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Introduction

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This volume is one of the fruits of a three-year research project, *Space and Time after Quantum Gravity*, funded by the John Templeton Foundation.[1] Our goal was to explore the idea that attempts to quantize gravity either significantly modify the structures of classical spacetime or replace them—and spacetime itself—altogether. It is a premise of our work that philosophy and physics are intertwined, so that advances in physics entail revisions in philosophy but also require conceptual—that is, philosophical—advances and refinement. Hence our project activities were focused on bringing interested physicists and philosophers into conversation.

Thus, in addition to their research, project members organized numerous colloquia, workshops, and schools and ran three essay contests (our work is archived at www.beyondspacetime.net). From the researchers who participated in these events we selected a group that represents the cutting edge of a range of topics concerning the nature of spacetime in the new physics of quantum gravity and invited them to contribute to a pair of volumes. One—*Philosophy beyond Spacetime* (Wüthrich, Le Bihan, and Huggett, forthcoming)—deals more directly with the implications of quantum gravity for traditional philosophical concerns. This volume deals more with questions that require philosophical analysis, arising in the development of different approaches to quantum gravity. This distinction is a somewhat hazy one; several articles could have fitted equally well in either volume. But roughly speaking, the former volume should interest a wider range of philosophers, and the present volume a wider range of physicists (also being the more technical of the two); physicists and philosophers with interests in our foundational questions should find both volumes valuable.

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Even with two volumes, we could select only a small proportion of the researchers who were involved with the project, and not every topic, and far from every speaker, could be included here. So we have attempted to select a representative collection of papers that cover (1) research in the most active foundational areas in the field and (2) a range of approaches and questions within each topic. We hope, then, to provide a fairly comprehensive snapshot of the state of the field, to encourage further dialogue between physics and philosophy, and to promote further work.

The chapters in this volume are organized around three main themes: the possible ‘emergence’ of spacetime, the role of time in quantum gravity, and more specific interpretational issues raised by quantum gravity. The remainder of this introduction sketches these themes and the contributions. The following sketches focus on some (not all) important ideas in order to show how the papers develop common themes from different angles; they are not intended to replace reading the chapters, which contain much more than can be discussed here! Rather, we hope that the sketches will whet the reader’s appetite for what follows.

1.1 Spacetime Emergence

The first part addresses the question of how the classical spacetime of general relativity (GR) and quantum field theory (QFT) might be derived or emergent in theories that attempt to quantize gravity: we shall say ‘quantum theories of gravity’ (QTG) in order to be clear that the category includes any approach that aims to unify gravity and the quantum (and not only those that attempt to apply quantization strategies to GR). One question is the different senses in which classical spacetime might be derived from, or emerge from, or reduced to a more fundamental theory, without the full structures of classical spacetime. Another question approaches the issue diachronically, asking whether classical spacetime could have been ‘created’ from something nonspatiotemporal at the big bang.

A traditional framework for thinking about the derivation of classical spacetime is given by the Bronstein cube (Bronstein 1933; see also Figure 2.1 in this volume), which can be thought of as picturing a system of physical theories as limits of one another. The dimensions are labeled with c, G, and $\hbar$, so that they represent nonrelativistic, nongravitational, and classical limits, respectively. The eight vertices are populated by various theories; for instance, Newtonian mechanics, special relativity and GR, and particle and field quantum mechanics; but, of course, the most significant vertex for our purposes is that occupied by a theory of everything (or at least ‘more’) incorporating a QTG. QFT (in flat spacetime) can be found in the $G \to 0$ limit of this theory, and GR in the $\hbar \to 0$ limit. Put this way, the picture seems to embody a fairly straightforward answer to the challenge of deriving spacetime;

classical spacetime is an effective description of a QTG, which holds in a formal limit and is a good approximation when the effects of the parameters in question can be experimentally ignored. But, of course, that is much too quick (even for known theories): What is the theory? Does the parameter actually appear in a way that lends itself to taking such a limit? And what is the physical significance of the parameter in the theory, such that we can argue that we live in a regime in which it can be neglected? These, especially the last one, are not purely formal questions but are the issues of interpretation that confront attempts to derive classical spacetime.

