowski spacetime background structure once the metric field has been built. Two options seem straightforward: One could for instance consider it to be a genuine background spacetime, or simply regard it as a "glorious non-entity" (see Brown and Pooley (2006))—as done in what is called the dynamical approach *to SR*: The Minkowski spacetime has no (fundamental) ontological status but is derivative on symmetry properties of the (matter) fields (see Brown (2005) for more details).

One might object that such a *field* view of GR (in which the gravitational degrees of freedom are in a sense treated *on par* with that of other interactions) is only granted if we subscribe to a vantage point external to GR—as the quantum field theoretic spin-2 view. At the same time, we promised a putative partial disappearance of spacetime *within* GR—how does this all square? It turns out that a fields-only view can exactly be found in the context of GR alone—namely in the dynamical approach *to GR* (cf. Brown (2005)). But let us proceed step by step: We first present GR as it is usually understood in physics and then turn to its possible philosophical interpretations, especially highlighting the dynamical approach to GR.

Now, the standard interpretation of GR is the geometric view (building on its usual geometric presentation), often taken so much

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[12] For a philosophical account of the spin-2 view, see Salimkhani (2017).

[13] The quantum spin-2 approach turns a classical field perspective into a quantum field theory perspective: GR and many of its properties (universal coupling, minimal coupling, ...) are interpreted as a low-energy limit from a higher vantage point—the theory of quantum field theory. In this sense then, the particle physicist's approach to GR is not an approach to GR *simpliciter* but to perturbatively quantized GR and only thereby to GR.

for granted that one generically does not even talk about interpreting GR. The geometric view can be spelled out as the view that g necessarily has chronogeometric significance, namely is necessarily identified with spacetime.[14] In other words, the metric g has chronogeometric significance in any GR model, which is to say that there can be rods and clocks which (at least approximately) give measurement results of spatio-temporal distances, provided that the circumstances allow for it.

In contrast to the geometric view, the dynamical approach to GR (see Brown (2005)) sees matters the other way around: The fields are there, realizing structures like rods and clocks, and the question is why they happen to give results in accordance with the metric field structure. From the dynamical perspective, the chronogeometric significance of g is thus not automatic, in the sense that it is a contingent fact that we happen to live in a world in which g has this chronogeometric significance.

According to the dynamical approach, the operational spatio-temporal significance of the so-called metric field is contingent. But does this view not entail an *anti-realist conception of spacetime* then? Not necessarily. Indeed, the dynamical approach builds on the strong conviction that the term "spacetime" should refer to that to which our operations of measuring space and time refer (cf. the defense of spacetime functionalism in Knox (2013)). At this point, one might want to object that the metric field g could have an operational spatio-temporal significance if and only if spacetime is genuinely fundamental. However, we believe it is important to keep in mind the distinction between two notions of spacetime that we made before: An operationalist notion of spacetime corresponding to what clocks and rods (would) measure, and a notion describing a richer theoretically-loaded physical structure. We take the main lesson of the dynamical view[15] to be that operational aspects of spacetime can exist in absence of any theoretically-loaded notion of spacetime.

Now, the dynamical approach helps with narrowing the explanatory gap as we only need to explain the existence of an operational

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[14] For more nuanced characterizations, see Read (2017a) and Menon (2017). This is by and large what Read (2017a) calls the "modal geometric view".

[15] The same holds for what Read (2017a) calls the "individualist geometric view"—the view that a certain geometric structure has chronogeometric significance. Which geometric structure this is is then a contingent fact, which depends on the concrete properties of the possible world under consideration. In fact, this notion helps distinguishing between the dynamical approach and the individualist geometrical view: According to the first, operational spacetime contingently exists in the absence of any richer theoretically-loaded spacetime, while according to the second, the operational spacetime corresponds to a theoretically-loaded spacetime, the existence of both being contingent.

spacetime:

