Spacetime Emergence: Collapsing the Distinction Between Content and Context?

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Abstract

Several approaches to developing a theory of quantum gravity suggest that spacetime—as described by general relativity—is not fundamental. Instead, spacetime is supposed to be explained by reference to the relations between more fundamental entities, analogous to 'atoms' of spacetime, which themselves are not (fully) spatiotemporal. Such a case may be understood as emergence of *content*: a 'hierarchical' case of emergence, where spacetime emerges at a 'higher', or less-fundamental, level than its 'lower-level' non-spatiotempral basis. But quantum gravity cosmology also presents us with the possibility of emergence of *context*: where spacetime emerges from some 'prior' non-spatiotemporal state (replacing the Big Bang), due to particular conditions in the early universe. I present a general conception of emergence which is plausibly able to accommodate both pictures. This is a positive conception that does not rely on a failure of reduction or explanation in any sense (indeed, reduction is a necessary feature of quantum gravity, and is useful in understanding emergence in this case). I also consider the possibility that the distinction between content- and context- based explanations is blurred, or usefully 'collapsed', in the case of spacetime emergence.

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1 Introduction

When you think of emergence, you might think of the collective behaviour of flocks of birds or colonies of ants; you might think of the emergence of life from non-living molecules, or of consciousness from collections of unconscious brain cells. Perhaps, you think of more exotic things, like the emergence of stable macroscopic objects whose behaviour can be described by deterministic laws, from some strangely behaved fundamental quantum particles. In any case, what you think of is most probably some behaviour, process, property, or object that occurs, or exists, in space and time. But what about the case of spacetime itself—can this be considered emergent from some collective behaviour of non-spatiotemporal objects? Or, could a spatiotemporal universe emerge from some 'prior' non-spatiotemporal state 'before' the beginning of the universe? Many philosophers and physicists believe that, indeed, both these scenarios are real physical possibilities in our own universe—these suggestions comes from research in *quantum gravity* and *quantum cosmology*, respectively.

Currently, our best description of spacetime is provided by Einstein's theory of *general relativity* (GR), which says that gravity is the curvature of spacetime due to massive objects. While this theory is incredibly successful, physicists do not believe that GR—along with the description of spacetime it provides—is fundamental. Instead, GR is thought to be incorrect at extremely short length scales (the Planck scale, 10^{-35}m), and in regions of extremely high spacetime curvature, where quantum effects cannot be neglected: these include black holes and the 'Big Bang'. In these domains we require a new theory, called quantum gravity (QG).

While there is no accepted theory of QG, there are several different attempts at finding it (i.e., different research programs) that are currently in development. Some of these approaches do not feature a concept of spacetime fundamentally. Instead, the existence of spacetime (and gravitational phenomena) is to be explained by reference to some more basic non-spatiotemporal objects that 'underlie', or 'compose' it. In other words, these theories describe 'atoms' of spacetime that do not themselves exist in space or time. Just as tables and chairs, and other familiar 'macroscopic' objects are not fundamental according to our 'microscopic' quantum theories of matter, so too spacetime is not fundamental according to these approaches to QG.

Does this mean that spacetime is *emergent*? If so, in what sense? So far, it has been argued that yes, on some approaches to QG, we can understand spacetime as emergent in a 'hierarchical' (inter-level) sense, where GR (and/or spacetime) emerges from the more fundamental theory of QG.[1] This can be understood as emergence of *content*, where 'objects'

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[1] See, e.g., Butterfield and Isham (1999, 2001); Crowther (2016); Huggett and Wüthrich (2013); Oriti (in

(taken in a broad sense), or phenomena, emerge at a higher ('macro') level that are not present at the more fundamental ('micro') level. But another sense of emergence has also been argued for as potentially possible, where spacetime emerges from a 'prior' non-spatiotemporal state replacing the Big Bang at the beginning of the universe, described by quantum cosmology.[2] This type of emergence occurs at a single level, so I refer to it as 'flat emergence' (Crowther, 2020). This can be understood as emergence due to (or *of*) *context*, where novel 'objects' (again, in a broad sense) emerge at a 'later' state which are not present at the 'initial' state of the system.

Given the unique case of spacetime emergence, however, it may be that the distinction between content and context just described is not a useful, or even sensible, one to draw. It is a case where both types of emergence are supposed to obtain 'simultaneously', and where the standard ways of distinguishing between these two types of emergence are not obviously available. For instance, in inter-level emergence (which I've called hierarchical, or content emergence), the levels ('micro' and 'macro') are usually characterised in terms of different scales—e.g., length scales, or energy scales—but how do we do this in the absence of space? And, for flat emergence, the states of a system ('earlier' and 'later'), are usually distinguished by reference to time—so how do we do this in the absence of time? Here, I explore the possibility that the emergence of spacetime is a case where we need a more general conception of emergence: one that collapses the distinction between content and context.

I begin by first describing QG (§2), including what it means to say that QG is more fundamental than GR (§3), which requires that the relation of *reduction* holds between the two theories (§4). I then describe the different senses of spacetime emergence (§5). Hierarchical emergence is explored in §6, with the example of loop quantum gravity §6.1. Flat emergence is explored in §7, with the example of loop quantum cosmology §7.1. I then discuss the example of phase transitions §8, arguing that these represent both hierarchical and flat emergence, as distinct notions. It is possible that spacetime also emerges in a phase transition, which I explore in §8.1. In this case, however, the two notions of emergence are supposed to obtain simultaneously, and are not so obviously distinguished. It may be more natural to not make the distinction between hierarchical and flat emergence in the case of spacetime: this possibility is motivated in §9.

2 Quantum Gravity

Currently, all fundamental particles and forces are described by quantum field theory (QFT), while gravity is described by GR. Although these theories are supposed to be universally applicable, we do not, in practice, need to use both of them together to describe any of the systems that we observe or directly interact with in the world. Yet, there are inaccessible domains of the universe whose description requires both theories, including the the Planck scale 10^{-35}m, black holes, and cosmological singularities (such as the Big Bang). The problem is that it is difficult to combine GR and QFT in a way that gives us acceptable answers about these domains. And so physicists are seeking a new theory, QG.

