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

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. 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. In addition, the property theory will be shown to offer advantages over other alternative approaches, such as structural realism or spacetime functionalism.

1. Introduction

The rise in importance 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 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 discussed in this context, such as spacetime structural realism and spacetime functionalism, will also be assessed, although the limitations of their respective ontological assessments will be shown to diminish their viability. While emergence is a much discussed topic in current analytic metaphysics, one might nevertheless question its application to QG on the grounds that these theories are too esoteric and/or hypothetical. That assessment is short-sighted, however, since one of the dominant QG approaches over the past few decades relies on non-spacetime elements and spacetime emergence, and thus the topic is of great importance for a scientifically informed metaphysics.

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 (which includes internal relations), and external relations. In section 4, the limitations of two recent interpretations of non-spacetime quantum gravity theories, structural realism and spacetime functionalism, in comparison with the property theory, 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 designed 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 such that it constitutes a discrete version of the lightcone structure of GR (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 half-integer spin representation for its nodes and links (via eigenvalues of operators), such that the classical spacetime metric of GR is then regarded as an emergent effect of the interconnections of these discrete non-spacetime spin networks (see, e.g., Rovelli 2004).[1] 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 an 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 in the context of GR, is reflected in some of the pro-substantivalist interpretations

[1] In slightly more detail, spin networks form a basis in a QM Hilbert space, with the spin representation on the nodes depicting volume, and the spin representation on the links providing the area of the mutual surface between two adjacent spin networks. As regards CST, for spacetime to emerge, there must be a map, φ, from the causal set elements to spacetime which preserves the causal structure: if one non-spacetime element, *p*, precedes another, *q*, then $\varphi(p)$ must be in the causal past of $\varphi(q)$.

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).

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 would seem 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).

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. 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. 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 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 also holds for LQG if the manifold can indeed be replaced with an algebraic equivalent), the spatiotemporal relations among the basal elements in CST and the spin networks in LQG are not direct. Spacetime comes about from the basal elements' connections in CST and the spin-network's adjacency relations in LQG as a higher level emergent effect. If the spatiotemporal relations in these theories were directly among the non-spatiotemporal elements, then there would be no need for the causal connections among those elements for spacetime's emergence. Likewise, those elements would already be present in spacetime prior to the connections, just as a single body in an otherwise empty universe is in spacetime according to traditional relationism—an individual CST element in that same scenario is, however, not in spacetime; see, Wüthrich (2020, 244). Specifically, a requirement imposed on CST is that different casual set structures must give rise to only one emergent spacetime, often labelled "many-to-one", but many structures fail to result in any emergent spacetime at all, a scenario that we will dub "many-to-none". 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 there would be no possibility of many-to-none cases (where the spacetime fails to emerge). 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"). If traditional spatiotemporal relationism were in effect, however, then there would be no divergence between the adjacency relations among the spin networks and the emergent spacetime, but rather a one-to-one correlation between those structures.

Among commentators that question the relevance of the substantivalist-relationist dichotomy for 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. Yet, while traditional relationism predicated on bodies is obviously endangered by these possibilities, advocates of the field-based form of relationism will insist that LQG's spin networks involve the quantum field and its energy, as will eventually CST. 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.[2]

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 "three meters to the left" only requires the existence of the relata (with no specific monadic properties necessitated for the relation). In short, since differences in relative position do not require differences in internal bodily properties, the consensus among contemporary expositions of the metaphysics of relations regards spatiotemporal relations as

[2] One might try to salvage substantivalism and relationism by invoking this dichotomy exclusively at the emergent level. That is, one could claim that the emergent entity comes in two types, metric and matter, with the debate then centered on whether the emergent metric entity plays the background role traditionally assigned to substantival space, and with external relations assumed to hold at the emergent level among metric and matter. However, those possibilities at the emergent level do not compromise the property/internal relations metaphysics that holds between the non-spatiotemporal foundational level and the emergent spacetime level, and thus they do not undermine the property theory's status as the more basic spatial ontology (i.e., between the foundational and the emergent levels). Whether this rather diminished form of substantivalism and relationism is acceptable to spatial ontologists is an open question.

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. 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.[3] 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, Belot 2000), there have been several advocates of the property theory, namely, Sklar (1974), Teller (1987), 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 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 definition of emergence normally offered concerns an "emergent property", e.g., O'Conner (2020), Gillett (2016), Wilson (2021), with Broad's early definition of emergence possibly having served as a template for later approaches: "the characteristic properties of the whole R(A, B, C) [where R signifies the joint composition of A, 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, play no role in the emergence of the higher-level entity (since external relations rely on independently-existing relata, 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

[3] See, Loux and Crisp (2017, chapter 3) on the varieties of substance and property concepts, and Takho and Lowe (2020) on ontological dependence.

