# The Property Theory of Space and Non-Spacetime Quantum Gravity Theories

Edward Slowik

Abstract: This essay will investigate the spatial ontology debate with regards to those quantum gravity theories that posit non-spatiotemporal elements from which spacetime emerges. As will be argued, whereas substantivalism and relationism both fail to capture the ontology of these non-spatiotemporal theories, such as causal set theory or loop quantum gravity, the largely neglected property theory of space (spacetime) stands out as the best ontological classification, and it also accords with the standard ontological division into substances, properties, and relations. Other approaches, such as spacetime structural realism of spacetime functionalism, will also be shown to be inadequate in comparison with the property theory.

## 1. Introduction

The rise in importance of a class of quantum gravity (QG) theories that conjecture that the spacetime of general relativity arises from a more fundamental level of non-spatiotemporal entities has posed a significant challenge for spatial ontologists. In particular, the traditional dichotomy— whether space is a unique independently existing entity, substantivalism, or merely the relations among material entities, relationism—is beset by severe obstacles in any attempt to incorporate these non-spacetime QG theories under its two-part classification. Nevertheless, there is a long neglected conception of space's ontology that is uniquely suited to capture the general details or broad outline of these non-spacetime theories, namely, the property theory of space. As will be argued, if one starts from the traditional ontological postulate that all physical existents fall under the categories of substance, property, or relation, then the property theory of space provides the natural classification for these emergent spacetime theories since spacetime is regarded as an emergent effect or property of a system of interconnected non-spacetime elements. Other approaches that have been recently discussed in this context, such as spacetime structural realism and spacetime functionalism, will also be assessed, although the inability of these concepts to provide a clear ontological assessment, as well as explain how they differ from the standard metaphysical categories, will be shown to greatly diminish their value and plausible application in this metaphysical debate.

In section 2, an overview of the difficulties associated with employing the standard substantivalism versus relationism dichotomy to non-spacetime quantum gravity theories will be analyzed, whereas section 3 will present the advantages that a property theory of space can offer for the classification of non-spacetime theories, along with a discussion of the three traditional ontological classifications, namely, substances, properties, and external relations. In section 4, the limitations of two recent interpretations of non-spacetime quantum gravity theories, structural spacetime realism and spacetime functionalism, will be briefly explored, whereas the concluding section 5 will offer a concise synopsis of the merits of the property theory.

2. Substantivalism, Relationism, and Non-Spacetime Quantum Gravity Theories.

Non-spacetime quantum gravity (QG) theories are a class of approaches to unifying general relativity (GR) and quantum mechanics (QM) that do not presume the four-dimensional metrical and topological spacetime structure of GR as the background for the construction or operation of the basic elements of the QG theory. Rather, spacetime is itself regarded as an emergent effect of the interconnections of these non-spatiotemporal elements. In what follows, causal set theory (CST) and loop quantum gravity (LQG) will serve as the basis of the discussion of the ontology classification of non-spacetime QG theories. Prompted by the discovery that the causal structure of GR can determine the geometry of that theory (up to a conformal factor), CST employs a causal ordering of a discrete set of elementary events to capture the spacetime structure of GR. The causal ordering is a partial ordering based on a "causal precedence" relation among the basic non-spatiotemporal elements (see, e.g., Dowker 2005). Whereas quantum theory has yet to be incorporated into CST, LQG starts by quantizing the metric of GR using a discrete quantum substructure of spin networks, the latter roughly defined as an abstract graph structure with spin representation for its nodes and links, such that the classical spacetime metric of GR is then regarded as an emergent effect of the interconnections of the non-spacetime spin networks (see, e.g., Rovelli 2004). For both theories, the interconnections among the fundamental elements are not spatiotemporal, and thus they pose a significant challenge for the standard ontological dichotomy represented by substantivalism and relationism.

*2.1. Substantivalism.* There are, to the best of our knowledge, no extant substantivalist interpretations of CST, but LQG has received a few, and these can be categorized into two different approaches. The first appears to be a continuation or extension of the debates between substantivalists and relationists on the status of GR's metric/gravitational field, *g*, into the realm of LQG's quantization of *g*. On the one hand, GR substantivalists lean heavily on the metrical aspect of the *g* field, and insist that relationism is inadmissible given the possibility of matter-less vacuum solutions to GR's field equations. On the other, GR relationists regard *g* as akin to other physical fields, such as the electromagnetic field, and note that *g*, unlike the traditional conception of absolute space offered by Newton (2004, 21), can interact with other physical fields. As Rovelli argues, "[i]n general relativity, the metric/gravitational field has acquired most, if not all, the attributes that have characterized matter (as opposed to spacetime) from Descartes to Feynman: it satisfies differential equations, it carries energy and momentum, and, in Leibnizian terms, it can act and also be acted upon, and so on" (1997, 193). This dispute, while possibly unreconcilable, is reflected in some of the pro-substantivalist interpretations of LQG offered by Norton (2020). Yet, since the spin networks and their operations are often characterized as quantum states of the gravitational field, a substantivalist reading seems less plausible in the context of LQG than for GR's metric field. In short, spin networks are not a unique *spatiotemporal entity* that exists prior to, as well as in the absence of, all material/physical entities and processes, as would need to be the case for a substantivalist classification. Rather, these "chunks of space" are quantum states that issue from quantum entities (i.e., the quantum field and its physical quantities). Additionally, this first strategy for defending substantivalism would seem to be implicated in those interpretations (e.g., Earman 2006, 21), that claim that the classical spacetime of GR has merely been replaced in LQG by a quantum spacetime, a maneuver that then allows one to opt for a substantivalist reading of that quantum spacetime, as well as possibly deny that spacetime has even emerged at all in LQG

(Earman 2006 does not appear to take these last two steps, but Norton 2020, 24, admits these possibilities).