QFT is a framework that combines quantum mechanics and special relativity. It describes various quantum fields in a fixed, non-dynamical (unchanging) background spacetime. What

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press); Wüthrich (2017, 2019).

[2] See, e.g., Brahma (2020); Crowther (2020); Huggett and Wüthrich (2018).

we call the fundamental particles and forces—the electromagnetic, strong and weak forces—are conceived of as local (point-like) excitations of these fields according to one particular model of this framework, known as the *standard model* of quantum field theory. While spacetime is used in this theory, it is not *described by* the theory. GR, on the other hand, is a theory of spacetime. It describes spacetime itself as a dynamical field (that does not exist in some further 'background' spacetime, and so is *background independent*), and says that gravity is due to the curvature of spacetime. Both of these theories are incredibly successful, yet, neither theory is thought to be fundamental (Crowther, 2019). QG is supposed to be more fundamental than both these theories, but since we are interested in spacetime emergence, I consider only how it is supposed to be related to GR (§3).

There are various different approaches towards finding a theory of QG. The most well-known of these is *string theory.* This approach describes tiny, 1-dimensional strings propagating on a fixed background spacetime, and the excitations of these strings correspond to the fundamental particles and forces of the standard model, as well as gravity. The approach can be seen as extending the methods of QFT at the expense of the lessons of GR, in that it employs a fixed background spacetime rather than a background-independent dynamics. Here, gravity is treated on par with the fundamental forces, coming from string excitations and corresponding to a QFT particle known as the graviton (whereas according to GR, gravity is not a force but the curvature of spacetime). We could thus say that the approach prioritises the principle of *unification* (all forces, including gravity, stem from the same origin) over that of *background independence* (that QG not feature a fixed, background spacetime).

Some other approaches to QG instead prioritise background independence; because these describe basic entities that are non-spatiotemporal (not existing in spacetime), they more completely demonstrate the emergence of spacetime. I briefly introduce one of these, *loop quantum gravity.*

2.1 Loop Quantum Gravity

Loop Quantum Gravity (LQG) is an attempt to construct a theory of QG by quantising GR. It describes quanta (roughly, discrete quantum 'chunks') of spacetime. In a quantum theory, the discrete values of a physical quantity can be found by calculating the *eigenvalues* of its corresponding *operator.* In LQG, the important operators are the 'area operator', $\hat{\mathbf{A}}$, associated with the area, $\mathbf{A}$, of a given surface, $\mathcal{S}$, and the 'volume operator', $\hat{\mathbf{V}}$, associated with the volume, $\mathbf{V}$, of a given spatial region, $\mathcal{R}$. The eigenstates of these operators are called *spin network* states, and are represented as graphs called *spin networks.* An example of a spin network is shown in Fig. 2, with an illustrative depiction of how the spin network relates to the quanta of volume shown in Fig. 1.

This describes the *kinematical* aspect of the theory (i.e., the spin network states provide a basis for the kinematic Hilbert space), rather than the dynamics, and so represents space rather than spacetime. There is more to say about the dynamics of the theory (and how this is supposed to relate to spacetime), but this very brief, informal introduction to LQG is sufficient to gain an understanding of how space might emerge according to LQG.[3]

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[3] For more on LQG, see Rovelli (2004); Rovelli and Vidotto (2014). Note that this latter reference is much more up-to-date than the brief sketch of the kinematic aspect of the theory that I present here; in particular, it has much more detail on the dynamics of the theory, using the covariant approach to LQG.

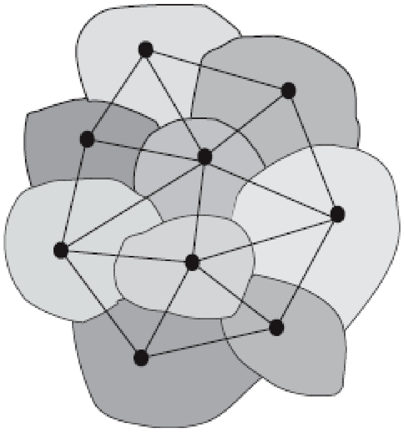

Figure 1: Quanta of volume (grey blobs). Adjacent chunks are separated by a surface $\mathcal{S}$ of quantised area. The corresponding spin network graph is overlaid. Each link intersects one quantised surface $\mathcal{S}$. (Rovelli, 2004, p. 20)

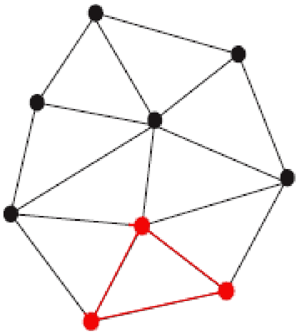

Figure 2: Spin network: Nodes represent quanta of volume, which are adjacent if there is a link between them. Connected links form loops, like the one highlighted in red. (Rovelli, 2004, p. 20).

Physical space is thought to be a quantum superposition of spin network states with well-behaved geometric properties, known as *weave states*.[4] The intuitive idea is captured by analogy: at familiar scales, the fabric of a t-shirt is a smooth, two-dimensional curved surface, but when we examine it more closely, we see that the fabric is composed of one-dimensional threads woven together.[5] The suggestion is that LQG presents a similar picture: while the geometry of space at large-scales is a three-dimensional continuum, at high-energy it is revealed to be a very large lattice of Planck-sized spacing (i.e. a spin network with a very large number of nodes and links).

