Philosophy Beyond Spacetime: Introduction

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Abstract

The present volume collects essays on the philosophical foundations of quantum theories of gravity, such as loop quantum gravity and string theory. Central for philosophical concerns is quantum gravity's suggestion that space and time, or spacetime, may not exist fundamentally, but instead be a derivative entity emerging from non-spatiotemporal degrees of freedom. In the spirit of naturalised metaphysics, contributions to this volume consider the philosophical implications of this suggestion. In turn, philosophical methods and insights are brought to bear on the foundations of quantum gravity itself. For instance, the idea of functionalism, borrowed from the philosophy of mind and discussed by several essays, exemplifies this mutual interaction the collection seeks to foster.

Keywords: spacetime, space, time. emergence, naturalised metaphysics, quantum gravity, loop quantum gravity, string theory, functionalism

Contemporary physics has much to teach us about the nature of space and time, as has become obvious with the advent of relativity theory at the latest. What is less obvious is that the relativistic revolution may only have been the first step in a longer process of deconstructing our pre-theoretical categories of space and time. In fact, attempts to unify the lessons of general relativity with the other great revolution of the twentieth century in physics, quantum physics, into a theory of quantum gravity suggest a rather strange idea: that *space and time as we know them do not fundamentally exist, but instead emerge from a non-spatiotemporal structure.* Thus, the physics under construction, which we hope will one day provide a more unified and fundamental view of reality, could lead to a novel understanding of the nature of space and time, radically opposed to everything previously believed. This volume is the results of our conviction that this stunning consequence, difficult as it may be to conceptualise, could genuinely change the way in which many discussions in philosophy are conducted—say, on the existence of space, the flow of time or the boundaries of space and time, to name but a few examples. Hence the title of this collection: *Philosophy Beyond Spacetime.*

The current situation in contemporary physics results from a long historical journey. As we have already mentioned, two revolutions took place in physics during the twentieth century: special and then general relativity, and quantum physics. The first gave a new understanding of gravity as a feature of the geometry of space and time, with dramatic philosophical consequences: the relativity of simultaneity, the dynamical relation between spacetime and matter, the possibility of temporal anomalies, and the existence of singularities in spacetime, for example. The second deals with the matter that inhabits spacetime, and poses equally deep philosophical challenges: the non-local connection between entangled systems, the appearance of a classical world, the very existence of particles. While being of enormous empirical power and accuracy, both have raised deep, and unresolved philosophical and foundational questions—as the ever expanding literature on the subjects attests.

There is as yet no satisfactory unified theory in which quantum matter is dynamically related to generally relativistic spacetime, i.e., into a *theory of quantum gravity* (QG). Quantum matter cannot easily be described as interacting with classical relativistic spacetime. But it seems as if matter and geometry must be closer in nature than they are in the two separate theories. By itself, this observation gives us reason to think that a successful theory of QG will raise similarly important challenges to our conceptions of space, time, and matter—perhaps abolishing them altogether as fundamental entities. Although such a theory does not yet exist, we may nevertheless see the silhouettes of coming changes in the fragmentary theories that do exist, and come to understand new possibilities for epistemology and metaphysics. But just as important, there is good reason to think that some of the problems in finding a theory of QG are themselves conceptual, in need of philosophical analysis by philosophers and physicists—just as relativity required Einstein's reconceptualising of the nature of space, time, and motion, and as quantum mechanics was driven by the competing pictures of Schrödinger and Heisenberg.

This volume is one of the fruits of a three-year research project, *Space and Time after Quantum Gravity* (2015-2018), funded by the John Templeton Foundation. The project involved both physicists working on the physics of QG and philosophers working on this topic or related notions in contemporary philosophy. We have selected a few outstanding works, the fruit of intense discussions over several years, and we have divided them into two volumes. One—*Beyond Spacetime: The Foundations of Quantum Gravity* (Cambridge University Press, 2020)—deals more with philosophical questions arising in the technical development of different approaches to quantum gravity. The other volume—this one—is more directly concerned with the implications of QG for questions traditionally seen as more philosophical in nature. Of course, this distinction is gradual at best and often blurred—not the least in foundational research in QG. Several of the articles of either collection could equally well have been included in either volume. To a first degree of approximation, the companion volume, which requires more technical skills in physics, addresses a wider range of physicists, while we hope to reach many philosophers beyond the narrow confines of technically demanding philosophy of physics with the present volume.

