# The emergence of spacetime in quantum theories of gravity

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The problem of unifying quantum mechanics with general relativity in a quantum theory of gravity has led to proliferation of approaches, each motivated by particular desiderata for such a theory, but none offering more than a partial solution to the riddle. Anyone venturing into quantum gravity faces multitudinous challenges of a technical and mathematical, of a physical and interpretational, and of a conceptual—indeed philosophical—character. Some occasions call for altogether novel mathematical tools, others for untested physical principles or seemingly contradictory combinations of established physics, yet others present us with apparently non-sensical implications for how the theory conceives of the world it seeks to describe. (One is reminded of the many attempts to formulate mechanics and solve the problem of the planets through the first half of the seventeenth century.) Moreover, all approaches must chart their course in what so far is empirically altogether inaccessible territory—we still await quantum gravity's Brahe and Kepler. This need for innovation unchecked by traditional experimental data has led to a confusing abundance of approaches, engaging in mostly friendly—but sometimes acrimonious—strife as well as in permissive, and pervasive, trading zones.

Although philosophers have acknowledged many implications of relativity, they have done little to address the revolutionary accounts of space and time found in quantum gravity; this special issue aims to start to fill that

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need, focussing on issues of particular philosophical salience. While different approaches to quantum gravity are often based on rather different physical principles, many of them share an important suggestion: that in some way spacetime as we find it in our existing theories is *not* a fundamental ingredient of the world, but instead, like rainbows, plants or people, 'emerges' from some deeper, non-spatiotemporal physics. What replaces spacetime and what aspects of spacetime remain in the ontology of fundamental physics differs, as one would expect, from approach to approach. But the idea that the universe and its material content might not, at bottom, be 'in' space and time, that these seemingly fundamental ingredients are just appearances of something more fundamental, would, if borne out, shatter our conception of the universe as profoundly as any scientific revolution before. It would complete an intellectual journey from a flat Earth, through a geocentered finite universe, an infinite Euclidean space, and a dynamical non-Euclidean spacetime—to (perhaps) nothing at all at a fundamental level.

A skeptic might dismiss as premature the philosophical project of engaging with what is very much science in action, not offering the warm comfort of assured insight that received theories promise. We beg to differ with this standoffish conception of philosophy of complete (hence dead) science; indeed, we urge philosophers of physics to roll up their sleeves at this opportune moment while the kitchen is still busy.

The reasons for this are twofold. On the one hand, while attempts to unify quantum physics and general relativity may be legion, most research programs have recently stalled, unable to remove major stumbling blocks on their road to successful completion. Encouragingly, physicists are increasingly aware of the need to reanalyze the philosophical foundations that undergird quantum mechanics and general relativity, and to explore the new concepts that appear in the partial unifications we possess, since they are steps towards the needed concepts of a full unification. We suggest neither that such work will suffice for a quantum theory of gravity, nor that philosophers are uniquely qualified to undertake it, but we do believe philosophers have something to contribute to such analytic work. Thus, philosophers should not engage with physicists and mathematicians over quantum gravity *despite* the theories' provisional character, but precisely *because* these theories are under construction.

The second kind of reasons are more selfish, as it were. The dishes starting to emerge from the quantum gravity kitchen smell irresistably delicious for a philosopher with a stake in the fundamental structure of our world.

## Brief outline of the contributions

Our own essay starts from the recognition that the fundamental structures postulated and described in many quantum theories of gravity seem to be quite different from any conceptions of space or time appearing in previous theories, even including the spacetimes of general relativity. Naturally, this divergence comes in degrees, and we give the reader a sense of the spectrum; we also show that the divergence occurs along different dimensions. Our main goal is to argue that theories denying the fundamental existence of spacetime are empirically coherent, i.e., that their truth does not undermine the very reasons we have for accepting them as true. Addressing this question requires us to survey how, formally speaking, spatiotemporal structures can be derived from a variety of partial theories; and to understand why we should consider such derivations as 'physically salient'.

One family of approaches to quantum gravity, the 'canonical' theories, takes classical general relativity as its point of departure and attempts to quantize the gravitational field using a canonical quantization recipe. This procedure very directly leads to the so-called 'problem of time', which seems to entail that there cannot be any genuine physical change at the fundamental level. Furthermore, to the extent to which the basic structures in these approaches are understood, their quantum states do not seem to lend themselves to a spatiotemporal interpretation. Lam and Esfeld investigate—"from an ontologically serious point of view" as they insist—claims that spacetime vanishes in the two main canonical approaches, quantum geometrodynamics and loop quantum gravity. They see a dilemma for those who deny fundamental spacetime: either spacetime emerges from a non-spatiotemporal structure—in which case one is hard pressed to explicate how local beables can be regained—or it does not—in which case the task at hand is to interpret the fundamental structures spatiotemporally. As we have made clear in our contribution, we believe that there is no in principle reason why grabbing the first horn cannot succeed.