3 Fundamentality

As stated above, QG is supposed to be more fundamental than GR. In this section, I first explain what it means for one theory to be more fundamental than another (for the purposes required here), and then explain how this applies in the case of QG as more fundamental than GR.[6]

Here, I just speak about *relative* fundamentality, rather than absolute fundamentality.[7] A *more fundamental* theory, M, of a given system, S, or phenomenon, P, provides a *more basic* description of S or P than a *less fundamental* theory, L, does. I take it that there are

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[4] These are semiclassical states; i.e., states in which the quantum fluctuations are minimal and the gravitational field behaves almost classically.

[5] The analogy comes from Ashtekar, Rovelli, and Smolin (1992).

[6] The following discussion is based on Crowther (2018a), although the definition of relative fundamentality differs here in that I include two conditions, while Crowther (2018a) requires only one.

[7] While QG must be more fundamental than GR, QG need not be a fundamental theory; i.e., it is not necessary to include the criterion of (absolute) fundamentality in the definition of QG (Crowther & Linnemann, 2019). For other ideas of fundamentality in physics and metaphysics, see Morganti (2020a, 2020b).

two necessary conditions for relative fundamentality:

Asymmetric dependence: The laws of L depend upon the physics described by M, *and not vice-versa*;

Broader domain: The domain of validity of M includes that of L (i.e., that M successfully describes all physical phenomena that L does).

A theory's *domain of validity* is the part of the world that is successfully described by the theory. In regards to this definition of relative fundamentality, note that M will typically describe the system, S at a different range of energy scales than L, or perhaps under different conditions. Also, M might not actually describe the phenomenon, P, that L does, but rather (some of) the physics underlying P (i.e., part of the more-basic physics responsible for the appearance of P).

The apparent influence or effect of the dependence of L upon M may not only be very minimal, but also obscured by the way it is incorporated into the parameters and structure of L. In other words, a less-fundamental physics may be largely robust and apparently autonomous, in spite of being dependent on the M physics. Often, the more fundamental theory provides a 'finer-grained', or more detailed, description of the system than the less fundamental one. The L is, in this sense, an approximation to M that works well in a given regime (e.g., a certain range of energy scales, or under special conditions).

There are two ways in which QG is more fundamental than GR: by being quantum (or by being *beyond* quantum) and by being a 'micro' theory of spacetime. Each of these is sufficient to satisfy both the 'asymmetric dependence' and 'broader domain' conditions of relative fundamentality. The recovery of GR from QG may be a two-step process, recovering the 'appearance of classicality' from the quantum theory, and moving to the 'macro' (low-energy) limit of the theory (which brings us back to familiar energy scales). The former is known as the quantum/classical transition, and the latter is called the micro/macro transition. While both address the question of why we do not need to use QG to describe much of the gravitational phenomena we observe, they are distinct, and may or may not be related to one another. Both transitions represent common problems in physics and the philosophy of physics; and both play a role in understanding the relationships of reduction and emergence.

The micro/macro transition is not something that happens to a system, but a change in the level of description: it is the move to a coarser-grained theory. The micro/macro transition may be represented by an approximation procedure, a limiting process (such as the thermodynamic or 'continuum limit'), or the renormalisation group flow. All of these different techniques are employed by various approaches to QG in their attempts to connect QG back to GR.

In the case of the quantum/classical transition there are two different issues. Quantum theories are supposed to apply universally; so, first, there is the question of why, in practice, they are usually only necessary for describing small systems. Secondly, there is the *measurement problem*: why it is that any measurement on a quantum system finds the system in a definite state even though the system evolves as a superposition of different states. The process of *decoherence* describes how the interference effects associated with superpositions become suppressed through a system's interactions with its environment, with the consequence that the quantum nature of the system is no longer manifest. Larger systems more strongly couple to their environments, so decoherence provides the beginning of an explanation for why quantum theory is usually only necessary for describing micro-systems. As such, it gives us some insight into the 'transition' that a system undergoes that prompts us to move from a quantum description of it to a "classical" one (although the system remains inherently quantum, as does the rest of the universe). Decoherence does not, however, give us an answer to the measurement problem.

We expect that the generic states of the objects described by QG will be quantum superpositions, but the quantum nature of spacetime is not manifest. An explanation of the quantum/classical transition is necessary for understanding why this is. Of course, this is an incredibly challenging task, given that the quantum/classical transition is poorly understood in general. It seems likely that a solution to the measurement problem is required if we are to fully understand the relationship between spacetime and the quantum objects that somehow underlie it; or it may be that the solution will be provided by the theory itself.[8] For the time being, however, we seek to better understand the relationship between QG and GR to any degree that will aid in the development of the theory, even without full knowledge of the quantum/classical transition.

4 Reduction

Reduction in physics means showing that the successful parts of the older theory (in this case, GR), are, in principle, *derivable* (i.e., deducible) from the newer one (QG) in the appropriate domain (where we know GR is successful), under appropriate (physically sensible) conditions. Reduction in this sense also demonstrates that the newer theory is *more fundamental* than the older one. The 'asymmetric dependence' condition of relative fundamentality is satisfied, because if the older theory is derivable from the newer one (and not vice versa), then there is a sense in which the older theory is dependent upon the physics described by the newer theory. If the newer theory is correct, and the older theory is appropriately derivable from the newer one, then the older theory will automatically be correct, since it is entailed by—or, a consequence of—the newer one.

QG is meant to be more fundamental than GR (as explained in §3): this means that the physics described by QG is supposed to be responsible for the success of the laws of GR, and that QG also describes all of the systems/phenomena that GR does. As such, the relation of reduction must obtain between these two theories. This is a strong constraint on QG, which serves to define the new theory: any prospective theory of QG will not be accepted unless physicists are satisfied that GR is appropriately derivable from the theory of QG. Standardly, howver, the derivability of the older theory from the newer one is not rigorously established: physicists employ various approximations and limiting relations, relying on different assumptions when doing so. We demonstrate that particular *correspondence relations* hold between the two theories in the shared domain where they are both supposed to apply. These are inter-theory relationships that connect the two theories, by, e.g., shared terms, numerical predictions, laws, or principles.[9] Reduction is taken to obtain when sufficient correspondence relations have been demonstrated (running in the direction from the newer theory to the

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[8] Penrose explores this second possibility, see e.g. Penrose (1999, 2002).