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 and many-to-none relationships between the fundamental non-spacetime entities and the emergent spacetime—is perfectly captured by the metaphysics of properties, since properties are commonly viewed as (i) contingent features of an underlying substance (which thus admits those scenarios where spacetime fails to emerge, many-to-none)[4], 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 outcomes). For QG hypotheses that require more than one non-spacetime element for spacetime's emergence, these criteria, (i) and (ii), would thus seem to represent the basic requirements (i.e., necessary and sufficient) for a theory to qualify as a property theory of space.

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 Copenhagen interpretation, a quantum system can 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. Specifically, 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 fail to obtain in certain cases. In addition, while quantum field theory does rely on Minkowski spacetime, there have been several interpretations of algebraic quantum field theory that aim to replace its point manifold by employing overlapping sets of subalgebras representing physical subsystems (although this strategy can also be used by the relationist; see,

[4] "A theory of quantum gravity need not take the emergence of spacetime to be necessary, i.e., as emergent in all circumstances judged physically possible by the theory" (Lam and Wüthrich 2023, 2).

Dieks 2001b, 238, on these strategies). Likewise, the case presented in Esfeld (2021), that metric structure is the "world-making relation" required to unite QG's fundamental elements, 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 (see, Jaksland 2021).[5] These approaches, while still tentative, provide a coherent strategy for explicating spacetime emergence without presuming manifold or metric structure.

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 an object's properties into the "bundle" which constitutes that object, where that unique relation can be "explained informally as the relation of occurring together", and "whose attributes enter into only contingently" (Loux and Crisp 2017, 88). Since the special relation, in the non-spacetime QG setting, cannot be colocation or any other that involves spatiotemporal notions, doubts can be raised over its applicability for QG theories. 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). Le Behan (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) 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

[5] It should be noted that QM entanglement challenges a clear division between internal and external properties/relations, for some have described QM properties, like spin or charge, as "structurally derived intrinsic properties" (Lyre 2012, 170), which suggests a unique fusion of both. Nevertheless, an interpretation of quantum properties that relies on external relations alone seems highly implausible. Additionally, Wüthrich (2020, 252) argues that the non-spatial causal structure of CST does not equate with external relations in Lewis' sense, but with internal relations instead. Finally, 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.

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 problems raised for relationism still hold, namely, that there is no direct one-to-one correlation between the bundle of non-spacetime QM properties and the emergent spacetime level. Put differently, on a bundle interpretation, the lack of a one-to-one correspondence between the non-spacetime and emergent space levels signifies that only some bundles of non-spacetime properties will bring about an emergent spacetime, and that form of contingent ontological dependency relationship is best captured by the property theory of space, not substantivalism or relationism. Consequently, the commitment of the property theory of space to criteria (i) and (ii) is not altered, at least for non-spacetime QG theories, if the part-whole relationship replaces the substance-property relationship.

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 [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 invariant theoretical structures across theory change, rather than a realism focused on the specific entities. The ontology of spacetime structural realism in the GR case is difficult to assess, but it has been regarded as a form of relationism (if confined to the false dichotomy between substantivalism and relationism) since the metric is claimed to be a physical field (see, Dorato 2000). While relations play a central role in the analysis, these relations, in the context of non-spacetime QG theories, are not spatiotemporal, as Wüthrich notes (i.e., "not straightforwardly" seems to indicate that spacetime is an indirect effect).

In QM, the ontic form of structuralism (OSR) takes two forms, the moderate (non-eliminativist) form, where both the relation and relata (particle) are on an equal ontological footing, and the eliminativist type, which places the ontological emphasis on the relation alone. As in the spacetime case, it is difficult to gauge the ontological commitments associated with OSR: e.g., what does it mean to say that a structure, as opposed to a substance, is non-eliminable? Thus, the obvious case that the property theorist can make for the advantages of their theory is that their ontology is not as counter-intuitive and opaque as OSR. Furthermore, when details are offered, the defenders of classical subject-predicate metaphysics can point out that the structural realists have merely appropriated substance, property, relation concepts, albeit clothed in a new nomenclature. For example, proponents of eliminativist OSR have often adopted a monistic or holistic ontology wherein the individuality of QM particles dissolves into the field encoded by the group structure representation (e.g., French 2014), but this maneuver renders structuralism vulnerable to the criticism that the particles or entanglement relations are playing the role of internal properties of a 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.