Also starting out from general relativity, at least in spirit, but in ways rather different from the canonical program, we find approaches such as causal set theory which postulate some discrete causal structure ab initio. In these approaches, the hope is to recover relativistic spacetimes as approximations to the fundamental discrete structure in some appropriate large-scale limit. D'Ariano and Tossini postulate a $(1 + 1)$-dimensional homogeneous lattice of causally related basal events and try to show how Minkowski spacetime can emerge from their toy model in a continuum limit. However, since no isotropic space can emerge from a classical homogeneous causal network in this limit, they argue that the isotropy of the propagation of signals (and the full Lorentz covariance) can be restored if one takes into account quantum superpositions of causal paths. In this sense, they conclude that the quantum nature of the network is essential, particularly since perfectly meaningful physics can be done at non-ultimate levels.

Of course, the other major approach to quantum gravity starts from high energy physics, and quantum field theory: this route leads to string theory. In this context, claims of emergence are often tied to claims of 'background independence'. String theory seems to violate an insight of general relativity by imposing a spacetime of fixed geometry, but (as we sketch in our essay), it is arguable that strong physical symmetries—'dualities'—mean that the geometry and topology of the background spacetime is not physically determinate after all. The two essays on the topic, by Teh and by Rickles, both address this issue in the context of 'AdS/CFT duality', according to which physics cannot distinguish between one space and its boundary, or hologram—thus, perhaps, even the dimensionality of spacetime is indeterminate. Both reach somewhat skeptical conclusions, but along the way explain how such a symmetry is possible, and the meaning and significance of duality and emergence.

There are less established approaches which fit into neither the canonical nor the string camp. Among these alternatives we find the effective field theory program, the focus of Crowther's contribution. This program conceives of general relativity and its relativistic spacetime as 'effective' low-energy phenomena arising from some unknown high-energy physics, just as condensed matter physics and its condensates arise from high-energy quantum field theories. Given the oftentimes heuristic techniques used in the approach, and given that what looks like a curved spacetime can easily be obtained from many different high-energy theories (which, however, all rely on some fixed, non-relativistic spacetime background), we should not take the analogy between the 'emergent' relativistic spacetimes and the condensates of condensed matter physics too seriously. In her discussion of the emergence of relativistic spacetimes in the context of the effective field theory program, Crowther helpfully contrasts two different directions that this program can take: "top-down" from the more fundamental high-energy theory to the effective low-energy theory, or "bottom-up" from the low-energy theory (such as general relativity) in an attempt to find a high-energy theory which might give rise to the effective physics used as vantage point.

The emergent-gravity program known as 'stochastic gravity' assumes that relativistic spacetime (or, better, the gravitational field) emerges stochastically in the hydrodynamic limit of the unknown fundamental quantum theory, i.e., as the collective quantum behaviour of more fundamental degrees of freedom. The goal is to compute the corrections of increasing order to the standard association of the expectation values of the quantum field and the classical spacetime found in the semi-classical Einstein equations. The main point of the program is not to venture a speculative fundamental theory only tenuously connected to 'old' physics, but rather to start out from established physics and to inch, step by step, into the unchartered territory. Mattingly urges the methodological point that efforts should focus on "expanding our explanatory resources" in this more modest and controlled way, rather than to expose our theory building to many major reconceptualizations at once, as is necessary if one attempts a fundamental theory directly. He takes this point to be justified by the fact that any fundamental theory of quantum gravity will have to pass through the sector studied by stochastic gravity.

A final approach in this broad category, as Bain explains, is to derive spacetime physics from models based on solid state physics, via the effective field theory program for finding low energy physics (philosophers have studied related issues in the context of renormalization theory). In the first place, Bain discusses how one should think about emergence in the context of effective fields. He goes on to show how the spacetime in which the solid state fundamental physics is formulated makes a difference to the nature of the emergence of the phenomenal spacetime to which it gives rise.

The final two essays focus on the classical side of the emergence relation. It is usually assumed that what has to be derived from a quantum theory of gravity is an emergent classical spacetime metrical geometry. But Knox argues that even in the case of the classical theory, physical spacetime structure is captured by the inertial frame structure, which the full geometry (over)represents—in this sense even classically spacetime is emergent, via an approximation relation. (To see this point it's important to distinguish the structure of *spatially extended* inertial frames from that of spatially pointlike timelike geodesics.) On the one hand, this argument shifts realism from the manifold of general relativity to concrete inertial frames (a cousin of entity realism vs theory realism, as we see it); on the other, theories with non-vanishing torsion make a gap between geometry and inertial frame more visible. In addition to making a contribution to the interpretation of general relativity, this paper raises questions of exactly what we need to emerge from quantum gravity.

Finally, Hagar and Hemmo question, in principle, and through examples, whether the idea of emergent spacetime is coherent. They interpret an important exchange between Einstein and Swann to support their claim that any derivation of spacetime will have to presuppose that length is welldefined. To that extent you can't expect emergence of something from nothing!

We are very grateful to our authors for the work that they have put into these pieces. We are very excited to share them with the readers of this special issue. Our call for papers asked for essays that would help start a philosophical dialogue and investigation of quantum gravity—we can't imagine a better collection of papers to achieve just that. But now, of course, it is over to our readers. We believe that you will find plenty in these pages to educate and inspire you about these topics: we look forward to reading and hearing your responses in the coming years.

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