The key aim of this volume is to expand knowledge and understanding of the philosophy of QG by the philosophical community. It emphasises how debates in metaphysics—regarding time, emergence, composition, or grounding for example—shed light on the conceptual questions of QG; and conversely, how quantum theories of space and time call into question philosophical views grounded in classical spacetime. Furthermore, the philosophy of QG raises methodological questions, for instance concerning the relation between physics and metaphysics. The essays in this volume have been chosen to demonstrate to a wide range of philosophers the significance of the subject, as well as making novel contributions to it.

The essays are organised around three main subjects: (i) the possible emergence of spacetime in various approaches to QG, (ii) philosophical (especially metaphysical and epistemological) discussions of the nature of this relation of emergence and (iii) a final section devoted to methodological aspects of the philosophy of QG. The remainder of this introduction sketches these topics and the contributions.

1 Searching for spacetime

The first series of papers explores various approaches to quantum gravity and examines how spacetime might emerge in these specific approaches. The first chapter categorises the way in which spacetime can be said to emerge from a more fundamental but less spatiotemporal structure into qualitatively different levels and exemplifies them in the context of loop quantum gravity. The first three chapters all aim to clarify, and perhaps to some extent downplay, claims of emergence of familiar spacetime structures in this context. The last paper, in contrast, proposes that the classical notion of spacetime would have to be generalized if nature turns out to be supersymmetric

The first chapter by **Daniele Oriti** proposes a levels view of the emergence of spacetime in QG. According to Oriti, the emergence of spacetime comes in degrees, where 'degree' or 'level' is not to be understood ontologically as metaphysical layers or a sequential succession. Rather, levels are intended to indicate a broadening of the perspective on the problem, such that at each step, novel conceptual, methodological, epistemological, or ontological issues show up as the complexity and the richness of the physics increases. He identifies four distinct levels of emergence of spacetime and of the gravitational field, and offers the helpful analogy of the emergence of hydrodynamic properties of (super)fluids from its atomic constitution.

The first level, Level 0, covers classical GR and direct quantisations of its geometric degrees of freedom. Already at the classical level, there is a sense in which space and time dissolve, as the general covariance of classical GR implies that, generically, there exists a multitude of notions of space and time. Moreover, in the Hamiltonian formulation of GR required for canonical quantisation, there is a 'problem of time' in that time and dynamics appear to vanish altogether. Even so, the fundamental degrees of freedom are still spatiotemporal, or geometric. These difficulties are exacerbated at the quantum level, where superpositions of exact geometric configurations are permitted. In the hydrodynamical analogy, Level 0 would correspond to the construction of macroscopic hydrodynamic observables as functions of different ones, with their quantisation adding difficulties. Following Carlo Rovelli, Oriti believes that these challenges can be resolved deploying a relational strategy.

Level 1 complicates this picture by adding new, distinct kinds of degrees of freedom, which are neither spatiotemporal or geometrical in any direct sense. Typically, the fundamental degrees of freedom are combinatorial or algebraic, and show no continuum structure. Many theories of QG, such as loop quantum gravity, string theory, causal sets, and causal dynamical triangulations are naturally interpreted to at least ascend to this level. While the explication of emergence at Level 0 involves the classical limit, to see spacetime emerge at Level 1, the continuum limit—to be carefully distinguished from the classical limit, must be taken (usually via coarse graining or renormalisation). Unlike the other levels, Level 1 includes an ontological aspect in that the postulated new kinds of degrees of freedom form a novel ontological category. This level is directly analogous to the move from macroscopic hydrodynamics to the grainy world of the atoms which constitute the fluid.