The second LQG substantivalist strategy also takes a cue from the ontology debates in GR, in particular, those versions that single out the point manifold, *M*, as the substantivalist entity rather than *g*. In the standard formulations of LQG, the manifold is required to form abstract spin networks, or s-knots, via equivalence classes of spin networks formed by spatial diffeomorphisms, hence the GR manifold substantivalist can insist that their ontology has not been replaced in LQG. This argument is undermined, however, if LQG can dispense with the point manifold by substituting an algebraic or combinatorial replacement, which is a tactic employed in Rovelli's constructions (2004). In addition, while manifold substantivalism in GR has often been criticized as inadequate to the task of representing spacetime, since it lacks metrical and causal structure (Hoefer 1996), a greater problem in the context of QG resides in the fact that the continuous structure of the manifold seems inconsistent with the discrete ontology of LQG's *QM-based* spin networks. On Rovelli's estimation, the geometric view of space centered on spatial points must give way, in QG, to an "the algebraic, or 'spectral' one, centered on the algebra of dual spectral quantities", since "continuous spacetime cannot be anything else than an approximation in which we disregard quantum noncommutativity" (2004, 10). A more plausible candidate for manifold substantivalism as regards QG theories would likely be those older quantization strategies that attempted to split the metric of quantum field theory into a continuous fixed background structure and a dynamical component that relies on perturbation techniques. Yet, those approaches were nonrenormalizable, and Rovelli comments that the "unphysical assumption of a smooth background [in those theories] may be precisely the cause of the ultraviolet divergences" (also, "[since] the structure of spacetime at the Planck scale is discrete. . . physical spacetime has no short-distance structure at all", 12). Finally, if one compares the role of diffeomorphism invariance in GR and LQG, the former offers a much better case for manifold substantivalism than the latter. Fields, such as stress-energy, are defined on the points of the manifold in standard GR, with diffeomorphisms only affecting the identity of the points relative to those shifted fields. The pivotal role of the manifold as the foundation for these fields remains, since as Earman has argued, "fields [in GR] are not properties of an undressed set of space-time points but rather properties of the manifold *M*, which implies that fields are properties jointly of the points and their topological and differential properties" (1989, 201). The situation in LQG is different, since that theory does not start from a tensors on manifold conception, but with a QM-based spin network, an abstract graph structure that, on its own, does not require a spacetime manifold (as Rovelli notes, "A spin network state does not have a position. It is an abstract graph, not a graph immersed in a spacetime manifold", 2004, 20; see also section 3). One "embeds" the spin networks in a manifold to obtain the abstract spin networks required for the theory via diffeomorphisms, but that strategy is consistent with a modal relationist outlook, since one can view the active transformations on the manifold as involving relations among "possible spin networks". That is, just as a modal relationist in Euclidean space, who is restricted to only a finite number of local bodies, can appeal to "possible bodies" in order to capture the space's global topology (without recourse to a pre-existing space), an LQG modal relationist can invoke the very same stratagem in explicating the role that diffeomorphisms play (and thus obviate the need to accept a pre-existing manifold).[1]

*2.2. Relationism.* While the substantivalist interpretations of non-spacetime QG theories are rare, a greater number of assessments have sided with relationism, although the type of relationism proposed typically has little in common with the traditional conception, often associated with Leibniz and Mach, that is based on relational states of position and motion among bodies (i.e., the claim that the only meaningful states of motion are the relative velocity and the relative acceleration among bodies). Rather, the relationist classification of QG theories seems predicated on accepting a restricted conception of ontology that admits substantivalism and relationism as the only alternatives, and thus relationism automatically follows if substantivalism is rejected. This outlook, namely, that "if it's not substantivalism, then it must be relationism", is evident in various works by Lee Smolin on non-spacetime QG theories, e.g., Cortês and Smolin (2014, 26), who correlate CST's causal structure with "relational spatio-temporal properties", and it forms the basis of the Norton's (2020) analysis of relational LQG options. Yet, while granting that this interpretative approach is not inconsistent, it does seem inadequate given the numerous alternative ontologies that also reject substantivalism (as will be discussed in later sections).

Nevertheless, spacetime relationism is strictly incompatible with a theory that posits the emergence of spacetime from non-spatiotemporal elements, such as CST or LQG. As presented in Earman (1989, 12), a major tenet of relationism is that "[s]patiotemporal relations among bodies and events are direct; that is, they are not parasitic on relations among a substratum of space points that underlie bodies or space-time points that underlie events". While CST does not rely on a substratum of spatial points (and this holds true for LQG as well, if the manifold can indeed be replaced with an algebraic equivalent, as mentioned above), the spatiotemporal relations among the basal elements in CST and the spin networks in LQG are not direct. Spacetime comes about from the causal connections in CST and the adjacency relations in LQG as a higher level emergent or supervenient feature or effect. If the spatiotemporal relations in these theories were directly among the non-spatiotemporal elements, then those non-spatiotemporal elements would, conversely, be spatiotemporal, i.e., those elements would be present in spacetime, just as bodies are present in spacetime under ordinary spacetime relationism. This aspect of non-spatiotemporal QG theories is confirmed by the "many-to-one" relationships between the causal structure of the elements in CST and the emergent spacetime, and the configuration of spin networks in LQG. In CST, different casual set structures (among the non-spacetime elements) can give rise to the same emergent spacetime, hence, many-to-one, but some structures may fail to result in any emergent spacetime. As Wüthrich explains, "while a single emergent entity [spacetime] can arise from distinct fundamental structures [of causal sets], one and the same fundamental structure cannot help but give rise to one specific emergent entity, if it does at all" (Wüthrich 2019, 319-320). If, on the other hand, the spatiotemporal relations among the elements were direct, then the relationship between the causal set structure and the emergent spacetime would be one-to-one, and not many-to-one, and there would be no cases

[1] Whether or not modal relationism is a successful ontology is a separate issue, of course, but there does not appear to be any reason to rule out recourse to modality in this case if also accepted for standard spacetime theories.

where the spacetime fails to emerge at all. In LQG, there is a similar divergence between the structure of the spin networks and the emerging spacetime in that the adjacency relationships of the former are not necessarily preserved in the latter: "parts of the spin network that may be connected by an edge and thus are fundamentally adjacent may end up giving rise to parts of emergent spacetime which are spatially very distant from each other as judged by the distances operative at the level of emergent spacetime" (321; in addition, the basis of the spin networks in a Hilbert space will be in a superposition of states "that will not have any determinate geometric properties"). Once again, if traditional spatiotemporal relationism were in effect, then there would be no divergence between the adjacency relations among the spin networks and the emergent spacetime.