[9] Correspondence takes various forms and plays many important roles in theory development and assessment; see, e.g, Crowther (2018b); Hartmann (2002); Post (1971); Radder (1991).

older one), such that we are convinced that the older theory is *in principle* appropriately derivable from the newer one.

This is where many attempts to construct QG have run into difficulties. For instance, although LQG starts out with GR, and uses correspondence relations running from GR to QG ('top-down') in order to construct the new theory, it has trouble naturally 'recovering' spacetime (going 'bottom-up') and establishing that GR is appropriately derivable from the new theory. This is not necessarily an indication that GR is not recoverable from the theory, however, since it is still under development and may eventually reach a stage where it succeeds. Given that it is a requirement upon any theory of QG that it appropriately recover GR in the domains where GR is successful, I will, in the rest of this essay, assume that GR is, ultimately, appropriately derivable from whatever the accepted theory of QG turns out to be—i.e., that reduction holds in the sense described above.

5 Emergence

Emergence is an empirical relation between two relata of the same nature, an emergent, E, and its basis, B. Depending on the case of interest, E and B may be objects, properties, powers, laws, theories, models, etc. Here, I am interested in emergence as a relation between theories or parts of theories. I take the general conception of emergence to comprise three claims,[10]

EMERGENCE: GENERAL CONCEPTION

Dependence: E is dependent on B, as evidenced by E being derivable from B, and/or supervenient upon B (supervenience means that there would be no change in E unless there were a change in B, but not vice versa);

Novelty: E is strikingly, qualitatively different from B;

Autonomy: E is robust against changes in B; or E is the same for various choices of, or assumptions about, the comparison class, B

This is a *positive* conception of emergence, since it is not characterised by a *failure* of reduction, deduction, explanation, or derivation in any sense in any sense. That is, the emergent E need not be irreducible to, or unexplained by, its basis B. Such a positive conception of emergence is now familiar in the philosophy of physics generally, and the philosophy of QG in particular.[11] The positive conception of emergence is the most appropriate for understanding the case of spacetime emergent from QG for two reasons. First, as explained above, GR must be reducible to QG—i.e., it is a requirement on any theory of QG that GR be approximately and appropriately derivable from it. This condition may be used to satisfy the 'Dependence' claim of emergence. Thus, we need an account of emergence that is compatible with reduction, at least in this sense. Second, none of the approaches to QG are complete, so basing any claims of emergence on their failure to explain, derive, or predict particular aspects of GR spacetime is risky, given that a central goal of each of the approaches is to

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[10] The discussion in this section is based on Crowther (2020).

[11] This is largely due to Butterfield (2011a, 2011b); Butterfield and Isham (1999, 2001).

develop a theory that approximately and appropriately *recovers* (i.e., derives and explains) GR spacetime.

This general conception of emergence admits more specific forms: for instance, it can accommodate either *synchronic* or *diachronic* conceptions of emergence. In the synchronic conception of emergence, B and E represent different levels of description: B is said to describe the system at the *lower level* and E at the *higher level*. In physics, B and E may be theories that apply at different ranges of length- or energy-scales, where, typically, B describes the system at higher energy scales (shorter length scales) than E, which applies at comparatively low energy scales (large length scales). These theories are supposed to apply to the system at the same time, or otherwise under the same conditions, i.e, there is no 'change' considered, except the level at which you view the system.

In the diachronic conception of emergence, E and B describe the system at the same level. These theories, or models, are supposed to apply to the system at different times, or otherwise under different conditions. The idea is that the system has undergone some change: typically, B describes it before, and E after. This conception of emergence is not associated with a notion of fundamentality. The difference between these two conceptions of emergence is illustrated in Fig.3.

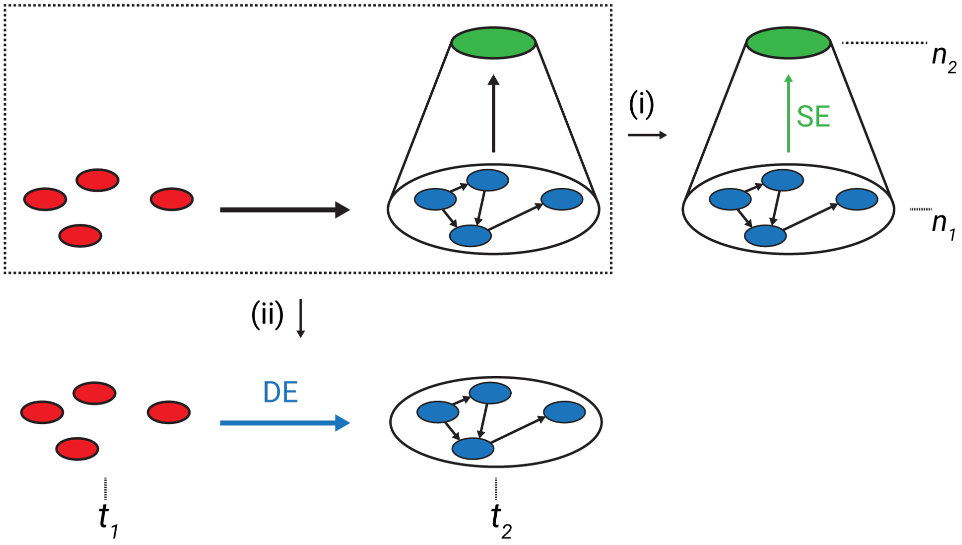

Figure 3: Two conceptions of emergence. A system **(a)** at time t_1 (red) has changed at time t_2 (blue), resulting in some novel higher-level phenomena (green). **(i)** If we are interested in synchronic emergence (arrow SE), we consider the system at level n_2 compared to the system viewed at n_1, at a single time, here t_2. **(ii)** If we are interested in diachronic emergence (arrow DE), we consider the system at t_2 compared to the system at t_1, at a single level, here n_1. Figure adapted from Guay and Sartenaer (2016).