Levels 2 and 3 do not proceed to a novel, qualitatively distinct kind of degrees of freedom. Instead, they involve different conceptual perspectives on the same basic ontology. Level 2 starts from the realisation that the continuum limit is often not unique, but leads to distinct macroscopic phases separated by possible phase transitions. Not all such macroscopic phases will be geometric or spatiotemporal. What needs to be shown to resolve this level is that there exists a spatiotemporal phase in some approximation and some limit. In case of such non-trivial macroscopic phase diagram, spacetime, argues Oriti, can be said to be emergent in a more radical sense compared to Level 1. In the hydrodynamic analogy, one and the same system can condense into different macroscopic phases such as solid, fluid, and gaseous, and will only obey hydrodynamic laws in one of them.

Finally, the existence of distinct macroscopic phases leads to the possibility that the system undergoes a phase transition. Thus, a system may transition from a non-spatiotemporal to a spatiotemporal or geometric phase, sustaining a 'geometrogenesis'. This is what may occur in quantum models of the big bang where one can distinguish an 'earlier', non-spatiotemporal phase from a 'later', approximately spatiotemporal one. While this transition ought to be regarded as a physical process, the difficulties involved in conceptualising these transitions as physical, yet non-temporal processes justify regarding them as Level 3 transitions. In comparison, appreciating the physical nature of phase transitions in the hydrodynamic analogy seems more straightforward.

Oriti's categorisation of qualitatively different kinds of spacetime emergence gives useful guidance to a field which has so far only started to appreciate the systematically different kinds of issues involved at the different level of emergence.

Jeremy Butterfield's essay addresses the nature and significance of 'dualities' in physics. These symmetries attracted a great deal of interest amongst physicists when they were discovered in string theory in the 1990s, sparking the 'second string revolution'. More recently they have been the subject of intense scrutiny by philosophers, for their implications for the interpretation of string theory (for a general overview aimed at philosophers, see Le Bihan and Read 2018). For instance, Huggett (2017) argues that duals should be understood as fully equivalent descriptions, so that any apparent differences are non-factual. If so, the T-duality between theories with different radii for the universe means that fundamentally space has no definite radius, and, developing a line of thought proposed by Brandenberger and Vafa (1989), the observed definite radius must be emergent.

Butterfield argues that such reasoning should be resisted. Drawing on work by (and with) Sebastian De Haro (e.g., 2020), he first gives a formal account of 'duality': broadly speaking, two theories are dual when they are different formal representations of a common 'bare theory'. For instance, one can represent the same system of moving bodies in frames of reference with different origins, orientations, and states of rest. There is an isomorphism between the two representations that allows one to see how they are describing a common set of quantities in the same way. However, this formal mapping says nothing by itself about whether one of the representations is right about absolute rest, or whether there is in fact no standard of absolute rest.

Such questions are a matter of the interpretation of physical theory, in this case the two duals. Do they automatically say the same things, or disagree substantively? Butterfield (and De Haro) therefore invoke a formal theory of interpretation, in which reference is handled by actual worldly extension, and sense by extension across possible worlds. Of course, in this framework, whether the duals say the same things depends on their intended sense: Newton's 'space' has an absolute standard of rest, which Newton hypothesised to be that of 'the centre of the world'. Of course in that sense of 'space', one could meaningfully disagree with him, even though Galilean symmetry means that no experiment can settle the issue. Similarly for T-duals: one could in principle understand their difference as either merely representational, or as real. For Butterfield, until we have a theory that explicitly unifies them, revealing the underlying bare theory, we must understand them as disagreeing about the actual world. Those advocating for emergence will disagree, arguing that one can in suitable circumstances infer that duals agree factually, even absent an explicit underlying theory (e.g., Huggett and Wüthrich 2020).