Additionally, 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 (many-to-none), then what accounts for those failures (as well as successes)? The only plausible answer, apparently, is that there is a *property* of that structure and its elements which is operative in those cases where spacetime emerges. For eliminative 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). For non-eliminative 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 entanglement), that tactic would also vindicate the property/internal relation outlook since the relata's internal properties are involved in 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, 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 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 offer an intuitive explication of 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 field substance.

The pervasiveness of the substance-property conception may also be evident in spacetime functionalism, an approach that naturally draws comparisons with its better known philosophy of mind counterpart. Originally developed to designate which structure within a specific spacetime theory best captures the function of spacetime, that approach has been adapted to defend non-spacetime QG theories from the charge of lacking "empirical coherence", where the ground of that allegation, put roughly, is that a theory's fundamental entities must exist in spacetime since no observable evidence can confirm non-spatiotemporal entities. The application of spacetime functionalism to QG aims to defuse this problem by insisting that the entities of non-spacetime QG theories can play the functional role of spacetime, and thus empirical coherence can be regained (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 GR's spacetime. However, utilizing Ramsey-Lewis semantics, which 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). In order to avoid this dilemma, which we will dub the “spatial presence” (or Yates) problem, Yates favors a 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 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 fundamental and 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). 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 role functionalism but may actually require it in order to evade the spatial presence problem.

Yet, whether spacetime functionalism, especially of the realizer variety, can provide a successful account of *ontological emergence* 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 features that are left unexplained once a 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 is a large class of theories (such as epiphenomenalism, property dualism) that reject the functionalist notion that a mental state is determined only by its functional relationships within a cognitive system; rather, mental states possess irreducible properties that are not amenable to a functional analysis. Hence, an emergent spacetime, conceived ontologically, would seem to be more accurately described employing some spatiotemporal counterpart of these non-functionalist theories of the mind than with the previously mentioned spacetime 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, non-reductive features which are distinct from material brain properties (but cannot exist in the absence of brain properties).[6] One can attempt to counter this allegation, as noted above, by insisting that spacetime functionalism is simply different than mind functionalism given the absence of spacetime qualia. Yet, by distancing the spacetime and mind versions of functionalism, the ontology of spacetime functionalism is cast into doubt, and one is left with only the theoretical reduction model to provide guidance—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. Hence, due to its capacity to offer an ontological account of emergence, as opposed to a mere reduction, the property theory avoids the pitfalls just revealed for spacetime functionalism.

In response, the spacetime structuralist (OSR) and realizer functionalist might claim that the criticisms levelled above are inadequate since both approaches can be interpreted as consistent with the broad outlines of the property theory given in section 3, i.e., criteria (i) and (ii), the many-to-none and many-to-one scenarios.[7] In other words, structuralism might be viewed as simply an alternative ontological perspective that is nonetheless compatible with the more traditional property theory. Likewise, the realizer functionalist can insist that their outlook is not intended to provide a complete ontology, and it is not mere reduction either; rather, it is a method for explaining how and why the same QG entities can be referred to in two different ways (spatiotemporal and non-spatiotemporal), hence realizer functionalism's full ontology does not preclude the property theory. This defense is entirely plausible, especially since (as noted above) both structuralism and functionalism often utilize property-like descriptions in explicating their respective ontologies. Yet, the property theorist can insist, once again, that their ontology is still preferable to OSR and realizer functionalism since the details of these latter ontological conceptions, as well as their differences from the property theory, remain unclear.

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 standard contemporary metaphysical categories—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

[6] Le Bihan (2021), in an extensive survey, reaches the same conclusion, namely, that realizer functionalism aligns with reduction and role functionalism aligns with property dualism. See, Chalmers 2021, a well-known advocate of the irreducibility of mental qualia who endorses functionalism for spacetime but not the mind.

[7] I would like to thank two anonymous referees from *International Studies in the Philosophy of Science* for suggesting these ideas.

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 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 short, while one can agree that the standard three-part metaphysical scheme (substances, properties/internal relations, external relations) is a somewhat crude means of assessing physical theory, it has nonetheless proved to be a serviceable and durable resource for explicating ontology—and, more importantly, it is unclear if any successful replacement can be developed: e.g., both structuralism and functionalism 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. 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 ideally 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.

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.

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

Lam, V., and C. Wüthrich. 2023. “Laws beyond Spacetime”. *Synthese* 202: 1-24.

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.

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

Lyre, H. 2012: “Structural Invariants, Structural Kinds, Structural Laws,” in *Probabilities, Laws, and Structures*, ed. by D. Dieks et al., 169–181. Dordrecht: Springer.

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

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., 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.

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.