There are many specific accounts, and examples, of synchronic and diachronic emergence described in the literature. However, any account of synchronic or diachronic emergence requires some modifications in order to be applicable to the case of spacetime emergence. Most obviously, these two conceptions rely on a notion of *time* for their distinction, as reflected in the names 'synchronic' and 'diachronic'. I suggest two accounts of emergence, roughly analogous to synchronic and diachronic accounts, but which do not rely on spatiotemporal notions; these are *hierarchical* emergence and *flat* emergence, respectively (Crowther, 2020). I briefly describe these in the next two sections.

6 Hierarchical Emergence: *Content*

Hierarchical emergence can be understood as an analogue of synchronic emergence that doesn't rely on a conception of space in order to distinguish the different levels involved, and which doesn't rely on a notion of time in identifying the system between levels. I will distinguish levels in terms of 'size of grain' ('size' is not here a reference to lengths, but refers to the amount of detail captured)—i.e., a lower-level theory provides a finer grained description of the physics, while a higher-level theory provides a coarser-grained description of the phenomena (abstracting away from the finer details, which are irrelevant at this level). Although we tend to think of finer-grained theories as describing 'shorter length scales', this is not a necessary correlation. Nevertheless, for convenience of notation, I will still distinguish the lower level physics described by B as 'micro' physics, and the emergent level E physics as 'macro' phenomena.

I suggest the following account of hierarchical emergence, which is based on other case-studies involving *effective theories* in physics (Crowther, 2016):

EMERGENCE: HIERARCHICAL CONCEPTION

Dependence: The coarser grained theory (model, or structure) E is constructed (i.e., derived) from the finer grained theory B. The physics described by the laws of E may be said to *supervene* on those of B.

Novelty: The physics described by the coarser grained, or low energy ('macro') theory E differs remarkably from that of the finer grained, or higher energy ('micro') theory B;

Autonomy: The physics described by E is robust against changes in the micro physics; B is underdetermined by E.

As in the more general conception above (§5), *Novelty* is a symmetric relation; this condition captures the ways in which the two theories differ from one another. The idea of *Autonomy* here comes from *universality* or *multiple-realisability*, which ensures the robustness of the higher-level physics compared to the lower-level physics: there are many different lower-level structures, systems, or states, that could 'give rise to' (or 'realise') the same higher-level, emergent physics (which is said to be 'universal' behaviour).[12] There are two different ways this can happen which are relevant here. First, different micro states described by, or models of, B can correspond to a single macro state/model of E. An an example is the way in which a number of different micro states described by statistical mechanics correspond to a single macro state in thermodynamics, i.e., how different configurations of molecules in your coffee give rise to the same homogeneous-looking liquid of a particular temperature (at the

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[12] See R. Batterman (2002); R. W. Batterman (2000, 2018); Crowther (2015); Franklin (2018a) for more on autonomy, universality, and multiple-realisability, particularly as related to emergence in effective field theory.

finer-grained, micro level, the individual molecules can have different positions and velocities, but you don't notice this at the coarse-grained, macro-level). Second, different micro theories can correspond to the same macro theory. An example is how fluids of different micro-constitutions (i.e., cells, molecules, atoms, or particles of different types) can give rise to the same hydrodynamic behaviour at a coarser-grained description. The fact that the macro physics is multiply-realisable leads to an *underdetermination* of the micro-physics, meaning that if you only know the E behaviour, you will not automatically be able to determine the specific B theory (state, or model), since there are many possible candidates that could be responsible.

We can consider hierarchical emergence as emergence of *content*. This can be understood in two ways: considering it as emergence of theoretical structures, or as 'ontological' emergence of some particular entities or behaviour associated with the emergent theoretical structures. In either case, the idea is that novel content appears at the higher level that is not present at the lower level, and which is autonomous from the lower-level content in the sense that many different structures at the lower level could 'give rise to' the same higher-level structures.

This conception of emergence can be used to understand hierarchical emergence in several different approaches to QG (Crowther, 2016). In the next section, I consider how it applies in LQG.

6.1 Hierarchical Emergence of Spacetime in LQG

LQG is still incomplete, and it is not yet clear how spacetime is to be recovered from the fundamental structures of the theory. For now, we will just assume that the kinematical aspect of LQG described above (§2.1) is roughly correct, which means assuming that *space* (rather than spacetime) is fundamentally constituted by a spin network. We will also take it that LQG is a serious contender for QG, and thus assume that GR is appropriately derivable from LQG. So, we assume that the *Dependence* condition for hierarchical emergence is satisfied.

The *Novelty* condition of emergence is plausibly satisfied because the spin network states differ from space in a number of ways; I mention three of these here. First, the spin networks represent discrete, quantum 'objects' rather than continuum spacetime.[13] Second, as has been emphasised by Huggett and Wüthrich (2013) there is a particular form of "non-locality", where it is possible for two discrete 'chunks of space' that are adjacent (directly connected to one another) in the spin network to not map to neighbouring regions in the corresponding spacetime (though this "non-locality" should be heavily suppressed, otherwise the particular spin network in question would correspond to a different spacetime, one which better reflects its fundamental structure). Third, space is supposed to be a quantum superposition of spin networks, so there is no clear notion of geometry at the fundamental level.

The *Autonomy* condition of emergence is plausibly satisfied because many different spin network states can correspond to the same (semiclassical) geometry—demonstrating the robustness of the emergent spacetime. Also, given that space is meant to correspond to a superposition of spin networks, it is autonomous from any particular definite (non-superposed) spin network state. Thus, there is a plausible claim to be made that GR spacetime is emer-

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[13] Actually, the dynamics can be thought of as not simply a 'quantum version' of GR, as this characterisation suggests, but a more radically different theory; see Oriti (2014, 2018) for more on this aspect.

gent from the fundamental structures of LQG. This is depicted in Fig. 4 as space emergent from a definite spin network state.