In the second chapter of this volume, Daniele Oriti argues that the cube in fact fails to capture an important formal and physical possibility; namely that the physical elements or atoms of a QTG may form spacetime only in special aggregate states, which have a spatiotemporal description in a large N, 'hydrodynamic' limit. In short, we need to add a fourth dimension, parameterized by the number of degrees of freedom, N, yielding a Bronstein–Oriti *hyper*cube of QTG. Traditional programs for QTG start with the ordinary cube in mind and so attempt either to quantize GR (as in the original loop quantum gravity [LQG] program), or to gravitize QFT (as in the first string revolution). But, as Oriti points out, the renormalization group revolution in statistical mechanics has yielded a formal and conceptual understanding of large N systems that was not available to Bronstein in 1933. Moreover, as these programs have developed, they have started to indicate that the fundamental degrees of freedom may not be obtained by the direct approach of quantizing or gravitizing; for instance, string dualities can be interpreted as indicating some structure that 'quotients' the apparent differences in spatiotemporal structure between duals. Oriti surveys similar clues from other programs.

His 'fourth dimension' gives substance to the idea of spacetime emergence. That is, if a set of physical quantities approximate those of a more fundamental theory in the limit in which a constant vanishes, there is a straightforward epistemic interpretation of the reduction; our observations are simply not fine grained enough to be sensitive to perturbations arising from the parameter, in the circumstances. That is a simple, really quantitative, sense in which one theory reduces to another. A large N limit might be of the same kind, but as Oriti explains, it highlights another possibility, suggested by various concrete proposals. That is, that the atoms of the theory might be intrinsically nonspatiotemporal and take on a spatiotemporal aspect only in suitable large N configurations. Note that for such a theory, the claim that the atoms are not spatiotemporal is not based on a direct interpretation of their degrees of freedom but rather on the fact that they simply do not constitute spatiotemporal structure in all states; if they were intrinsically spatiotemporal they would have to constitute something spatiotemporal however they were configured. (Of course, this argument depends *in*directly on the interpretation, specifically on claims about how the atoms can be physically combined to produce spacetime.)

This possibility carries a deeper, qualitative kind of reduction of spacetime from nonspacetime, and in the $N \to \infty$ limit, which underwrites a sense of 'synchronic emergence' often found in the literature. Though what is also generally expected is a formally and conceptually well-controlled map between the theories, constituting a 'reduction' in the classic sense, rather than the strong emergence found in other parts of the philosophy literature.

As Oriti explains and illustrates, a theory in which atoms may or may not combine to constitute spacetime offers a further, even stronger sense of emergence. Namely, there may be the possibility of a transition from a nonspatiotemporal to a spatiotemporal state, at the big bang perhaps: diachronic emergence, or 'geometrogenesis'. Indeed, the work of Oriti and his collaborators on group field theory strongly suggests just this. Of course, geometrogenesis is formally and conceptually very puzzling, for the very concept of a transition seems to imply time throughout the process, but by assumption there is no time before geometrogenesis!

The possibility that the history of the universe includes the emergence of the temporal from the atemporal also arises in the third chapter, by Suddhasattwa Brahma. (The more general question of time in QTG is discussed in Part II.) He presents results developed within the framework of loop quantum cosmology (LQC), which implements high-level principles drawn from LQG. As such, it is to a considerable extent neutral on the nature of the atoms of spacetime, their formal expression and conceptual significance; by assuming certain general features to be consequences of the underlying theory, LQC does not directly speak to the manner in which they are derived. The reasons for adopting such an approach are of course to obtain a framework in which concrete empirical consequences can be derived, without needing full knowledge of the fundamental theory or details of how to take appropriate limits; the results are assumed. While we cannot see a full story of emergence from studying such a theory, it is still a quantum theory, and as Brahma explains, LQC does entail a significant result about the derived nature of spacetime. (Moreover, because LQC is based on general principles, the lesson holds of any theory that realizes them. Brahma argues that the results do not depend on idealizing assumptions in the derivation—e.g., of sphericity—but follow from the physical principles of the theory alone.)

Specifically, the assumptions made appear to suffice for the resolution of classical singularities, at the big bang and (it seems likely) in black holes. Moreover, as Brahma explains, the resolution involves a transition from a Lorentzian metric signature in the classical region to a fully Euclidean metric signature in the region of the singularity; without a change in the number of dimensions, there is spacetime classically, but only space in the quantum region! (As the chapter discusses, a similar idea occurs in the distinct context of the Hartle–Hawking no boundary proposal [Hartle and Hawking, 1983].) We have in a sense the emergence of time from the nontemporal, but three points should be noted: First, we do not have full-blown geometrogenesis because the quantum regime is not strictly nongeometrical, as in the cases Oriti discusses. Second, as a result, it is in principle possible to consider one of the spatial dimensions as that in which the space–to–spacetime transition occurs, potentially providing the basis on which that issue can be resolved. However, third, one should not expect a well-defined Euclidean signature metric in the quantum regime resolving the singularity, but rather a fuzzy one; so the situation is not straightforward. To make progress on these questions, as Brahma discusses, one would need to open up the question of the atoms of the theory; and perhaps in that case one would see that geometrogenesis does after all underlie the process.