Among the commentators that question the relevance of the substantivalist-relationist dichotomy for interpreting non-spacetime QG theories, Wüthrich offers an additional obstacle for the relationist reading in that "[t]he fundamental structures of quantum gravity are not obviously material (324-325), a claim that seems to implicate those scenarios in LQG where the spin networks lack the requisite quantum excitations for the existence of matter (a point also raised by Rickles 2005, 426–427). Yet, while the traditional relationism predicated on extended bodies and their relations is obviously endangered by these possibilities, advocates of the field-based form of relationism will insist that the spin networks of LQG involve the quantum field and its energy, as will CST when quantum theory is eventually added. That is, like the relationist interpretations of the gravitational field in GR noted above, the relationist can insist that the quantum energy field is itself a physical (if not necessarily a material) entity, and thus relationism is saved. Nevertheless, resurrecting the ill-fated dispute over the ontological status of GR's metric/gravitational field is not an ideal defense (see section 2.1), and it would only support relationism if one were forced, once again, into the false dichotomy between substantivalism or relationism. The next section will offer a better ontological option.

## 3. The Property Theory of Space in the Non-Spacetime Quantum Gravity Setting.

If one does take the erroneous stance that the substantival-relational debate exhausts the possibilities for spatial ontology, then it is tempting to view this distinction as a reflection of the more general substance-property dichotomy in ontology, with substantivalism aligning with the substance view and relationism with the property view. But this reading only works if the category of relations is included in the property category, such that there is no difference between properties and relations, or among different types of relations, which is quite problematic given their often different status and function. For our purposes, the development in in twentieth century metaphysics of the distinction between internal relations and external relations is of a particular importance, where the former are based in part on internal or intrinsic non-relational features of an object (monadic non-relational properties), and the latter are not: e.g., "the sibling of" is an internal relation since one must have the correct internal properties (a particular genetic code, in this case) to bare that relation to another person, whereas the spatiotemporal relation of "three meters to the left" only requires the existence of the relata (with no specific monadic properties necessitated for the relation). In short, the consensus among contemporary expositions of the metaphysics of relations regards spatiotemporal relations as purely external (e.g., Armstrong 1989, 43-44; Lewis 1986, 62). Consequently, the best modern taxonomy in general metaphysics that can serve to assess the ontology of the substantival-relational dichotomy should comprise the tripartite division between substances, properties (which include internal relations), and external relations, with substantivalism and relationism correlated with the first and third entries, substances and external relations: substantivalism posits external relations between spacetime and matter, both comprising substances, whereas relationism employs external relations exclusively among material bodies. The spatial ontology analogue to the second option, properties/internal relations, is, of course, the property theory of space (and time). In order to avoid confusion given the myriad of interpretation in the metaphysics literature, "substance" and "property", as used in the proceeding analysis, will be given a very broad characterization, equivalent to "subject" and "predicate", with the main emphasis placed on the ontological dependence relationship between the underlying "subject" and the "predicate" that it possesses or manifests.[2] A substance is thus required to instantiate the property, and it retains a degree of independence from its properties in the sense that it can remain the same while the properties vary, whereas properties are contingent and cannot exist apart from the substance.

While many explorations of spatial ontology only offer a brief critical discussion (e.g., Earman 1989, 13-15; Belot 2000, 576), there have been several advocates of the property theory, namely, Sklar (1974), Teller (1987, 1991), and Dieks (2001a, b). Most of these versions of the property theory are constructed with classical gravitation theories in mind, with the envisioned monadic property identified as an internal feature of a macrolevel body, e.g., acceleration for Sklar (1974, 230), and spatial location for Teller (1987, 427). These strategies are not suitable in the context of non-spacetime QG theories, needless to say, but Dieks' version of the property theory, which offers a lengthy treatment of non-relativistic QM, has the potential to incorporate the non-spacetime cases, as will be examined below. Overall, the main criticisms raised against the body-based version of the property theory of space is that it appropriates the same mathematical spacetime structures as the substantivalist but without the same ontological commitment, (e.g., Earman 1989, 127).

Nevertheless, non-spacetime QG theories represent a totally different setting, along with a host of possibilities, than the classical spacetime and macrolevel body scenarios employed by previous version of the property theory. Indeed, given the standard metaphysical ontology of substances, properties (which includes internal relations), and external relations, spacetime emergence naturally falls within the property category—and for the obvious reason that emergence is a property conception. In the contemporary literature, the technical definition of emergence that is normally offered concerns an "emergent property", e.g., O'Conner (2020), Mclaughlin (2008, 93), Gillett (2016, 176), although Wilson (2021, 2) favors the term "features" (which she further characterizes as "states, properties, behaviors, or other ways for a particular to be"). The British Emergentists of the early twentieth century likely began this tradition, with Broad's definition of emergence possibly serving as a template for later approaches: "the characteristic properties of the whole R(A, B, C) [where R signifies the joint composition of A,

[2] See, Loux and Crisp (2017, chapter 3) on the varieties of substance and property concepts, and Takho and Lowe (2020) on ontological dependence. External relations are also ontologically dependent on entities, but purely external to those entities, as described above. Finally, in order to avoid potential confusion with substantivalism, the ensuing discussion views both internal and external relations as ontologically dependent on physical/material entities alone (since one might claim that spatiotemporal relations are properties of a unique non-material substance called "spacetime").

B, and C] cannot, even in theory, be deduced from the most complete knowledge of the properties of A, B, and C in isolation" (Broad 1925, 61). Furthermore, emergence is not an *external* relation between a fundamental layer of ontology and an emergent entity, since that would imply that the QM-based properties/variables of the entities of that underlying ontology, whether LQG's spin networks or CST's basal elements (once QM is added), play no role at all in the emergence of the higher-level entity (since external relations, as noted above, are purely external, and thus both levels of ontology, fundamental and emergent, would be fully independent of each other, contra emergence). Likewise, while one might claim that the emergent spacetime is an entity of sorts, it is still the case that it is a property of that underlying ontology since the emergent spacetime only exists as long as that underlying QG ontology exists; hence, given this ontological dependence relationship, the emergent entity fails to meet the traditional independence criterion for substances. The property theory of space is, accordingly, the natural, if not inevitable, home for the classification of non-spacetime emergent QG theories given the available alternatives for spatial ontology, i.e., if one relies on the standard tripartite division in metaphysics between substances, properties (including internal relations), and external relations. Indeed, one of the most notable aspects of CST and LQG discussed in section 2.2 above—namely, the many-to-one relationship between the fundamental non-spacetime entities and the emergent spacetime, or the possibility that some arrangements of these entities will not result in a spacetime at all—is perfectly captured by the metaphysics of properties, since properties are commonly viewed as (i) contingent features of an underlying substance (which thus admits circumstances where the property, in this case, spacetime, fails to obtain), and (ii) the same property can be instantiated by different substances or different arrangements of the parts of the same substance (which thus accounts for the many-to-one relationships in these QG theories).