In her essay, **Alyssa Ney** asks whether there is evidence for the emergence of spacetime—specifically metrical—structure from quantum entanglement entropy: this is an idea that has received recent attention (for instance, Cao et al. 2017). A starting point for this way of thinking (though related ideas go back further) is the Ryu-Takayangi conjecture that 'holographically' relates the entanglement on the boundary of anti-de Sitter spacetime to an area in the bulk, using the AdS-CFT duality. (Specifically, the entropy arising from the entanglement between the conformal fields in two regions on the boundary, is directly related to the area of the minimal surface in the bulk that separates them.) It is quite striking that two things as disparate as quantum entanglement—which at root measures the ability to factorise vectors in Hilbert space—and metrical quantities, can be related in this way. It is an insight that led Cao and co-authors to describe how to reconstruct a spatial metric from an abstract quantum system.

Such an idea strongly suggests emergence. The quantum structure, from which the spatial structure is supposedly recovered, is seemingly non-spatial, as we noted. However, as Ney explains (drawing on the earlier work of others), that conclusion is hasty, for the mere correspondence does not entail emergence. Amongst other possibilities, which, if either, of the two sides is more fundamental? The correspondence alone does not tell us that it is the Hilbert space side. If, Ney argues, one looks at the derivation of the Ryu-Takayanagi conjecture, the reasoning seems, if anything, to show that it reflects the way spatial structure constrains the quantum entanglement. (And, she claims, similarly in earlier derivations of the Hawking-Bekenstein entropy that also relate entropy and area: e.g., Bombelli et al. 1986.) In that way of looking at things, space seems to be at the same level as entanglement. Thus, she concludes, these derivations of space from Hilbert space, do not support the claim of emergence. Of course, that is not to say that they are incorrect, or that there may not be other motivations for seeking to derive space in this way: for instance, one might hope that by starting from such a solidly quantum foundation, one might eventually recover emergent general relativity, thereby providing a route to a full theory of QG. But Ney's claim is that such motivations are future-oriented speculations, not at present well-supported by metric-entanglement correspondence.

According to what **Tushar Menon** calls 'Earman's principle', dynamical and spacetime symmetries ought to coincide in a theory. Thus, if the dynamics of matter is Lorentz covariant, as is the case for the standard model, then the appropriate spacetime venue for the theory is one which is Lorentz symmetric, i.e., Minkowski spacetime. If it turned out to be the case that matter enjoys an additional, and hitherto undetected, symmetry, the spacetime should follow suit and be generalised accordingly.

In his contribution, Menon explores the possibility that matter is supersymmetric, which is the case if the theory's Lagrange density remains invariant under transformations mapping bosons to fermions and vice versa. As it turns out, such transformations 'mix' with spacetime translations in the sense that repeated applications result in a net translation in spacetime. Menon concludes from this that supersymmetry is inherently spatiotemporal, giving us all the more reason to extend the spacetime arena for supersymmetric physics. Such a superspace consists in a 'supermanifold'—constructed from commuting and anticommuting 'supernumbers'—endowed with a 'super-Minkowski metric'. The reward for formulating supersymmetric physics in superspace is that the resulting equations of motion are manifestly supersymmetric, allowing the theory to wear its symmetry on its sleeves.

As it turns out, the light postulate of special relativity is violated in such a supertheory: the speed of light is no longer invariant in all superspace coordinate systems. Menon concludes from this that we should be hesitant to read off the operational information concerning the behaviour of measuring devices such as rods and clocks made from supersymmetric fields from the structure of superspace. Maybe so, but this might alternatively be counted as a strike against the extension of Earman's principle to the supersymmetric context.

2 The metaphysics of spacetime emergence

That space and time or spacetime might emerge from a non-spatiotemporal structure seems frankly puzzling—and difficult to articulate conceptually. Hence the second series of selected papers, devoted to the philosophical analysis of the claim that spacetime is emergent. The series comprises four chapters written by David Yates, David J. Chalmers, Alastair Wilson and Jenann Ismael, respectively. They discuss the prospects of analysing the dependence of spacetime on a non-spatiotemporal structure via a *relation of functional realisation* (an important milestone in a debate which is gaining momentum—cf. the forthcoming special issue of *Synthese* on the topic, edited by Karen Crowther, Niels Linnemann and Christian Wüthrich), a *relation of causation*, or even the possibility to *fully eliminate spacetime from the furniture of the world*.