1. The way the metric field is typically seen to couple to the matter fields ("minimal coupling") is a contingent fact (the coupling behaviour for instance directly changes once one accepts rather exotic matter fields). This sort of contingency suggests that the existence of spacetime is an accident.[16]
2. Recovering GR spacetime from QG, in the framework of the dynamical approach, only means recovering operationalist spacetime, that is—more or less—this specific coupling behaviour of one field to all other fields.[17]
3. Coming from QG, we only need to explain why the fundamental ontology (described by QG), leads to this particular derivative ontology—namely to the metric field being specifically coupled to the other fields. Thereby, we are not assuming from the start the existence of an independent structure called "spacetime".
4. In other words, we do not need to recover all theoretically-loaded features of spacetime that we can attribute to the notion of spacetime in order to explain spacetime emergence but only operationalist spacetime. This narrows the explanatory gap.[18]

What matters here is that this operationalist notion of spacetime remains highly flexible with respect to the existence of various aspects of spacetime, if any, that we could want to ascribe to spacetime. This operationalist notion heavily rests on distinguishing locally between space and time, something, we shall see in the second part of the paper, that is still the case in most approaches to QG. This is interesting for the problem of spacetime since many striking features of spacetime (say, its particular ordering of events) are said to be described by GR and missing in QG, or vice versa. If this is true that GR "spacetime" is more an operational than a theoretical notion, as signaled by

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[16] More precisely, the view is held that the chronogeometric significance of the metric field (and thus its status as spacetime) is only earned if the symmetries of the matter fields coincide with that of the metric field. In the case of GR, this would mean that the dynamical equations of the matter fields need to be locally invariant under (passive) Poincaré transformation (the $\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$ needs to be fulfilled). Even that the $\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$ holds, is arguably not sufficient for chronogeometricity of the metric field, as only recently argued for by Menon et al. (2018).

[17] We only need to recover operationalist spacetime, and this operationalist spacetime is consistent with both the geometrical and the dynamical approach. But the dynamical approach posits less behind the operationalist spacetime: it posits a contingent field, when the geometrical approach posits a necessary structure.

[18] Arguably, this operationalist move relates closely to how Lam and Wüthrich (forthcoming) suggest narrowing the explanatory gap through a functionalist notion of spacetime.

the very existence of the debate between geometrical and dynamical proponents, then the explanatory gap is reduced by by deflating the existence of specific spatio-temporal features of the metric field.

Note that operating in the context of QG, the geometrical versus dynamical debate should not be interpreted as being about the ontology of the actual world. In particular, these interpretations should not be regarded as aimed at answering to the following question: What is the correct ontological interpretation of GR? Rather, since the goal is to reduce GR to QG and to deny that some conceptual specificity of GR is irreducible to QG, there is no point in asking which of the geometrical or the dynamical approach is true *per se.* Rather, our point is that the dynamical formulation of GR might be more easily related to the real ontology of the world described by QG. In other words, the dynamical approach, by offering a way out with respect to the hard problem of spacetime might offer a useful interpretation of GR, being granted that only the correct interpretation of the most fundamental physical theory could actually deliver an ultimate accurate ontological description of the physical world.

Independently of the discussion above, the very fact that the dynamical approach eases the resolution of the problem of spacetime emergence in the context of QG might count as a reason to accept it. Indeed, the extension of the explanatory gap between GR and QG relies on the extension of the explanatory gap between the primitive notions of the two theories. If the traditional philosophical reading of the derivative theory (here GR) may be replaced by another reading of GR (here the dynamical approach) in order to get primitive notions in the derivative theory that are in line with the primitive notions of the fundamental theory, then the new reading of the derivative theory constitutes a new path in the resolution of the problem of spacetime emergence. More precisely, this move simplifies the easy problem of spacetime emergence by eliminating the primitive notions in the derivative theory that are too different from the primitive notions of the fundamental theory (thereby simplifying the finding of the bridge principles between the two sets of primitive notions); more importantly, this elimination also offers a way out of the hard problem of spacetime emergence by denying the existence of any important conceptual discrepancy between the two sets of primitive notions.