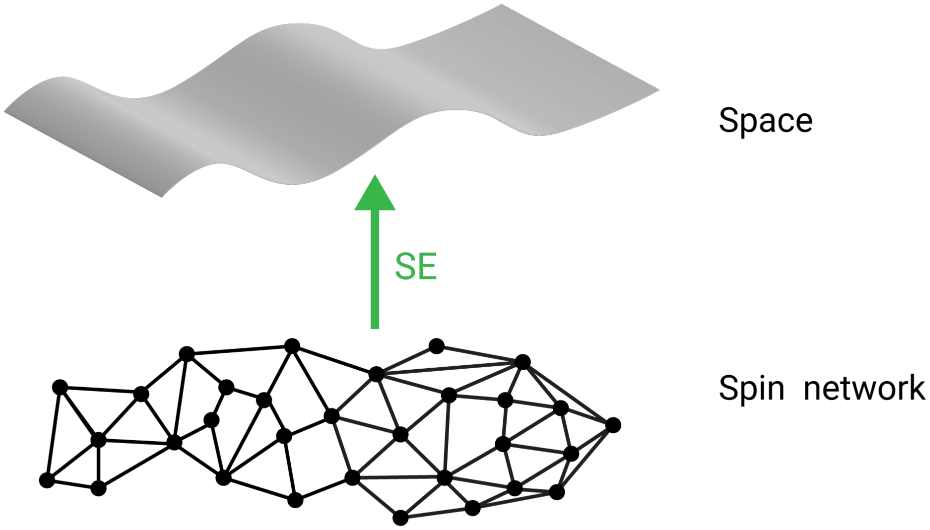

Figure 4: Space as hierarchically emergent from a spin network.

7 Flat Emergence: *Context*

Flat emergence is an analogue of diachronic emergence which does not rely on spatiotemporal notions. This conception is potentially applicable to spacetime because one of the domains where GR is expected to be incorrect, and to require replacement by QG, is at the very beginning of the universe. Using GR and current observations of the large-scale structure of the universe, cosmologists extrapolate backwards in time in order to produce a description of the past evolution of the universe. The resulting picture (described in the direction of increasing time) is the standard, or 'Big Bang', model of cosmology, which describes the universe expanding from a state of extremely high temperature and density approximately 13 billion years ago. Before this, however, there is the Big Bang singularity, which is difficult to interpret physically.

One interpretation of the singular behaviour of the model is that GR is incorrect in this domain, due to its neglect of quantum effects that become important at extreme density and temperature (in which case GR likely becomes incorrect at some finite time approaching the singularity). On this view, the singularity is an unphysical artefact—a signal that GR is inapplicable here—and thus, QG should provide a correct, non-singular description of the physics in this domain. Some approaches to QG cosmology suggest that the 'pre-Big Bang' physics is non-spatiotemporal (though there are different things this could mean, e.g., perhaps there is space, but not time, or vice-versa, or there is nothing corresponding to spacetime), in which case spacetime might emerge 'after' from this 'prior' non-spatiotemporal physics.

In order to develop an account of emergence that could potentially be applicable in this case, I consider a characteristic account of diachronic emergence, from Guay and Sartenaer

(2016) and Sartenaer (2018). On this account, the *Dependence* condition holds that E is the product of a spatiotemporally continuous process going from B, and/or E is caused by B. The Novelty condition states that E exhibits new entities, properties or powers that do not exist in B. And the *Autonomy* condition states that these new entities, properties or powers are forbidden to exist in B according to the laws governing B.

This account is not generally applicable to the case of spacetime, since it relies on spatiotemporal notions such as causation, location, and continuous processes.[14] If a spatiotemporal state is to emerge from a state that is non-spatiotemporal (or, rather, less-than-fully-spatiotemporal), we cannot assume that this is a process that itself takes place in space and time (although, in fact, some approaches to QG do utilise a notion of time, this is not in all cases able to be identified with our familiar conception of time). A more general conception of flat emergence is required if we are to account for the 'flat' emergence of spacetime from the "Big Bang" state[15] Additionally, the Guay and Sartenaer (2016) account of emergence is a negative one, requiring that E exhibit forbidden entities, properties, or powers. As explained above (§5), a negative conception of emergence is ill-suited for the case of QG, and a positive conception is to be preferred.[16]

The more general, positive conception of flat emergence that I propose is best-suited for understanding the flat emergence of our spatiotemporal universe from a non-spatiotemporal state is one that is analogous to the hierarchical conception of emergence presented in the previous section (§6).

EMERGENCE: FLAT CONCEPTION

Dependence: E flatly supervenes on B. (Flat supervenience means that there would be no change in the E state unless there were a change at the B state, but not vice versa);

Novelty: E differs remarkably from B;

Autonomy: The physics described by E is robust against changes in B. The 'prior' state, B is underdetermined by E. (This sense of underdetermination can be understood as a non- temporal form of indeterminism, meaning that many different 'initial' conditions at the B state could give rise to the same E state. If we only have knowledge of the E state, this would not be enough information to determine the 'prior' B state that it 'evolved from').

This account of emergence is very permissive, yet, it is still not trivially satisfied in the case of QG cosmology. I present an example from loop quantum cosmology that has recently been claimed to represent the emergence of spacetime from a 'prior' non-spatiotemporal state (§7.1), and argue that it is not clear how we can make sense of this. Later, I present the example of *geometrogenesis*, which is a type of approach to QG that conceives of spacetime emergent in a phase transition (§8.1). This is a case which is more readily able to be understood as flat emergence of spacetime; however, in §9, I argue that this example also is a good

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[14] Although these notions may have non-spatiotemporal analogues, e.g., causation without time (Baron & Miller, 2014, 2015; Tallant, 2019).