In his contribution, **David Yates** examines the problem of empirical incoherence in QG: if spacetime is not part of the fundamental ontology of physics, how is it possible for fundamental physical theories to be justified by observations of spatiotemporally located things like rods, pointers and clocks? As a solution to the problem, he distinguishes between views that accept and reject the reality of a spatiotemporal structure over and above the more fundamental non-spatiotemporal structure. Drawing lessons from the philosophy of mind, he argues that we should adopt a form of realism about the dependent spatiotemporal structure in order to solve the problem of empirical incoherence.

This dependent spacetime, according to Yates, can either be grounded in or caused by the more fundamental non-spatiotemporal structure. Thus, Yates sees spacetime as a set of functional roles implemented by a more fundamental structure, a view called 'spacetime functionalism', which was developed in the context of QG by Lam and Wüthrich (2018). The spatiotemporally located things that act as evidence for physical theories are thereby regarded as being real entities caused by, or grounded in, more fundamental non-spatiotemporal entities. Yates thereby makes a case for a specific sort of spacetime functionalism that takes the existence of spatiotemporal roles, ontologically speaking, very seriously—against another sort of spacetime functionalism, more linguistic in nature, that regards spatiotemporal roles as mere linguistic roles some predicates occupy in the architecture of the theory. The view is at odds with Linnemann (forthcoming) who argues that spacetime functionalism as a general view does not help with the problem of empirical incoherence.

David Chalmers focuses first on the emergence of space rather than of spacetime with a focus on philosophy of mind and the possibility of identifying what he calls 'Edenic space'—namely, space as we immediately find it in the manifest image of the world—with real physical space. His main claim is that we should be functionalists about the manifest image, and that we should not expect the Edenic space of the manifest image to faithfully mirror the structure of the physical space. Rather, we should construe space as the structure triggering (our experience of) the manifest spatial image. In other words, Chalmers argues against what he dubs 'spatial primitivism', namely the view that space is just as it appears in the manifest image. He favours instead *spatial functionalism*—the view that space is what causes the Edenic space of the manifest image.

The move from spatial primitivism to spatial functionalism has major fallouts, not only for the status of the physical space in which we live, but also for other sorts of more abstract spaces involved in virtual reality experiences. Indeed, he argues that the rejection of spatial primitivism in favour of spatial functionalism has a straightforward consequence: virtual spaces should be regarded as real spaces, functionally implemented by an ontology to which we have no direct epistemic access via our experience of the virtual reality. Then he moves on to analysing the interpretation of spacetime in the context of general relativity and of the relation of emergence existing between the relativistic spacetime and the more fundamental non-spatiotemporal structure of QG. Likewise and in line with other works, he discusses the strategy of finding spatiotemporal functional roles in the general theory of relativity before turning to quantum theories of gravity to identify the realisers of these roles. There again, he defends the view that the functionalist strategy justifies realism about the spacetime of general relativity. Drawing from discussions about the existence of an explanatory gap between a non-spatio-temporal theory of QG and a theory of general relativity, Chalmers then focuses on the possible existence of another explanatory gap between general relativity and the manifest image this time; he argues that spacetime functionalism may close this gap. In brief, according to him, we should free our ontology from Edenic space assumptions; but we should nonetheless be realists about a functional physical space, identified with the structure that triggers our experience of Edenic space.