At the end of this section, a word of caution is in order: Since we offer in the next section another road for the downsizing of the conceptual discrepancy between GR and QG, the possibility to ease the resolution of the problem of spacetime emergence may not be counted as a strong argument in favor of the dynamical approach but only as an interesting attribute of the dynamical approach. Our claim is merely that the dynamical approach leads to one possible and interesting road in the resolution of the problem(s) of spacetime emergence.

3 QG as Spatial and Temporal

In this section, we point out that (local) Lorentz symmetry or at least some codification of a local difference between (quasi-)space and (quasi-)time is a decisive feature of current QG approaches. From our point of view, this shows first that spacetime emergence could, in principle, be more radical than what we actually find in current approaches to QG, and second that the explanatory gap between the fundamental non-spatio-temporal structure and the derivative spatio-temporal structure is not as deep as what is usually thought: the promising QG theories we are aware of embed a local distinction into their basic structure between entities that may be traced back to the space-time split in GR.

3.1 The Local Split Criterion in QG

The Lorentz group features prominently in our two best physical frameworks: In GR, matter fields *standardly* used are locally Lorentz invariant (that is, fulfill the $\text{SEP}_{\text{Read-Brown-Lehmkuhl}}$ as introduced before), and of the metric field (at every point p in spacetime, a coordinate system x^μ can be found[19] such that the spacetime metric $g_{\mu\nu}(p) = \eta_{\mu\nu}(p)$, and $\eta_{\mu\nu}(p)$ will be invariant under Lorentz-transformations). In QFT, Lorentz transformations act as a symmetry on states through corresponding unitary representations: Different fields are linked to different kinds of unitary representations.

In both QFT and GR (local) Lorentz symmetry encodes major properties of what there is: Within QFT, fields—and thereby matter types—can be categorized in terms of which representation of the Lorentz group—or more accurately the larger Poincaré group—they transform under: A scalar field is said to have spin 0, a vector field spin 1, the metric field spin 2, ... The crucial aspect of local Lorentz symmetry is that it reflects a difference between space on the one hand, and time on the other hand. But local Lorentz symmetry also makes connection to time by serving as a necessary criterion for chronogeometry *in the (general) relativistic context*: the (locally Lorentz invariant) g metric would not earn its usual chronogeometric significance if not all

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[19] However, derivatives (including higher derivatives) of g at this point will in general not vanish.

other matter equations of motion were locally Lorentz-invariant (consider for instance the case of partly Galilean-invariant matter equations). After all, the reason why a clock made from any sort of matter field can, to some degree, read out the worldline interval as time is that these matter fields behave as in local Minkowskian spacetime, which requires at least local Lorentz symmetry (cf. for instance Brown (2005)).

It should be stressed that, at this date, no sign of Lorentz violation has been detected (cf. Mattingly (2005)). A putative violation of (local) Lorentz symmetry would be expected to occur—if at all—in two ways: First, through the existence of a preferred observer/fixed background structure or alike (violation of the relativity principle), and second in the form of a deformation of the Lorentzian algebra.[20] Whereas the latter is surely interesting[21], it is not at all as radical as the former, which would imply a loss of democracy of observers (see in particular section 6 of Read et al. (2018) for two very accurate examples of this kind).

Now, Lorentz symmetry encodes a distinction between space and time.[22] Any theory which starts with Lorentz symmetry of some kind cannot underlie what we would call a *highly radical emergence* of space and time. We do not want to compare quantitatively various kinds of emergence, though; we only point out that this emergence could be said to be more radical than what we find on the QG market for the following reason: All of these approaches keep a local distinction between something quasi-spatial and something quasi-temporal. Insofar as the elimination of this local distinction between space and time is a logical possibility, we conclude that a much more radical scenario would be possible if any split in the basal theory that could be mapped onto the structural space-time split of the derivative theory was eliminated.

We noted before that the (local) Lorentz symmetry of fields plays a decisive role in GR and QFT in encoding the split between space and time. Now, if a certain feature plays a similar role in the fundamental theory—i.e. in encoding a local split between something quasi-spatial and something quasi-temporal—and since it might differ substantively

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[20] Call a family of Lie algebras $(\mathcal{A}_\epsilon)_{\epsilon \geq 0}$ a (continuous) deformation of the Lie algebra $\mathcal{A}'$ if, for $\epsilon = 0$, $A' = A_0$. For a detailed technical discussion of how for instance the Lorentz algebra gets deformed into the algebra of Doubly-Relativity, see for instance Kowalski-Glikman (2005).