Furthermore, the coupling of the property theory of space to the metaphysics of properties/internal relations has an added advantage in that it captures the function and status of position in QM far better than its rivals, substances and external relations. As argued in Sklar (1974, 229), both substantivalism and relationism in the context of classical physics view position (velocity, acceleration) as an external relation between, respectively, substantival space or other material entities. But QM treats position more like an internal property of the system, much like its other internal properties, such as spin or momentum. As Dieks explains:

> [T]he Hilbert space formalism does not start from a space-time manifold in which particles are located. . . . Rather, "position" is treated in the same way as "spin" or other quantities that are direct particle properties: all these quantities are "observables", represented by Hermitian operators in Hilbert space. In particular, particles generally do not have a well-defined position in quantum mechanics, just as they generally do not possess a well-defined value for their spin, momentum, etc. (Dieks 2001a, 16)

For instance, given the complementarity of position and momentum under the traditional Copenhagen interpretation, a quantum system can even lack a spacetime position in some experimental arrangements, a scenario that would appear to raise havoc for the conception of position as an external relation between the quantum system and either substantival space or other material particles. Since an external spatiotemporal relation does not depend on the internal properties of its relata, a quantum particle that exists yet fails to instantiate a spatiotemporal relation to substantival space or other particles seems a much more problematic, if not contradictory, state-of-affairs than if position is viewed as a contingent property of a quantum particle (that can thus fail to obtain in certain cases). In addition, while some interpretations of non-relativistic QM insist that quantum systems always possess a position (trajectory), and quantum field theory relies on Minkowski spacetime (see, e.g., Lam and Esfeld 2013), there have been a number of interpretations of algebraic quantum field theory that aim to replace the point manifold of Minkowski spacetime by employing overlapping sets of subalgebras representing physical subsystems. On these approaches, "the structural properties of the physical system, encoded in its 'phase space' [Hilbert space], are used as the primary data", while "[t]he spacetime manifold is secondary, and has a role that is analogous to that of [a] colour space" (Dieks 2001b, 238).

Likewise, the hypothesis put forward in Esfeld (2021), that distance (metric structure) is the "world-making relation" required to explain how QG's fundamental elements can be meaningfully united, not only begs the question against the non-spacetime proposals, but various strategies have been advanced that employ the entanglement of quantum properties of LQG's spin networks to serve the role of the world-making relation rather than distance. The entanglement in question involves the polyhedral-shaped surfaces that border a spin network, and which lie adjacent to the polyhedra of the neighboring spin networks. As Jaksland (2021, 18) argues, "entanglement is an extrinsic property; something is entangled with something else", and "entanglement shares the universality of distance: distance can relate everything in space to everything else and likewise, entanglement can obtain between any quantum degrees of freedom". The reference to "extrinsic properties" in this quotation correlates with internal relations, and not external relations, for the entanglement involves the polyhedra belonging to different spin networks that share a link in a graph, and thus the internal properties of the two spin networks are essential to their entanglement relationship. This approach may ultimately fail, on theoretical or evidential grounds, of course, but it provides a coherent physics-based strategy for explaining the emergence of metric structure from a non-spacetime fundamental ontology. While there currently has been much discussion of the prospects for conceiving a non-spatial process that can connect a collection of basic elements to bring about spacetime emergence, the recourse to entanglement would appear to represent just such a process (as would phase transitions, see section 4 below).

Following up on this last point, another beneficial feature that the ontology of properties/internal relations offers the proponents of non-spacetime quantum gravity theories is the option to defend a full-fledged notion of *ontological* emergence, as opposed to the more limited, and partly epistemological and explanatory, reliance on emergence as a species of theoretical reduction. On the basis our three-part ontological distinction, emergence as a form of ontological dependence relationship correlates with properties/internal relations, and not substances (which are ontologically independent) or external relations (since the relata of external relations are ontologically independent of the relation). Overall, various proponents of non-spacetime QG theories do seem to favor an ontological reading of emergence for theories such as LQG and CST, and they often employ the property concept in their description: e.g., "[o]ne has to accept a multi-level ontology of some sort, in which both fundamental and emergent properties and entities are real in an appropriate sense", with a corresponding "radical revision of metaphysics . . . concerning what is meant to be *real* (which has to be independent to some extant from spatiotemporal properties)" (Oriti 2021, 26). Once again, the only plausible candidate in the traditional three-part metaphysical division that would accommodate this type of depiction of an emergent spatiotemporal reality is the properties/internal relations classification.