[15] Note that the "Big Bang" strictly refers to the GR singularity, whereas in QG cosmology, this state may not be singular.

[16] Shech (2019) also suggests weakening the novelty condition along these lines.

illustration for why it may make more sense to collapse the distinction between hierarchical and flat emergence.

7.1 Flat Emergence in Loop Quantum Cosmology

Loop quantum cosmology (LQC) is the attempt to use LQG in describing the structure and evolution of the universe. Brahma (2020) describes a particular model of LQC that aims to resolve (i.e., remove) the Big Bang singularity present in the standard model of cosmology. It must be emphasised that, like all attempts at QG cosmology, the model is not fully developed nor understood, so any interpretation is reliant upon speculation, and is highly precarious. It is not clear whether these models are physically meaningful at all.

The model discussed in Brahma (2020) starts by simplifying the system being described, so that it is a spatial geometry with just one parameter, the 'scale factor', with quantum operator $\hat{p}$. According to Huggett and Wüthrich (2018), the resulting simplified dynamical equation can be interpreted as describing the evolution of the universe, with the scale factor acting as a 'time variable' (though this reading is problematic in many ways). Running this backwards through what would otherwise be the Big Bang, we find that the singularity is not present, and that 'on the other side' of (what would otherwise be) the Big Bang, there is a 'mirror world': an expanding universe in negative 'time'. The resulting picture is standardly interpreted as 'Big Bounce', or a universe undergoing a 'Big Crunch', contracting to a maximally hot, dense state, before re-expanding (this is depicted in Fig.5a).

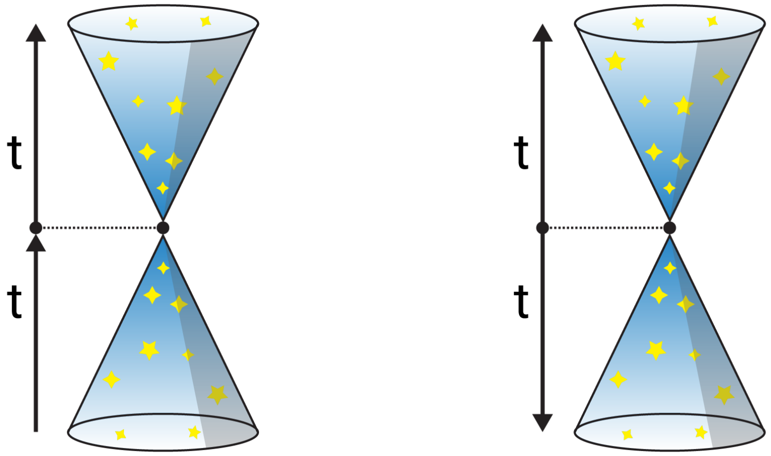

Figure 5: Two interpretations of LQC. **(a)** The standard interpretation, as a single universe contracting (bottom cone) then expanding (top tcone) in time, is made difficult by the intermediate state (middle point) having no notion of time. **(b)** Huggett & Wüthrich interpretation, as of two expanding universes that 'emerge' in positive time from the single non-temporal state (point).

At least in one particular type of model, however, Huggett and Wüthrich (2018) argue that there is an alternative picture that is better supported by the physics. In the particular model being referred to by Huggett and Wüthrich (2018) and Brahma (2020), going backward in time leads us from a relativistic spacetime to a region of Euclidean space (without time), and then back into a region of relativistic spacetime on the 'other side'. In other words, the state that replaces the Big Bang is one without any notion of time (at the macro level), and so there is not a way of 'connecting' or 'ordering' the spatiotemporal states with respect to the purely spatial state. Without a continuous time variable running through these three states, why should we say that the purely spatial state lies 'in between' the collapsing universe and the expanding one? In fact, because the collapsing universe and the expanding universe are otherwise symmetric, and its more natural to understand time as directed away from the Big Bang, Huggett and Wüthrich (2018) argue that this model is better interpreted not as a Big Bounce, but rather as a "twin birth" of two expanding universes that arise 'after' the purely spatial state (Fig.5b).[17]

Brahma (2020) claims that this model represents the emergence of time, and Huggett and Wüthrich (2018) says that it is an example of the "(a)temporal emergence of spacetime", though neither paper goes into detail about what this means or how it fits with standard conceptions of emergence. This is difficult because the physics in this example, at the macro level, can be interpreted either as a bounce or as a "twin birth". Which state emerges from which? In the bounce picture, it could be that space (without time) emerges from a collapsing spacetime, and that an expanding spacetime emerges from a space without time. While in the "twin birth" picture, it is supposed to be two expanding universes emerging from space without time. In order to apply the account of flat emergence sketched above (§7), we need to understand which state depends on which, if we are to specify what the emergent state E is, and what its basis state B is. There is not a clear way of doing this, since the model could arguably just as well represent the dissolution of spacetime as its emergence (i.e., we have these two different pictures of what the model represents). So, the Dependence condition of flat emergence is unable to be assessed, as is the Autonomy condition (since this requires understanding which state is E and which is B). Clearly, however, the Novelty condition is satisfied in this example, however (Crowther, 2020).

8 Phase Transitions

Here, I discuss phase transitions, which can be seen as examples of both hierarchical and flat emergence. It is useful to understand this, too, because there are some approaches to QG that imagine spacetime emergent in a phase transition,§8.1.

Phase transitions are qualitative changes in the state of a system; most familiar are the examples of water freezing to ice, or boiling to vapour. Of particular interest as examples of emergence are second-order phase transitions, where systems exhibit *critical phenomena.* These represent conditions under which there is no real distinction between two states of the system–for instance, between the liquid and vapour phases of water.[18] Second-order

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[17] In other LQC models, however, the 'Big Bounce' picture is arguably better-supported.