[21] Consider for instance the program of doubly special relativity (cf. Amelino-Camelia (2002)).

[22] A similar observation has already been made with respect to Lorentz *signature* by (Callender, 2017, ch.6).

from Lorentz symmetry, we will refer to this feature as "locally split" or as the existence of a local split, and refer to the associated criterion as the local split criterion.

3.2 The Quasi-Spatial/Quasi-Temporal Split in QG

In this subsection, we illustrate in what sense the most standard approaches to QG[23] build on a difference between something quasi-temporal and something quasi-spatial. As we shall see, these approaches to QG already include a split between two elements which—upon applying an appropriate reduction scheme[24] for obtaining GR—will become associated with space and time respectively.

There are different ways to categorise approaches: For instance, one could purely proceed in a technical manner, that is in terms of whether the approach rests on quantization of GR in some sense or not, and if so, whether this is done canonically or covariantly. Or to take another example, one might examine whether perturbative or non-perturbative formulations are used. Finally, one might distinguish approaches on a purely conceptual basis—namely, in terms of what kind of principles are used. QG approaches might for instance be sorted based on their major guiding principles such as UV completion (asymptotic safety), discreteness (causal set theory), restoration of unitarity (Horava-Lifshitz gravity), etc. (Which guiding principle(s) should count as major in an approach, is of course not always uncontroversial.) For our purposes, it is however useful to categorize approaches by whether Lorentz symmetry or another feature playing the same role obtains. After all, as we have already seen before, the standard representation of the Lorentz symmetry group in a four-dimensional setting explicitly contains an asymmetry with respect to how one dimension is treated. More generally, independently of its group-theoretical representation, the Lorentz group has an in-built asymmetry—already expressed by its standard notation Lorentz$(1,3)$.

When sorting approaches in terms of whether a local split feature obtains, we only find two cases: (1) Lorentz symmetries do obtain (in terms of usage of unitary representations of the Lorentzian group), (2) the local split is expressed through another principle. For a compre-

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[23] We follow the selection of QG approaches in textbooks such as Kiefer (2007) as to what counts as standard.

[24] Generally, this is expected to involve approximation (as coarse-graining) and limit operations (as the quantum-to-classical transition), see Butterfield and Isham (1999) and Butterfield and Isham (2001).

hensive[25] categorization see table 1.

Concerning (1), let us quickly go through the major approaches to QG in which the Lorentz symmetry group plays a central role:

Perturbative GR might be best described as the straightforward particle physics approach to QG for which the spacetime metric g is linearized around a Minkowski background metric, its linear fluctuations being treated and quantized as any other field within a Minkowski background spacetime (basically the quantum spin-2 approach already depicted in footnote 13).[26] Subsequently, higher and higher curvature corrections to the linear expansion are considered, and quantized as well. The resulting theory is usually expected to only hold as an effective field theory, namely under imposition of an energy cut-off. As a consequence, such a theory is not predictive up to arbitrary energy scales, as with any increase of the cut-off energy, new parameters need to be added for determining the interaction strengths featuring in the theory (the values of these parameters can only be obtained through experiment). This lack of predictivity—is generally regarded as turning perturbative GR into an unsatisfactory candidate for a theory of quantum gravity. There are however also hints at the theory's UV completeness, namely that it does after all hold (at least formally) up to arbitrarily high energies (as promoted by proponents of asymptotic safety).

Similarly, standard *perturbative string theory* amounts to treating strings (and higher dimensional objects than the two-dimensional worldsheets of strings) in a Minkowski (or some other) background spacetime geometry—the so-called target space. Importantly, in both perturbative GR and perturbative string theory, the Lagrangian is constructed in such a way as to obey local Lorentz invariance or typically even full Lorentz invariance (given the prominent status of Minkowski spacetime as a background spacetime in these approaches).