Alastair Wilson also examines spacetime functionalism as a way to analyse the dependence of spacetime on a non-spatiotemporal structure. He begins with the following question: should we construe the dependence of spacetime on the non-spatiotemporal structure as causal or non-causal? As Wilson points out, distinguishing between causal and non-causal relations—also called 'grounding relations'—requires a demarcation criterion. This criterion is supposed to allow us to decide, in the face of a relation of dependency, whether this relation is causal or not. An intuitive demarcation criterion is related to time. Causation would refer to cross-temporal dependency relations—the two relata of the relation being located at different times—and grounding to synchronic dependency relations—the two relata being located at the very same time. As Wilson notes, if this temporal demarcation principle were to be right, then it would follow that the emergence of spacetime cannot be causal (and not grounding either), since time doesn't exist at the fundamental level—thereby preventing us from identifying the dependence of spacetime on the non-spatiotemporal structure to a causal relation.

But Wilson takes another road as, drawing on previous work (Wilson 2018), he rejects the temporal criterion and proposes an alternative mediation criterion: causal relations are dependence relations mediated by a law of nature, while grounding relations are mediated by constitutive principles—what it is to be a particular thing or kind of thing. This suggests that we can use our understanding of what it is to be a law of nature to grasp the distinction between causation and grounding. Of course, as Wilson acknowledges, this amounts to replacing questions about the nature of dependency relations by questions over the nature of those mediating principles. For instance, if we construe causal relations as relations mediated by a law of nature, then we need to understand what a law of nature is—without appealing to causation, at risk of vicious circularity—which might or might not be problematic, depending on which of the two notions one takes to be more fundamental. Nonetheless, it is an important result that the difference between grounding and causation can be illuminated this way as we can then analyse, in some approaches, emergent spacetime as being caused by a non-spatiotemporal structure.

As Wilson notes, this idea might surprise the reader as, at first sight, this seems at odds with the common assumption found in the literature that spacetime does not emerge via a causal process, causation being too tightly related to the existence of space and time (a possible exception could be found in cosmological models based on quantum gravity; see e.g. Huggett and Wüthrich 2018). Usually, this relation of dependency is considered to be both non-temporal and non-causal, either because it is a primitive relation of grounding (i.e. not to be specified further via another relation) or because it is a relation of mereological composition. But Wilson's new criterion suggests that spacetime could literally be *caused by* a non-spatiotemporal structure, in particular in loop quantum gravity. Wilson then shows that there is a way to avoid this surprising consequence by using the functionalist machinery. Spacetime functionalism offers a new way to interpret the situation in LQG, spacetime being functionally realised—a constitutive principle—and hence grounded in, rather than caused by, the non-spatiotemporal structure, according to the mediation criterion. Wilson closes with a discussion of the many-instant landscape view defended by Gomes (2017). According to this view, the world is a 'timeless' state space of spatial field configurations. Wilson argues again that the existence of spacetime in this approach should be regarded as mediated by a functional principle and so, because of his demarcation principle, as grounded in the non-spatiotemporal structure.

In her essay, **Jenann Ismael** argues for an expansive view of what the 'emergence of spacetime' might amount to, which opens an unnoticed and perhaps surprising route to recovering spacetime. It is typically assumed that conscious experience will be recovered from fairly high level physics, so that reduction from any lower physics can (with a sigh of relief) ignore the mind—to be taken care of later. Ismael cites Maudlin (2007) as an example of this position. Since the physics which is supposed to explain the mind is spatiotemporal, the corollary is that physical space itself will have to be recovered from any non-spatiotemporal theory—as programmes in QG typically assume.

However, of course all that need be recovered, strictly speaking, is the conscious experience of spatiotemporality. If one assumes that that is given immediately in experience, then the result is the same—physical spacetime must emerge. But, Ismael argues, spacetime is not at all immediately experienced. Empirical studies support the view—which has antecedents in Berkeley, Poincaré, and Mach (on whom she focusses)—and provide evidence that the concept of spacetime is a construct from experience. More specifically, different sensory modalities present different perspectives on the physical world, each in its own 'sensory manifold'. But the mind unifies these through sensory and motor interaction with the world, finding that a representation in which they are viewed as different takes on a single spatiotemporal world simplifies their relations greatly. (The significant plasticity in this unification shows that it is not a fixed given.)