Classical singularities are, of course, one of the consequences of classical physics of greatest interest in QTG. Not exactly anomalies in the sense of a failure of the laws (if one is prepared to accept manifolds with singular points removed) but places at which one expects a more fundamental theory to diverge substantially from GR, yielding novel predictions. For instance, a QTG might predict specific traces in the cosmic microwave background (CMB) or in the Bekenstein–Hawking thermodynamics of black holes. The first possibility is the topic of Robert Brandenberger's chapter.

He explains the nature and content of the CMB and the conclusions about the origins of the universe that can be drawn from it using the theory of cosmological perturbations, in whose development he played a central role. In particular, isotropy implies that today's Hubble radius is smaller than the future horizon of early points, while causality requires that currently observed structures were within the Hubble radius at early times. Moreover, there are two further criteria, inferred from the observed power spectrum of the CMB: first, acoustic oscillations require that the universe has been isotropic above the Hubble scale for a long time, and second, any theory of the early universe must explain the scale invariance of the spectrum. Inflation is the conventional response to these constraints, but in the context of QTG it can only be an effective theory, to be understood in terms of some deeper quantum account of gravity. For instance, one might well expect to find a mechanism for inflation within string theory, but despite the efforts of theorists, no definitive mechanism has been found (e.g., Baumann and McAllister, 2015; see also Bojowald [2002] for a proposed account of inflation within LQC). (Moreover, inflation is not without problems.)

However, as Brandenberger explains, there are alternative accounts of the early universe to inflation, which also satisfy the CMB criteria; these solutions typically try to take into account proposals for more fundamental physics, QTG. For instance, the initial singularity could be smoothed out with a bounce solution, in which the universe extends through the big bang into an earlier classical spacetime. Unlike the

LQC bounce discussed by Brahma in Chapter 3, Brandenberger focuses on models based on string theoretic concepts, including the possibility of a T-dual universe on the other side of the big bang. While these proposals are speculative, they illuminate the way in which new physics in a QTG might resolve the puzzles of the CMB. Moreover, they again illustrate the idea that spacetime might be emergent in a diachronic sense, from a quantum state at the big bang; though again, whether they involve full geometrogenesis from nonspatiotemporal atoms depends on details of the scenarios that are not yet understood. (Some of the philosophical implications of this situation have been further explored in Huggett and Wüthrich [2018].)

In Chapter 5, Daniel Harlow returns to the question of synchronic emergence—the derivation of spacetime as an effective structure rather than its creation. Specifically, he addresses two important lessons for QTG that black holes may be teaching us. He first argues that one can best understand the enormous difficulty encountered in quantizing gravity by considering the tension between GR and QM caused by the possibility of black holes. Specifically, a rod capable of measuring Planckian lengths must have a sub-Planckian position uncertainty, hence a minimum momentum uncertainty according to QM. Assuming a low (with respect to the speed of light) velocity, a minimum mass follows, which is easily seen to exceed the Planck mass. But a Planck length-sized object of mass greater than the Planck mass is inside a black hole, according to GR, and incapable of measuring lengths. That is, black holes exemplify the difficulty in defining quantum observables for arbitrarily small regions in QTG.

Harlow's second lesson is how black holes help illuminate the nature of holographic duality (the latter is discussed further in Chapters 12 and 13) and plausibly show the existence in string theory of the synchronic emergence described by Oriti. Harlow makes the point that the duality is (if correct) an exact correspondence, holding between *fundamental* quantum theories on the boundary and the bulk of anti–de Sitter spacetime, known as AdS/CFT duality: a conformal field theory on the boundary and some form of string theory in the bulk. On the other hand, the bulk gravitational *field* arises as a derived, *effective* theory of the fundamental bulk quantum theory. The value of AdS/CFT duality is that the bulk quantum theory is not understood well enough to carry out such a derivation, but the boundary CFT is under enough control to allow the exploration of emergent gravitational—spacetime—features.

As Harlow points out, the philosophical literature has focused on the question of whether the duality between exact theories can be an asymmetric relation of emergence, generally concluding that instead it is some symmetric relation of physical equivalence. Harlow's central claim is that this focus ignores the fact that bulk spacetime physics is derived from boundary physics and hence indirectly from exact bulk physics, an asymmetric relation of derivation.