Loop Quantum Gravity is a quantization approach to GR and exists in both a canonical and a covariant version (which are arguably two approaches—two different perspectives—of the same theory). See Rovelli and Vidotto (2014). In covariant loop QG, the resulting spinfoam structure—loosely speaking a granulation of 4d-spacetime structure—is (explicitly) locally Lorentz-invariant. Each element of the spin foam state structure—its vertices and edges—covariantly

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[25] We do not aim at comprehensiveness in a very broad sense including any approach available on the quantum gravity market, but only at comprehensiveness with respect to the standard list of approaches as dealt with in textbooks as Kiefer (2007).

[26] One might also choose a different fixed background metric for this. Given the extreme technical and conceptual challenges linked to QFT in curved spacetime, this route is however rarely taken.

transforms under Lorentz transformation in an appropriate representation (see Rovelli and Speziale (2011); for a critical view on this take, see Gambini and Pullin (2014)).[27]

Concerning (2): (a) *Causal dynamical triangulation* is a quantization approach to GR which aims at evaluating the path integral of the classical Einstein-Hilbert action over discrete spacetime geometries first, before taking a continuum limit for the coarse-graining length linked to the discrete spacetime geometries. If this continuum limit is meaningful, quantum GR has a UV fixed point—which is what is argued for within the asymptotic safety approach to QG.[28] In this approach, the local split is obtained through the discretization scheme that is used; we will say more on this below.

Indeed, not even summation over discrete spacetime geometries turns out to be technically straightforward: Already at the continuous level (before discretization), one thus introduces further restrictions. One imposes the so-called causality condition which states that "*only those histories for which the final three-geometry lies wholly in the future of the initial one*" (p.10, italics by Görlich) contribute in the path integral summation central to this approach. By this, CDT limits itself to summing over discretized globally hyperbolic spacetime geometries which—this is an additional restriction—have to be topologically invariant across foliation slices.

The discretization rests on a specific form of four-dimensional triangulation procedure (causal triangulation): The edge lengths in temporal direction and those in spatial directions are required to be opposed to each other—namely $a_t^2 = \alpha a_i^2$ with $\alpha < 0$ where a_t is the length of a temporal edge and a_i that of a spatial edge (measured in terms of an Euclidean background metric). The discretized geometry can be understood as a simplicial manifold, which consists of piecewise linear spaces corresponding to the faces of the 4d-triangles. The curvature of continuous spacetime can then be modelled by how these 4d-triangles meet at their joints. Importantly for our topic, an asymmetry between spatial (a_i) and temporal (a_t) is imposed into the discretization scheme at every level, which—importantly—should not be expected to vanish in the continuum limit.

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[27] In the last years, a close relative to covariant LQG—Group field theory (GFT)—gained momentum. In fact, from the viewpoint of GFT, GFT is seen as the non-perturbative continuation of so far only perturbative covariant LQG. Interestingly, the special emphasis on the presence of the Lorentz group as fundamental group structure is even more pronounced in GFT than in covariant LQG: A complex group field ϕ in GFT is a map from D copies of a group manifold G into the complex numbers, i.e. $\phi : Gx...xG \to \mathbb{C}$) where G is standardly taken to be the Lorentz group.

[28] The following paragraph largely follows Görlich (2011).

(b) *Causal set theory* (CST) is inspired from a theorem by Malament (1977) according to which the formal metric structure in GR can be split up into a continuous causal structure on the one hand, and local volume information on the other hand. Assuming that spacetime structure will be discrete in the quantum realm, the crude idea behind CST is then to model the structure underlying GR spacetime through a causal graph for which local volume information—relevant at lower energy scales, and the limit to GR—can be obtained through a simple counting procedure of nodes (a region made up of N nodes should more or less display a volume proportional to N). In this approach then, spacetime is modelled as a causal set—a set of featureless events equipped with a finite partial ordering structure.[29] The events are directly understood as spacetime events, and the partial order relation is supposed to cash out the causality relations known from GR—in particular Malament's theorem (for a philosophical account and references to the original literature see Wüthrich (2012); Wüthrich and Callender (2017)).