The upshot of course is that strictly speaking, a theory without spacetime is not required to deliver spacetime itself, but only to explain the sensory modalities, to recover the sensory manifolds. Then the brain itself will take care of spacetime, which would be recognised as a mere appearance. Ismael notes that such an account would fit a functionalist model: the functions of the modalities could found to be played by the non-spatiotemporal. She does not necessarily advocate such a strategy, but argues that it should be recognised to understand the epistemology and goals of spacetime emergence. At first glance the strategy appears radical, but Ismael points out that it may not be so far from what has already been suggested. For instance, Rovelli (1991) suggests a strategy of recovering rods and clocks instead of spacetime: it is not such a great leap to consider instead recovering 'information gathering and utilising machines', cashed out functionally in non-spatiotemporal terms (see also Baron 2020).

3 Methodological issues

The last series of chapters reflects the diversity of works in the growing community of philosophy of QG. If a central issue in QG is the conceptual articulation of the potential emergence of spacetime, many other issues in QG arise along the way. With this last section, we want to invite philosophers to delve deeper into those other questions related to the construction of a theory of QG—and thus to draw their attention to a number of points that could have important repercussions for many philosophical questions.

The first chapter by Richard Healey deals with the perhaps most famous problem in the foundations of quantum mechanics, *the measurement problem.* However, it does so in the context of one specific approach to quantum gravity, loop quantum gravity, raising the difficult question of whether or not we should solve the measurement problem in order to make progress with QG. The second chapter by Kerry McKenzie focuses on the connection between physics and philosophy, and on the possibility of obtaining metaphysical knowledge from the current state of physics where we lack, one must note, a final theory applying to all domains of observation. The final chapter by Adam Koberinski examines a deep puzzle about vacuum energy, sometimes called the 'vacuum catastrophe' or 'cosmological constant problem'. The problem arises from a clash between the value of the vacuum energy we calculate via quantum field theory—which must be extremely high—and the value we get from cosmological data when we observe the way the energy is distributed in the observable universe, suggesting an extremely low value.

These three issues, although quite different, may serve to show just how fertile research in the philosophical foundations of QG is for very different questions, traditional and new, technical and fundamental.

Richard Healey's contribution discusses critically, but sympathetically, Carlo Rovelli's relational interpretation (1996) as a way to solve the quantum measurement problem in the context of (covariant) loop quantum gravity. Although Rovelli was of course one of the main architects of this theory, Healey shows that there are significant tensions between the two. Healey believes that these can be overcome in his own pragmatist approach to quantum physics.

Rovelli's relational interpretation of quantum mechanics departs from von Neumann's notion of a measurement resulting in a correlation between the initial state of the 'system' and the final state of the 'measurement device'. In Rovelli's interpretation, there is no place for an absolute and objective state of a system; instead, all states are relational in that a system is in a state only relative to another system, which may be an observer who has or gains knowledge about the first system. Consequently, Rovelli rejects the idea that there is such a thing as the complete description of the total state of the world.

Applying the relational interpretation to covariant loop quantum gravity, Rovelli and Vidotto (2014) propose to understand its transitions between spin network states as physical processes enclosed between interactions between systems whose boundaries are ultimately conventional. It is these *processes* which are ultimately nothing but spacetime regions. The resulting 'relational loop quantum gravity', Healey argues, struggles to accommodate the concept of an observer capable of registering the outcomes of measurement interactions as it deals exclusively in spacetime regions (and their conventional boundaries). Since observers are not mere spacetime regions, more work is required to show how they (and thus von Neumann measurements) can be modelled in the context of relational loop quantum gravity.

As one of the morals to be drawn, Healey concludes that the characterisation of observing or measuring systems needs to be established as emergent in loop quantum gravity. In this sense, he requires the emergence of spacetime for the quantum measurement to be resolved. As he notes, this is in disagreement with Wüthrich (2017), who argues that instead, the emergence of spacetime in QG requires the resolution of the measurement problem, not the other way around.