One might respond, however, that there are alternative property conceptions that differ significantly from the standard three-part classification in that they reject the assumption that properties require a substance for their instantiation. In particular, the bundle theory of properties postulates a special type of relation that ties all of an object's properties into the "bundle" which constitutes that object, where that unique relation can be characterized as "an unanalyzable or ontologically primitive relation" that can "be explained informally as the relation of occurring together", and "whose attributes enter into only contingently" (Loux and Crisp 2017, 88). The special relation, in the context of non-spacetime QG, cannot be colocation or any other that involves spatiotemporal notions, needless to say, which thus raises concerns over its applicability in this case. Furthermore, this metaphysical strategy is susceptible to the counterargument that the special relation is playing the role of a substance, i.e., an ontologically fundamental basis which "possesses" contingent properties; or, more generally, that the bundle theorist is still committed to a subject-predicate ontology (see, Rickles and Bloom 2016, 105, n.9, who make this last point). Likewise, the status of the special relation, when translated into the traditional metaphysical scheme, would correlate with properties/internal relations given QM entanglement and its holistic implications, rather than as purely external relations. Le Behin (2018) offers a modified form of bundle theory for non-spacetime QG theories that relies on a mereological sum of logical parts of a maximal structure (identified as the whole cosmos) in order to secure the non-spatial bundling relation. This proposal supposedly obviates the need for different ontological levels as well as an emergence relation, but it has been criticized on the ground that part-whole composition (i.e., where non-spatial parts are the building blocks that compose space) is inadequate to the task of explicating spacetime emergence (see, Baron 2021). In Baron and Le Bihan 2022, however, an alternative mereological conception is put forward for CST which seems much closer to the emergent property conception advanced in this essay, for they argue that "[s]pacetime thus exists because causal properties emerge via the mereological arrangement and binding" of CST's basal elements, their ordering relation, and a mereological fusion and parthood relation (2022, 52). As an example, they recite the non-QG case of a diamond's emergent causal properties: "A diamond is hard even though *hardness* is not a property of any of the molecules that compose it. The properties of the whole may be completely novel or *emergent* compared to the properties of the parts" (45). On the whole, and leaving aside its deviations from traditional substance-property metaphysics, conceiving space as a bundle or mereological sum of QM properties remains within the province of a property theory of space *if* the alternatives are substantivalism and relationism: QM entities/processes do not constitute a unique spatiotemporal substance but are physical/material, contra substantivalism; and the problem raised for relationism in section 2.2 still holds, namely, that there is no direct one-to-one correlation between the non-spacetime level (in this case, a bundle of non-spacetime QM properties) and the emergent spacetime level (which is also a bundle of QM properties, but now constituting spacetime). A central commitment of the property theory of space is the ontological dependence relationship, and that relationship is not altered, at least in the case of non-spacetime QG theories, if the part-whole relationship replaces the substance-property relationship. Put differently, on a bundle interpretation, the lack of a one-to-one correspondence between the two levels signifies that some bundles of non-spacetime properties will bring about an emergent spacetime, and some will not, and that form of ontological dependency relationship is best captured by the property theory of space, and not substantivalism or relationism.

## 4. Structuralism, Functionalism, and Spatial Ontology.

A further option in the spacetime ontology debate is structuralism, an approach that Wüthrich claims is "most naturally adapted to the present context [of non-spacetime QG theories]", although "the relevant structure in our ontology will not be straightforwardly spatiotemporal as is again assumed in the traditional formulation of spacetime structuralism" (2019, 325). As a species of structural realism, spacetime structural realism accepts a realist commitment to the invariance or preservation of certain theoretical structures across theory change, rather than on a realism focused on the specific entities in each theory. The ontology postulated by spacetime structural realists in the case of GR is difficult to assess, but it might be regarded as a sort of hybrid of sophisticated versions of both substantivalism (since it rejects manifold substantivalism for the metric field form) and relationism (since the metric is claimed to be a physical field; see, Dorato 2000). Interpretations of structural realism in a QG setting would thus seem to be saddled with the same problems as diagnosed for both substantivalism and relationism as discussed above (section 2), with the relationist criticisms standing out as more relevant given the QM basis of these non-spacetime theories.

At this point, it is useful to examine more closely the metaphysics of substances, properties/internal relations, and external relations with the various forms of ontic structural structuralism (OSR) that have been proposed in the context of QM and QG, for structural realist sometimes claim that their ontology is preferable to the standard metaphysical scheme. As described in section 3, an internal relation is one that is based on some internal feature of the relata, such as a person's intrinsic genetic property establishing the basis of the "sibling of" relation to another person. This "sibling of" relation cannot be the cause of the intrinsic genetic property possessed by the two individuals; likewise, the intrinsic genetic property remains even if one of the two individuals ceases to exist or could somehow change their genetic state. Hence, it might seem at first glance that all forms of ontic structural realism (OSR) will fall short of the property/internal relation classification since OSR deems the relation to be at least as ontologically robust (or non-reductive) as the relata. But QM entanglement, where a pair of entangled particles behave as if they are two parts of the same thing, does allows a revised form of a properties/internal relations metaphysics to fit the OSR outlook. Returning to our "sibling of" example, quantum entanglement as applied to this case would entail that a change in one of the individual's internal genetic structure results in a change in the other's genetic property, and thus quantum entanglement qualifies as a special type of property/internal relation, one in which neither the relata nor relation are more basic or fundamental. Consequently, if the class of properties/internal relations incorporate quantum entanglement relations along these lines, then the moderate (or non-eliminative) varieties of ontic structural realism, where the relation and the relata are on an equal ontological footing, would accord with the property/internal relations conception, as would the eliminativist form of OSR (more on this shortly). Finally, entanglement is inconsistent with an external relation construal, since, as was noted previously, the internal values of a particle's spin or momentum serve as the relata, unlike external relations (which only depend on the existence of an entity, and not on its monadic properties).[3]

In response, proponents of OSR may reject the property/internal relations account of QM and QG put forward above on the grounds that the standard subject-property metaphysics that undergirds our three-part distinction (among substances, properties, and external relations) is simply no longer suitable or applicable given these revolutionary, non-classical theories. Proponents of eliminativist OSR have thereby often adopted a monistic or holistic conception of QM's ontology, wherein the individuality of particles dissolves into the field encoded by the group structure representation (e.g., Ladyman 2009, French 2014), but this maneuver renders structuralism vulnerable to a similar criticism as raised previously for the bundle theory (see section 3). If viewed from our three-part metaphysical perspective, this monistic field interpretation equates with a substance conception, with the particles or entanglement relations playing the role of internal properties of that quantum field "substance". Rickles and Bloom demonstrate this point by insisting that structure is irreducible, while relata are contingent: "relational structures are prior to things that might 'emerge' from such structures" (2016, 102, n.3)—but posterior contingent things that emerge from prior irreducible things are, respectively, properties and substances. In short, subject-predicate metaphysics is not only difficult to evade, but the intended replacement would seem to simply re-erect the older metaphysical categories but with a new nomenclature.