Now, a causal set—being a discrete structure—can hardly be said to feature Lorentz symmetry as a property.[30] Although CST does not display any sort of Lorentz symmetry, it implements a local split through its causal structure—allowing for locally distinguishing between (quasi-)space and (quasi-)time.

Some care is needed here: CST is a subtle case in that this approach is often associated with a "growing block interpretation" (see e.g. Wüthrich and Callender (2017))—the view that what evolves is not space but spacetime. However, even if we subscribe to a growing block interpretation of CST, the local split should be conceived of as obtaining between (quasi-)space and (quasi-)time and not between (quasi-)spacetime and (quasi-)time. Indeed, given that the local split is associated with the internal "causal" structure of the causal set (the structure obtained with the application the partial ordering relation to the nodes), it must obtain between (quasi-)space and (quasi-)time. In any case, and independently of whether the split should be best thought of as obtaining between (quasi-)spacetime and (quasi-)time, or (quasi-)space and (quasi-)time, our point remains that CST exemplifies a local split between two structures.

Therefore, all the candidates for a theory of QG include a difference between something quasi-temporal and something quasi-spatial. More

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[29] A partial order is a finite partial order iff, if two events stand in that partial ordering relation, then there must be a finite number of events standing in a partial ordering relation in between them.

[30] All of what its proponents claim is that it eventually allows for recovering Lorentzian invariant structure.

Split between quasi-temporal and quasi-spatial	Approaches
(1) encoded by Lorentz symmetry	perturbative GR perturbative string theory (target space is locally Lorentz invariant) asymptotic safety covariant LQG
(2) not encoded by Lorentz symmetry	
... through a discretization scheme	causal dynamical triangulation
... through a partial order	causal set theory
... through foliation prior to quantization	canonical QG/canonical loop QG

Table 1: Status of the space-time split in different approaches

precisely, they all feature some sort of split that maps onto—or could in principle map onto—the split between space and time present in GR. However, a more fundamental theory underlying GR could lack, in principle, a form of asymmetry between space and time. Indeed, we do not defend that the split between space and time is an *a priori* constraint on the nature of the world. Rather, we observe that our theories, based on empirical evidence and rational theorizing, and aimed at describing the actual physical world, always embed such a split.

Focusing on a classical Euclidean space, as a toy model, opens a window on the conceptual problems that occur in a possible world lacking an inbuilt local asymmetry between space and time. Set up fields and equations on an Euclidean space: The local metric field then takes the form δ_{ab} in suitable coordinates, and the signature is $(4, 0)$.[31] The equations of motion are then locally invariant under Euclidean transformations. Now, assume that this can be done such that a local Cauchy problem is well-defined *even if* the global problem is not well-posed–as has been argued for by Read (2017b). How could a direction, at any point—either at the fundamental level or at some higher level—get marked as a special one? At some point, we must make contact with the physical theories that apply at higher levels. And these theories, after all, do involve such a split. But again, take note that we do not claim that "split free worlds" are impossible but only that these would be radically non-spatio-temporal. Indeed, we would lack the resources to distinguish, even locally, between space and time.[32]

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[31] Or $(0, 4)$, depending on the convention.

[32] In this context, it might also be worth mentioning the Euclidean-Lorentzian signature scenario occurring in certain applications of LQG to cosmology (cf. Bojowald and

3.3 Further Decisive Features of QG

In contrast to the local split criterion, the following features are as a matter of fact often said to emerge, quite radically, from QG (cf. for instance Huggett and Wüthrich (2013)): classicality out of superposition, continuity out of discreteness, a GR structure out of a differently ordered structure (a sort of "geometrical deviation" or "disordered locality"[33]), or a 4D out of a higher dimensional or lower dimensional structure. Although we agree that these conceptual discrepancies are of a radical nature, actually none of these cases threaten the existence of a local distinction between (quasi-)space and (quasi-)time. Let us have a look at the missing features in QG in order to see that they remain consistent with a local distinction between (quasi-)space and (quasi-)time in GR.