Using a simple black hole model, in the formal framework of quantum information theory, Harlow goes on to illustrate how this relation is one of spacetime emergence. Briefly, three qutrits (states in 3-dimensional Hilbert spaces) live on the boundary, comprising a $3^3 = 27$-dimensional Hilbert space of a boundary quantum theory. The effective bulk theory is represented by a single qutrit, living in a 3-dimensional subspace of the full theory, corresponding to the few degrees of freedom of a classical black hole. But the fundamental bulk theory is dual to that on the boundary and so also lives in a 27-dimensional Hilbert space; what has happened to the other 24 dimensions? It's not at all surprising that the effective theory has fewer degrees of freedom than the fundamental; that's more-or-less what it means to be effective, in a general sense. Rather the question is, since these extra degrees of freedom are not those of effective bulk gravity, what bulk physics do they describe? Harlow's work indicates that they represent microstates of a bulk black hole within the fundamental bulk theory. This toy model then represents the situation envisioned by Oriti; one has effective spacetime only to the extent that the quantum state of the system has a component in the appropriate subspace; other degrees of freedom belong to a fundamental, nonspacetime theory. Insofar as the model accurately represents nonperturbative bulk string theory, AdS/CFT duality shows that that too is a theory of emergent spacetime.

1.2 Time in Quantum Theories of Gravity

It has long been understood that a successful QTG could have significant implications for our understanding of the nature of time. Many of the difficulties—especially those related to the problem of time—in constructing such a theory seem to stem from the tension between needing a classical time parameter in the dynamics, yet quantizing time by quantizing the metric. In Part II, we have collected four chapters that focus on time in the construction of QTG: what the implications might be and how the conception might have to be changed in order to successfully quantize gravity.

The chapters draw on philosophical thought about the nature of time in this effort, showing nicely the interaction between the two disciplines. In particular, a central theme is the question of whether various QTG do or should realize a form of temporal becoming. Physics typically views time from the point of view of analysis, in which quantities 'flow' only in the sense of taking on different values at different times, with rates understood as limiting ratios $\Delta f(t)/\Delta t$. This picture seems adequate, and indeed natural, in a classical spacetime background, since it mirrors the mathematical treatment of physical quantities. Traditional temporal becoming is the view that there is more to the passage of time than this picture captures, that later states are in some further sense *produced* by earlier ones, or the later times are *created* after the earlier, or that successive presents *come to be*. The italics indicate that these terms don't merely redescribe the standard, analytic, account of physical time; what more they denote depends, of course, on the specific account offered (Savitt [2017] provides a survey). Becoming is also often combined with 'presentism', the view that in some substantive way the present is more real than other times: reality is becoming. Such a view is often contrasted with a 'block' conception of time, according to which the present is merely a matter of perspective, within a full space*time*.

These concepts are unpacked more fully in the following chapters, in relation to QTG. Three of them see becoming, in three different conceptions, as important to quantizing gravity. The final chapter in Part II takes an even more radical view: no becoming, but no block either, just (in some sense) a collection of frozen moments, fundamentally speaking, temporally unconnected.

In Chapter 6, Carlo Rovelli discusses how he thinks that spacetime—particularly time—should be understood in LQG (the chapter also includes a useful appendix summarizing the theory for nonspecialists). He argues that a number of confusions regarding space and time arise because people mean different things when using the expressions *space* and *time*; he describes the concepts as 'stratified, multi-layered'. To counter these confusions, he distinguishes five senses of time (and parallel senses of space).

Relational time involves only the relations between events; the temporal position of one event is specified by temporal adjacency with the occurrence of another. This conception of time is common to many theories, including LQG. In contrast, *Newtonian time* is a fixed metrical structure, independent of the unfolding of events and indeed of whether anything changes at all; it is exemplified by both Newtonian and special relativistic physics. Things are very different with the introduction of dynamical *general relativistic time*, which is understood in terms of clock time between events, which of course depends both on a dynamical metric and the path of the clock (as in the special theory as well). Rovelli explains how, with some subtleties due to quantum effects, this conception of time holds in LQG, thereby preserving what he takes to be an important lesson of GR.

In addition, he distinguishes *irreversible time*, connected with thermodynamics, statistical mechanics, and the entropy gradient, and *experiential time*, our experience or feeling that time flows. For Rovelli, these should be distinguished because they do *not* have any direct bearing on the nature of time from a distinctively LQG perspective but have to do with statistical and neurological effects, respectively. They are thus distinguished because bringing them into the current discussion can sow confusion.