Furthermore, both eliminative and non-eliminative versions of OSR face an obstacle as regards the manner by which their structural ontology of non-spatiotemporal basic elements brings about GR's spacetime. If, as discussed in section 2.2, there are many structural arrangements of the basic elements in CST and LQG that fail to give rise to spacetime, then what accounts for those failures (as well as successes)? Put simply, if the structure is either ontologically prior to, or "on a par" with, its non-spacetime basic elements, then what converts that non-spacetime structure and its elements into a spacetime ensemble? The only plausible or coherent answer, it would seem, is that there is some *property* of that structure and its elements which is operative in those cases where spacetime emerges, and not operative in those instances where spacetime fails to emerge (and the same for the many-to-one outcomes, i.e., some property of the various non-spacetime ensembles that result in only one emergent spacetime). OSR thus faces the following dilemma. Given the eliminative form of OSR, the property that converts the non-spacetime structure to a spacetime structure would have to be an internal property of that structure, since they conceive structure as akin to a holistic entity, thereby vindicating both the property/internal relations account over its rivals (substances, external relations) in explicating spacetime emergence, as well as demonstrating, as argued above, that this radical form of structural realism treats structure as akin to a substance that possesses properties. For the non-eliminative brand of OSR, on the other hand, while it could be argued that the relata are responsible for the conversion of the structure to spatiotemporal status (possibly via QM

[3] Interpretations of QM and QG that posit an individuating essence or haecceity, or a bare numerical diversity or plurality criterion (see, e.g., Lam 2016), would also remain within the property/internal relations category, since they are neither substances nor external relations but internal monadic states. Importantly, Wüthrich (2020, 252) argues that the causal structure of CST does not equate with external relations in Lewis' sense, but with his conception of internal relations instead.

entanglement), that tactic would also vindicate the property/internal relation outlook since the relata's internal properties are the source of spacetime emergence. The structuralist might once again dismiss the quandary just outlined as emblematic of the limitations of the standard substance-property ontology, but then it is incumbent on the part of the structuralist to provide an answer as to how spacetime emerges from structure, and how its conception of structure differs from the standard ontology.

For the property theorist of space, conversely, there are several options for a viable candidate to explicate spacetime emergence: besides entanglement, which is a property/internal relation of the relata/particles or the holistic field (relation and relata), the possibility that a non-geometric phase transition triggers spacetime emergence has also been discussed with respect to LQG and CST (see, Oriti 2021, 27-32), where the phase transition could be viewed, once again, as a property of either the relata alone or both the relation and relata—with the latter combination thus possibly viewed as a unified substance that possesses or manifests the phase change property. The phase change property is likely a causal power of the non-spacetime entities, but causal powers fall under the properties/internal relations classification, for they are neither purely external relations nor substances. The property theory of space is, in other words, the best, and possibly the only, theory that can successfully and coherently explicate spacetime emergence (given the choice between substantivalism, relationism, structural realism, and the property theory), whether that property belongs to individual relata connected through internal relations or is internal to a holistic substance.

The pervasiveness of the subject-predicate (substance-property) conception may also be evident in the most recent entry in the spacetime ontology debate, namely, spacetime functionalism, an approach that naturally draws comparisons with its better known philosophy of mind counterpart. Originally developed to designate which particular structure within a specific spacetime theory best captures the function of spacetime (Knox 2013), that approach has been adapted to defend non-spacetime QG theories from the charge of "empirical incoherence", where the ground of that allegation, put roughly, is that a theory's fundamental entities must exist in spacetime (e.g., Lam and Esfeld 2013, 290). The application of spacetime functionalism to QG aims to defuse this problem by insisting that the ontology of non-spacetime QG theories can play the functional role of spacetime, and thus empirical coherence can be regained without the need to posit a separate spacetime entity (see, e.g., Lam and Wüthrich 2018). One of the two brands of spacetime functionalism is realizer functionalism, which places the emphasis on the specific entities/properties of the non-spacetime ontology that instantiate the role of spacetime. However, utilizing Ramsey-Lewis semantics, which (in this case) explicitly defines GR's theoretical terms in relation to the non-spacetime QG theory, Yates has argued that any non-spatiotemporal entity/property that plays the role of spacetime is, in effect, in spacetime, thus undermining the alleged emergence of spacetime. The problem, put succinctly, is that the functional property and the physical property that fills that functional role "are instantiated in the same object" (Yates 2021, 147).[4] In order to avoid this dilemma, which we will dub the "spatial presence" problem,

[4] "If Ramsified GR terms succeed in referring to the fundamental properties of a theory like LQG or string theory, then each GR role is (approximately) occupied by such a property. But in that case, the fundamental properties in question can be identified with GR spatiotemporal properties, in which case the relevant fundamental ontology can't be non-spatiotemporal" (Yates 2021, 142).

Yates favors the adoption of the second functionalist strategy, role functionalism, which invokes a distinction between the non-fundamental entities/properties (local beables) of GR that instantiate the functional role, and the fundamental non-spatiotemporal entities/properties of a QG theory that bring about those non-fundamental entities/properties in GR: "The fundamental particulars don't have ordinary spatial or temporal properties and relations, but perhaps local beables [of GR] can have their spatiotemporal properties in virtue of the non-spatiotemporal properties and relations of their proper parts" (and where "local beables need not instantiate the same locality properties as their fundamental proper parts", 148). Presumably, this role functionalism strategy accepts different ontological levels, or at least an ontological distinction, between the fundamental and the non-fundamental entities/properties, since otherwise it is difficult to comprehend how the spatial presence problem raised for realizer functionalism can be avoided in this case as well. That is, if the non-fundamental entities/properties of GR that are in spacetime are theoretically reducible to the fundamental QG basis in full, and thereby lack any ontological distinction compared with the fundamental level, then those fundamental entities/properties are, likewise, in spacetime. Regardless of this debate, what remains clear is that role functionalism in QG depends on a stratified conception of the fundamental and the emergent non-fundamental entities/properties, with the latter instantiating spacetime roles, but not the former—and the closest approximation to this scheme within the traditional ontological categories is the property/internal relations account (and not external relations or substances), and the property theory of space (and not substantivalism or relationism), as first argued in section 3. The ontological dependence relationship that is intrinsic to the familiar subject-predicate conception—with emergent GR spacetime as the predicate (property) of the QG subject, i.e., the basic elements and interconnections of CST and LQG—is therefore not precluded by recourse to spacetime functionalism, but may actually require it in order to evade the spatial presence problem (under the role functionalist strategy, that is).