Classicality out of superposition One might think that our picture of GR spacetime radically changes once GR spacetime as a whole is subject to quantum evolution. These approaches (call them quantum GR approaches) either (1) build on a foliation of GR spacetimes into spacelike slices (known as the ADM formulation of GR)[34] and then treat the resulting GR-*space* as subject to a quantum evolution (canonical approach) involving evolution into superposition states[35], or (2) directly quantize GR spacetime in a covariant fashion (covariant procedure).[36]

The first case—the evolution of GR-space into superpositions—does not strike us as more bizarre than the generic evolution of the non-spatial spin-up state into a superposition of a spin-up and a spin-down state, i.e. $|\uparrow\rangle\,(t_0) \rightarrow (\alpha\,|\uparrow\rangle + \beta\,|\downarrow\rangle)(t)$ for $t > t_0$.

The second case—the evolution of GR spacetime—can be conceived of in terms of transition amplitudes[37] between GR spacetime slices again (see Rovelli and Vidotto (2014)). Instead of a determinate evolution as in the classical case, there is now

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Brahma (2016); Brahma (forthcoming); see also Huggett and Wüthrich (forthcoming) for a philosophical discussion). The signature of the derivative "spacetime" near singularities—including black hole singularities and the Big Bang singularity—is Euclidean and thus non-Lorentzian. However, since these Euclidean regions are *connected* to Lorentzian regions, what comes under attack here is not the *existence* of a local split between space and time (encoded by a Lorentzian structure), but the *universality* of this split—namely, the fact that it applies everywhere in the cosmos.

[33] See e.g. Markopoulou and Smolin (2007).

[34] This requires restriction to globally hyperbolic GR spacetimes.

[35] Canonical QG and loop QG belong to this category.

[36] This is standardly done by some kind of path integral formulation (cf. CDT and covariant loop QG).

[37] This arguably amounts to a specific stance in the measurement problem already.

a probabilistic evolution from one slice to another—a situation which does not strike us as particularly conceptually challenging either.

Continuity out of discreteness Certain approaches of QG imply that the fundamental structure corresponding to "spacetime" is discrete: It is generally assumed that this is the case for LQG and causal set theory. It is quite trivial that the discrete/continuous correspondence is a problem of its own, with no particular consequence on the existence of an asymmetry between quasi-spatial and quasi-temporal structures. This possible emergence of a spacetime feature (continuity) out of a non-spatio-temporal feature (discreteness), therefore, remains independent of the even more crucial feature of spacetime that we discuss, namely the local asymmetry. Furthermore, asymptotic safety is at least compatible with a minimal physical length (see Percacci and Vacca (2010)). But, note that this discreteness might only be of operational nature. Indeed, it could turn out that this discreteness is not ontological but only epistemological. The appearance of discreteness could arise from our mathematical tools, or from theoretical limitations, in the case of LQG, if LQG is not a final fundamental theory of everything, which is a genuine possibility. Indeed, unlike string theorists, proponents of LQG generally regard their approach as aimed at formulating a theory of quantum gravity proper, not necessarily a final theory of everything.

But if this is what is meant, then note that GR already implies an operational minimal length in spacetimes in which the hoop conjecture[38] applies (which roughly states that any kind of localization of matter in a sufficiently small "hoop" leads to the formation of black holes).

Disordered locality/Non-locality In LQG, some relations of adjacency at the fundamental level correspond to large distance relations at the classical level such that what is local at the more fundamental level described by LQG does not need to directly correspond to something local at the classical level (see for instance Huggett and Wüthrich (2013)). But once again, this feature is orthogonal to the existence (or non-existence) of a local asymmetry between space and time. Indeed since the asymmetry between quasi-spatial and quasi-temporal structures is local, any feature regarding *global* features of the structure under consideration will remain silent on this particular local feature. Furthermore, we might already be familiar with this kind

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[38] Cf. Thorne (1995).

> of disordered locality through non-locality in quantum mechanics, where locality at the level of the wave-function corresponds to some non-locality—or non-separability—at the classical level. Therefore disordered locality, even if afflicting the QG structure corresponding to GR spacetime, remains consistent with a local distinction between quasi-spatial and quasi-temporal structures.