With these distinctions drawn, the chapter unpacks the notion of time in LQG, focusing on the importance of temporal becoming. First, while accepting that the relativity of simultaneity undermines an absolute present and presentism—something challenged by Lee Smolin in his chapter—Rovelli argues that a block conception of time, devoid of becoming is not the inevitable consequence. Instead, he identifies the transition amplitudes of LQG with the coming to be of one state from another; moreover, since these are between spacetime states they can be further identified with regions of spacetime. Such a scheme does not require the global now of classic presentism, but it does rest on becoming at a local here and now and so is not a block universe picture either. Thus according to Rovelli, the choice between presentism and the block is a false one! In his view, time passes, things become, but locally rather than globally; this is the lesson for time from LQG. The remainder of the paper is devoted to showing in more detail how his interpretation of time (and the related understanding of space and spacetime) play out in LQG: the picture that emerges is one in which the universe is a 'network of quantum processes'.

One might ask whether his account of time leans more heavily toward a kind of local presentism or a block universe. The answer depends on how one fleshes it out. On the one hand, the system of transitions that make up a universe has something of the structure of block universe. However, Rovelli rejects questions of whether all regions or just the here-now is real, as a merely conventional one about the definition of 'real'. On the other, if describing quantum transitions as becoming is not merely verbal, but denotes some strong ontological status, then the view is more sympathetic to presentism. Here Rovelli's view of experiential and irreversible time (and his 2017 view that it may be perspectival) suggests that he does not subscribe to a 'thick' notion of becoming either.

We now turn to the chapter by Fay Dowker, which also addresses the question of temporal becoming and the block universe, but in the context of causal set theory (CST), which she argues realizes temporal becoming in a strong ontological sense, against defenders of a block universe. According to CST, the universe is constituted by a casual set, a discrete structure consisting of elements with causal or temporal relations between them; the manifold picture of spacetime used in GR is an approximation, applicable in some regimes. As the theory currently stands there is no full quantum version of the dynamics; instead what is given is a classical but stochastic description that gives rise to classical sequential growth models, according to which the causal set grows dynamically—'becomes'—by the addition of new elements. Dowker sees the births of new events as something that objectively happens, underwrites the irreversibility of time, and that moreover could be a physical underlying objective process that explains experiential time. In other words, her account of becoming not only has a different source from Rovelli's, she argues that quantum gravity has implications for conceptions of time that Rovelli thinks it does not.

Now, traditional conceptions of time flowing or becoming typically rely on some form a global present, either in presentist or growing block accounts. The problem is, of course, that a global spacetime present allows for an objective time parameter and so is not generally covariant; this seems to be an undesirable step backwards toward a prerelativistic understanding of time. Dowker argues that CST, however, provides an alternative model of flow without such a global now. Elements of the causal set are objectively created only before or after one another when they are in each other's causal pasts or futures, but there are no facts of the matter about the order in which elements that are not causally related were created. In turn, this is encoded in the equality of transition probabilities for paths that reorder the creation of such elements. The resulting temporal becoming is what Rafael Sorkin (2006) has dubbed 'asynchronous becoming', a localized form of becoming in a multiplicity of 'nows'. (An earlier version of Dowker's proposal has been critically discussed in Callender and Wüthrich [2017].)

Dowker argues that CST can thus accommodate both being (the baby) and becoming (its birth)—unlike the block universe, which fails to capture the latter aspect. In this manner, it reconciles two sides of a long-standing debate about which of these features ought to be given priority by embracing the essence of both. Arguably, one would expect *being* to refer to the objective structure of spacetime or of a causal set, while *becoming* would be rendered subjective by virtue of being relativized to a frame or a worldline. Surprisingly, Dowker defends the opposite view that being is subjective, whereas becoming is objective. According to her, the birth process of an atom of spacetime, and hence the becoming, is independent of any observers or frames as it constitutes an objective physical process. Conversely, there is no objective world of being; being is derivative in that it depends on a prior process of birthing, and what is objective is only each atom's past as that is what has become as of this atom. Thus being is relative to each atom and in this way subjective. Finally, Dowker asserts that this view of 'asynchronous becoming' is possible only in a discrete spacetime and hence not available in GR.

In the next chapter, Lee Smolin lays out the philosophical framework of his work over the past 20 or more years, a research program aimed both at providing a realist interpretation of quantum mechanics and at quantizing gravity. (While the chapter discusses how the two aims are intertwined, here we will focus on the latter.) At the foundation of this work is a commitment to an aspirational form of relationalism, a methodological imperative (rather than a priori truth) to seek to remove arbitrary—'absolute'—elements from physical theories. In part, he sees this principle in the history of science: eliminating absolute spacetime structure, including point identity in favor of equivalence-up-to-diffeomorphism, to give one example among the many he presents. In part, he sees it as guiding the search for a QTG.