Yet, whether spacetime functionalism can provide a successful account of *ontological emergence*, as opposed to a theoretical reduction construal, is open to debate, and part of the rationale for this uncertainty pertains to its inevitable comparison with functionalism in the philosophy of mind. Some of the main exponents of QG spacetime functionalism are adamant that there is no "hard problem" of spacetime emergence as there is for mind functionalism, i.e., that an emergent spacetime will not possess qualitative aspects or other features that are left unexplained once a successful, complete QG theory has been established, unlike the alleged case of mental "qualia" (e.g., Lam and Wüthrich 2018). In the philosophy of mind, there are a large class of competing theories (such as biological naturalism, epiphenomenalism, or the many versions of property dualism) that reject the main functionalist notion that a mental state is determined only by its functional relationships within a cognitive system (relations among sensations, behavior, and other mental states); rather, mental states possess irreducible properties that are not amenable to a functional analysis. Hence, an emergent spacetime, conceived ontologically, would seem much closer to these non-functionalist theories of the mind than the functionalist proposals. If, for example, one envisions spacetime emergence as ontological in the sense just discussed for role functionalism, where the non-spatiotemporal elements possess different properties than the emergent entities/properties at the macrolevel that instantiate the spacetime functional role (e.g., the non-spatiotemporal elements have foundational degrees of freedom that are combinatorial or algebraic, and not spatiotemporal), the natural analogue for this type of theory in the philosophy of mind is property dualism, the view that mental properties are emergent but distinct from material brain properties (but cannot exist in the absence of brain properties, unlike substance dualism).[5] Property dualists, and the many variations on that general outlook, reject functionalist conceptions of the mind, once again, offering an assortment of arguments (Chinese nation, inverted spectrum, absent qualia, zombies, etc.) to demonstrate that a functional explanation of cognitive processes is incapable of providing a full mental ontology (see, Chalmers 2021, a well-known advocate of the irreducibility of mental qualia who endorses functionalism for spacetime but not the mind, and for the reasons just mentioned). One can attempt to counter this allegation, as noted above, by insisting that spacetime functionalism is simply different than mind functionalism: besides the absence of qualia, it might be claimed that causation is either not applicable or of a different sort than in the mind case. Yet, the QG theorist's appeal to functionalism as a strategy typically draws analogies with, and inspiration from, the mind variant, so jettisoning the comparison with its better known counterpart would seem to cast the ontology of spacetime functionalism even further into doubt. More problematically, by distancing the spacetime and mind versions of functionalism, one is left with only the theoretical reduction model to provide guidance on the ontological interpretation of the relationship between emergent GR and the foundational CST/LQG—but theoretical reduction is not an ontology, and it also renders spacetime functionalism vulnerable to the spatial presence problem described earlier, namely, that if GR can be reduced to the fundamental elements of QG, then the latter are in spacetime.

## 5. Conclusion.

As advertised at the outset, the property theory of space, after long neglect, has finally found a home in a class of physical theories that naturally, if not inevitably, fits its assessment of the ontology of space. To recap our findings, if one starts from the basic metaphysical categories that gained prominence since the start of the twentieth century (but follows closely the Early Modern format advanced by, e.g., Locke 1975, 164)—namely, substance, properties (including internal relations), and external relations—then a spacetime that emerges from a non-spacetime QG foundation falls under the property/internal relations classification, i.e., with the emergent spacetime comprising a property of the non-spacetime ontology. Furthermore, the property theory of space, unlike its rivals, is the ideal match for a spatial ontology that is based on properties/internal relations, for substantivalism and relationism are linked with substances and external relations. And, while earlier formulations of the property theory of space, which viewed position or acceleration as a bodily property, have been charged with impersonating substantivalism, that criticism is not applicable in the case of non-spacetime QG theories, for emergence is a property concept. In addition, as discussed in section 4, both structuralism and functionalism are plagued by a host of problems that render them inadequate for an ontological assessment of non-spacetime QG theories: both approaches are obscure as regards the details of their ontologies, and when some of these details are fleshed out, they typically mimic standard subject-property metaphysics. Consequently, if the property theory is itself challenged on the grounds of opacity, then that criticism rings hollow if advanced by the structuralists and

[5] This point is also noted in Le Bihan (2021), who provides a thorough examination of both mind and spacetime functionalism, and ultimately concludes that realizer functionalism aligns with reduction, and role functionalism with property dualism.

functionalists. This is not to say that some future formulation of these newer ontologies may ultimately prove more effective, but, until they do, an examination of the spatial ontology of non-spacetime QG theories employing the standard metaphysical categories clearly favors the property theory of space (via its reliance on properties/internal relations). In short, while one can agree that the standard three-part metaphysical scheme (substances, properties/internal relations, external relations), as well as the more the general subject-predicate outlook, are not ideal, and at worst unsatisfactory, assessments of physical theory, they have nonetheless proved to be a serviceable and durable resource for capturing the ontology of scientific theories. As a final note, Martens (2019) has argued that the traditional metaphysics of substantivalism and relationism fails to adequately explicate the emergence of spacetime in QG theories, and that a new third ontological option, "emergent spacetime", is thus required—but the contention of this essay is that a successful third option for the metaphysics of emergent spacetime is already available in the form of the property theory of space, an approach that is perfectly suited to the ontological classification of emergent spacetime theories like CST and LQG.

## Bibliography


Armstrong, D. M. 1989. *Universals: An Opinionated Introduction.* New York: Routledge.

Baron, S. 2021. "Parts of Spacetime". *American Philosophical Quarterly* 58: 387-398.

Baron, S., and B. Le Bihan. 2022. "Composing Spacetime", *The Journal of Philosophy* 119: 33-54.

Belot, G. 2000. "Geometry and Motion". *British Journal for the Philosophy of Science* 51: 561–595.

Broad, C.D. 1925. *The Mind and Its Place in Nature*. London: Routledge.

Chalmers, D. 2021. "Finding Space in a Non-Spatial World", in *Philosophy Beyond Spacetime: Implications from Quantum Gravity*, ed. by C. Wüthrich, B. Le Bihan, N. Huggett, 154-181. Oxford: Oxford University Press.

Cortês, M., and L. Smolin. 2014. "The Universe as a Process of Unique Events". *Physics Review D* 90.

Dieks, D. 2001a. "Space-time relationism in Newtonian and relativistic physics". *International Studies in the Philosophy of Science* 15: 5–17.

Dieks, D. 2001b. "Space and time in particle and field physics". *Studies in History and Philosophy of Modern Physics* 32: 217–241.

Dorato, M. 2000. "Substantivalism, Relationism, and Structural Spacetime Realism", *Foundations of Physics* 30: 1605–1628.