However, other features in certain QG approaches seem to be radically different from those of GR spacetime. In these cases, it is hard to see how exactly to erase the conceptual discrepancy. But, as we shall see, albeit radical, these conceptual discrepancies are fairly less radical than those induced by the non-existence of a local distinction between space and time. Dimensional shift from the usual four spacetime dimensions is such a feature. String theory features additional (compactified) dimensions. At first sight, they seem to be straightforwardly integrable into our phenomenal conception of spacetime—they are simply small and rolled up when zooming out. However, in string theory, even the regular four dimensions might be—provided that they are closed—subject to a duality (see Huggett (2017)). A duality is a formal mapping between the spaces of solutions of two empirically equivalent theories. Interestingly, it has been shown that different string theories defining strings and branes on target spaces with different dimension compactification radius are dual in this sense. Dualities could thus possibly render the so-called target space on which strings are defined in string theory quite different from our regular GR spacetime—the dimensional shift would then amount to more than the simple addition of some extra non-temporal dimensions.[39]

Other approaches like causal dynamical triangulation and asymptotic safety—even more problematically perhaps—predict that random walkers will at higher and higher energy scales move in smaller and smaller (including non-integer fractal) dimensions. Again, it is not straightforwardly clear how to make sense of dimensional reduction.

However, take note that the sorts of dimensional shifts mentioned here occur in settings with a presupposed distinction between space and time. For this reason, we do not take the occurrence of dimensional shifts per se to be in any sense as radical as that of an emergence of a difference between something quasi-spatial and something quasi-temporal.

At the end of the day, the dimensional shift does not bear the same degree of radicality as a potential lack of distinction between something quasi-spatial and something quasi-temporal. Only the rejection

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[39] For a discussion of the possible ontological interpretations of duality more generally cf. for instance Le Bihan and Read (2018).

of the local distinction between space and time would constitute a maximally radical revision. But, as we have argued, all the main approaches to QG accept a principle that does encode a local distinction between something quasi-spatial and something quasi-temporal—namely a distinction between two structures that give rise to space and time as we experience them and measure them with rods and clocks.

4 Conclusion

If one believes that there is a problematic discrepancy between the spatio-temporal concepts used in the derivative spatio-temporal theory and the non-spatio-temporal concepts used in the fundamental non-spatio-temporal theory, one should be interested in privileging the dynamical interpretation of GR spacetime. Indeed, this move narrows significantly the explanatory gap between the two theories, by treating spacetime as being already partially missing in GR. Furthermore, after examining the most popular approaches to QG, we do not find the conceptual discrepancy between GR and the various approaches of QG to be substantive enough to prevent, in principle, a reduction of GR to QG. Insofar as QG embeds a local distinction between two distinct and local quasi-spatial and quasi-temporal structures, this ensures—at least in principle—the possibility to recover the familiar space-time split in relativistic physics from these local separations in the fundamental structure.

Finally, let us conclude with a remark on the relationship between the two moves presented in this paper. In the first part, we argued that, according to the dynamical approach to GR, the chronogeometric significance of the metric in GR is contingent. The reasoning involved however standardly rests on that the equations of motion of a matter field in GR do not need to be locally Poincaré (and thus not Lorentz) invariant. However, this permissiveness may appear, at first glance, to be in tension with the second part of the paper in which we saw that Lorentz symmetry *is* a generic property all approaches to quantum gravity. Rather than concluding that the two moves we introduced are necessarily exclusive, one can simply stipulate a less permissive version of the dynamical approach which requires all matter fields to be locally Poincaré (and thus Lorentz) invariant. This is possible if—as argued for by Menon et al. (2018)—the coincidence of symmetries of the metric field and the symmetries of the matter fields is not sufficient for the metric to have chronogeometric significance. In any case, whether mutually compatible or exclusive, each of these two moves eases the way for a narrowing of the explanatory gap between GR and QG. In a slogan, spacetime is already partially missing in GR, and/or still partially present in QG.

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