The second chapter of this series, by **Kerry McKenzie**, begins with the observation that many philosophers dream of a final physical theory of everything that will answer some of the deepest and most intriguing metaphysical questions. For instance, is time really flowing or is it just a perceptual artefact of the way we experience a static four-dimensional world? Is there a sort of modal glue connecting events in a systematic way and explaining why the world seems to obey to some laws of nature? We do not have such a final, absolutely fundamental theory, but this situation does not prevent metaphysicians from engaging in metaphysical activity by using constraints from empirically well-confirmed physics.

McKenzie argues that this kind of naturalised metaphysics is problematic. If we step back and look at theoretical physics as a whole, we can see that the empirically well-confirmed theories on which it is based should ideally be replaced by another more fundamental, and perhaps definitive, theory. Until we find this Holy Grail—assuming that it exists—we are stuck in a far from ideal epistemological situation. Indeed, it seems difficult to reliably draw metaphysical knowledge from the current state of physics. Why should we trust our currently most fundamental physical theories to give us empirical access to the fundamental structure of the world? After all, we know that those theories are not absolutely fundamental.

After characterising her preferred sense of 'naturalistic metaphysics', McKenzie shows that claims in metaphysics had to change their truth value as science, and especially physics, progressed. With regard to the classic debate between scientific realists and anti-realists, she argues that friends of scientific realism may appeal to the notion of approximate truth and argue that certain structures are preserved by the change in theory and, therefore, can be seen to justify certain claims about the world. McKenzie goes on to argue that this notion of approximate truth is of little use in dealing with more metaphysical issues. Indeed, metaphysical questions (say, regarding the existence of past and future entities) are often ontological or substantive questions that are difficult to answer in terms of approximation. McKenzie concludes that the value of engaging in metaphysical speculation based on our currently most fundamental physical theories is unclear.

We believe that this situation offers a powerful motivation to shift our attention from the well-established theories of physics to QG. Indeed, McKenzie's challenge to naturalised metaphysics does not necessarily oblige us to wait for the development and empirical confirmation of a final theory. Le Bihan (2020), for example, argues in response to McKenzie that we can obtain substantial metaphysical knowledge from speculative physics by examining the field of QG as a whole and looking for features present in all or almost all approaches to QG.

The last paper, by **Adam Koberinski**, engages with a topic at the interface of QG and cosmology. The notorious 'cosmological constant problem' concerns what some physicists have labelled the 'worst prediction in physics of all times': theoretical expectations for the value of the cosmological constant Λ based on considerations from particle physics overshoot observational limits anywhere from 50 to 120 orders of magnitude (depending on a choice of 'cutoff'). The problem arises because quantum field theory seems to suggest that empty space has an enormous energy density, which, according to general relativity, ought to manifest itself in the geometry of spacetime, coupling to the Einstein equation as a cosmological constant term, inflating the latter to gargantuan proportions inconsistent with observations.

After clarifying what exactly the problem is supposed to be, Koberinski argues that this argument ought to be resisted at each turn. First, he shows that there is little basis on which to accept an objective zero-point energy scale in quantum field theory and hence to take the vacuum energy as real. Second, even if one did accept this, the vacuum energy turns out to be badly divergent on standard renormalisation procedures and hence does not deserve to be trusted. Third, it turns out that there exist more rigorous ways of coupling quantum field theory to general relativity than is assumed in the standard argument to the cosmological constant problem, and that under these approaches, vacuum energy, and so the cosmological constant problem, does not arise in the first place.

In the last part of his contribution, he shows that even assuming that all these steps to the cosmological constant problem can all be justified, the presently dominant attempts to solve it all fail. These attempts include 'naturalness' approaches such as supersymmetry, apparent violations of the equivalence principle (for example due to higher dimensions as we find them in string theory), or statistical avenues based on anthropic reasoning or quantum statistical considerations. All of this leads Koberinski to the sobering conclusion that the cosmological constant problem has not been established as an actual problem, and physicists taking it as a heuristic to develop new physics may well be barking up the wrong tree.

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