Dowker, F. 2005. "Causal sets and the Deep Structure of Spacetime", in *100 years of relativity: Space-Time Structure: Einstein and Beyond*, ed. A. Ashtekar, 445–464. Hackensack: World Scientific.

Earman, J. 1989. *World Enough and Space-Time*. Cambridge: MIT Press.

Earman, J. 2006. "The Implications of General Covariance for the Ontology and Ideology of Space-Time", in *The Ontology of Spacetime*, vol. 1, ed. D. Dieks, 3–23. Amsterdam: Elsevier.

Esfeld, M. 2021. "Against the Disappearance of Spacetime in Quantum Gravity", *Synthese* 199 (Suppl 2): 355-369.

French, S. 2014. *The Structure of the World*. Oxford: Oxford University Press.

Gillett, C. 2016. *Reduction and Emergence in Science and Philosophy.* Cambridge: Cambridge U. Press.

Hoefer, C. 1996. "The Metaphysics of Space-Time Substantivalism". *Journal of Philosophy* XCIII: 5–27.

Huggett, N., and C. Wüthrich. 2013. "Emergent spacetime and empirical (in)coherence". *Studies in History and Philosophy of Modern Physics* 44: 276–285.

Jaksland, R. 2021. "An Apology for Conflicts between Metaphysics and Science in Naturalized Metaphysics", *European Journal for the Philosophy of Science* 11: 1-24.

Knox, E. 2013. Effective Spacetime Geometry. *Studies in History and Philosophy of Modern Physics* 44: 346–356.

Ladyman, J. 2009. "Structural Realism". The Stanford Encyclopedia of Philosophy, ed. E. Zalta. http://plato.stanford.edu/entries/structural-realism/.

Lam, V. 2016. "Quantum Structure and Spacetime", in *Metaphysics in Contemporary Physics*, ed. by M. Bigaj and C. Wüthrich, 81-100. Leiden: Brill.

Lam, V., and M. Esfeld. 2013. "A Dilemma for the Emergence of Spacetime in Canonical Quantum Gravity". *Studies in History and Philosophy of Modern Physics* 44: 286–293.

Lam, V., and C. Wüthrich. 2018. "Spacetime is as Spacetime does". *Studies in History and Philosophy of Modern Physics* 64, 39-51.

Le Bihan, B. 2018. "Space Emergence in Contemporary Physics: Why we do not need Fundamentality, Layers of Reality and Emergence". *Disputatio* 10: 71–95.

Le Bihan, B. 2021. "Spacetime Emergence in Quantum Gravity: Functionalism and the Hard Problem", *Synthese* 199: 371–393.

Lewis, D. 1986. *On the Plurality of Worlds*. Oxford: Blackwell.

Locke, J. 1975. *An Essay Concerning Human Understanding*, ed. by P. Nidditch. Oxford: Clarendon Press.

Loux, M. J., and T. M. Crisp. 2017. *Metaphysics: A Contemporary Introduction*, 4th ed. New York: Routledge.

Martens, N. C. M. 2019. "The Metaphysics of Emergent Spacetime Theories". *Philosophy Compass* 14 (7).

McLaughlin, B. 2008. "Emergence and Supervenience", in *Emergence*, ed. by A. Bedau and P. Humphreys, 81–98. Cambridge: MIT Press.

Newton, I. 2004. *Philosophical Writings*, trans. and ed. by A. Janiak and C. Johnson. Cambridge: Cambridge University Press.

Norton, Joshua. 2020. "Loop Quantum Ontology: Spacetime and Spin-Networks", *Studies in History and Philosophy of Modern Physics* 71, 14-25.

O'Connor, T. 2021. "Emergent Properties", The Stanford Encyclopedia of Philosophy, ed. by E. Zalta, https://plato.stanford.edu/archives/win2021/entries/properties-emergent/.

Oriti, D. 2021. "Levels of Spacetime Emergence in Quantum Gravity", in *Philosophy Beyond Spacetime: Implications from Quantum Gravity*, ed. by C. Wüthrich, B. Le Bihan, N. Huggett, 16-40. Oxford: Oxford University Press.

Rickles, D. 2005. "A New Spin on the Hole Argument". *Studies in History and Philosophy of Modern Physics* 36: 415–434.

Rickles, D., and J. Bloom. 2016. "Things Ain't what They Used to Be. Physics without Objects", in *Metaphysics in Contemporary Physics*, ed. by M. Bigaj and C. Wüthrich, 81-100. Leiden: Brill.

Rovelli, C. 1997. "Halfway through the Woods: Contemporary Research on Space and Time", in *The Cosmos of Science*, ed. J. Earman and J. Norton, 180–224. Pittsburgh: University of Pittsburgh Press.

Rovelli, C. 2004. *Quantum Gravity*. Cambridge: Cambridge University Press.

Sklar, L. 1974. *Space, Time, and Spacetime*. Berkeley: University of California Press.

Tahko, T. E., and E. J. Lowe. 2020. "Ontological Dependence", in *The Stanford Encyclopedia of Philosophy*, ed. by E. Zalta, https://plato.stanford.edu/archives/fall2020/entries/dependence-ontological/.

Teller, P. 1987. “Space-Time as Physical Quantity”, in *Kelvin’s Baltimore Lectures and Modern Theoretical Physics*, ed. P. Achinstein and R. Kargon, 425–448. Cambridge, MA: MIT Press.

Teller, P. 1991. “Substance, Relations, and Arguments about the Nature of Space-Time”. *Philosophical Review* 100: 362–397.

Wilson, J. M. 2021. *Metaphysical Emergence.* Oxford: Oxford U. Press.

Wüthrich, C. 2012. “The Structure of Causal Sets”. *Journal for General Philosophy of Science* 43: 223–241.

Wüthrich, C. 2019. “The Emergence of Space and Time”, in *The Routledge Handbook of Emergence*, ed. by S. Gibb, R. Findlay Hendry, T. Lancaster, 315-326. New York: Routledge.

Wüthrich, C. 2020. “When the Actual World is Not Even Possible”, in *The Foundation of Reality*, ed. by D. Glick, G. Darby, A. Marmodoro, 233-254. Oxford: Oxford University Press.

Yates, D. 2021. “Thinking about Spacetime”, in *Philosophy Beyond Spacetime: Implications from Quantum Gravity*, ed. by C. Wüthrich, B. Le Bihan, N. Huggett, 129-153. Oxford: Oxford University Press.