[18] Under these conditions, the system has a fractal structure, not changing as we view it at smaller length scales. In this example of the second order phase transition between liquid and vapour, as we look at smaller scales we would see liquid water droplets containing bubbles of steam, within which float even tinier liquid droplets, and so on... until we reach the scale of atoms.

phase transitions present clear examples universality (multiply-realised behaviour), where where a number of different systems—different types of fluids (e.g., with different molecular constitutions), as well as magnetic materials—exhibit the same critical phenomena.

An example is the ferromagnetic phase transition. A magnetic material at the micro level, can be pictured as comprising atoms with magnetic spins. When the temperature is low, the spins of adjacent atoms are parallel (the energy is lower if the spins on adjacent atoms are parallel than if they are antiparallel). Below a certain 'critical' temperature, (in this case it is called the Curie temperature), T_C, most of the spins in the material are parallel, and so add up constructively to give the material a net magnetisation, known as ferromagnetism. Above T_C on average half the spins point in one direction and the other half in the opposite direction, and so the material has no net magnetisation: it is a then a paramagnet. Thus, at T_C, a phase transition occurs where the material undergoes a sudden qualitative change in state: it goes from being paramagnetic, having no net magnetisation, to suddenly being ferromagnetic, having a magnetisation. This is illustrated in Fig.6.

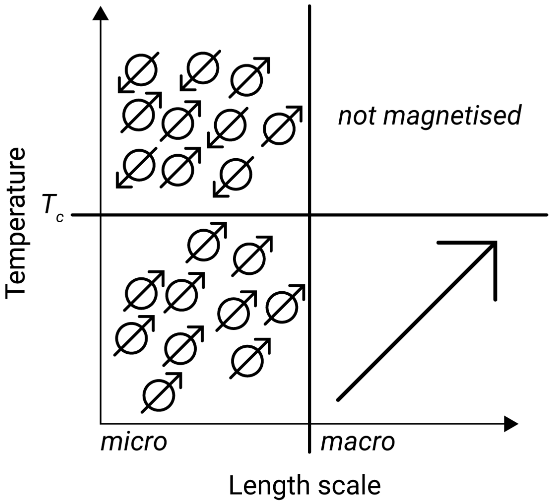

Figure 6: Ferromagnetic phase transition. At temperatures below the critical temperature, T_C, most of the atoms' magnetic spins are parallel (viewed at the micro level), and the material has a net magnetisation (ferromagnetic phase). Above T_C, the spins point in different directions and the material has no net magnetisation (paramagnetic phase).

This example represents a symmetry-breaking phase transition. When the spins are randomised, there is no preferred direction in the system: it is symmetric (looks the same no matter how you rotate it). After the phase transition, however, the spins are aligned and so there is a preferred direction: the symmetry has spontaneously been broken.

We can understand critical phenomena as heirarchically emergent behaviour, as well as flatly emergent. But these are understood separately, and depends on the perspective of interest—the two types of emergence are not related to each other in this case. Start by considering hierarchical emergence, by reference to scenario (i) of synchronic emergence (SE) depicted in Fig.3. Here, the emergent physics E (green) is at the higher level n_2 from the basis state B (purple) at the lower, micro level of atoms at n_1. The emergent physics is described by a different theory, with different degrees of freedom, than the micro physics. This is after the phase transition has occurred (at time t_2). The Dependence condition is satisfied because we can derive the emergent macro behaviour from the micro dynamics; the macro physics supervenes on the micro physics. The Novelty condition is met because there are new laws describing the emergent degrees of freedom compared to the laws governing the micro-system. The Autonomy condition is met because of the universality of the emergent behaviour: many different types of systems, of diverse micro-constitutions, nevertheless exhibit the same behaviour at criticality. This is explained by the mathematical apparatus known as the *renormalisation group*, which is used to obtain a simple coarse-grained description from a complicated micro description; it shows that the micro-details are irrelevant for describing the macro physics. This is an independent framework that is used in many different areas of physics, and demonstrates that the macro physics is largely robust against changes in the micro physics.[19]

Symmetry breaking is also a strong explanation of the universality: the emergent physics can be said to depend only on the particular symmetry-breaking pattern, and not on the details of the micro physics. Even if we can derive the macro behaviour of any given micro-system by starting out with the details of that system, the fact that there are many other different micro systems that exhibit the same macro behaviour under those conditions means that any particular 'reduction' based on a given micro-system will fail to capture the universality of the phenomena. In this sense, we might say that the micro-story *does not* and *cannot* provide an account of the emergent (universal) phenomena. Laughlin and Pines (2000) present symmetry breaking as an example of a "higher-order" organising principle, and the phenomena that depend on it are "transcendent"—insensitive to, and unable to be deduced from, micro-details. As Morrison (2012) states, too, the notion of symmetry breaking is not itself linked to any specific theoretical framework, rather, it functions as a structural constraint on many different kinds of systems, both in high-energy physics and condensed matter physics.

Phase transitions can also be understood as examples of flat emergence. This means looking only at the system at one level, in this case we consider the micro level. This can be understood by reference to the depiction (ii) of diachronic emergence (DE) in Fig.3. The basis state, B is the state of the system before the phase transition (as depicted at time t_1 in Fig.3) and the emergent state E is the one after the phase transition (at t_2). E and B are different states of the same system, described by different models of the same theory. The change has occurred in the system because of the different conditions (i.e., the change in temperature). The way in which E depends on B is not so obvious, but perhaps we can say that there is some non-temporal notion of causality that can give a sense of flat supervenience, where there would be no change in the E state unless there were a change in the B state, and not vice versa.[20]. The Novelty condition is more obviously satisfied, with B being a state in which there is no preferred direction (symmetric), and E being one with a preferred direction (broken symmetry). The Autonomy condition would hold that E can arise from many different B micro states, e.g., there are many random arrangements at a temperature

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[19] See Bain (2013); R. W. Batterman (2005, 2011); Franklin (2018b); Rivat and Grinbaum (2020) for more on this.

[20] Cf. Footnote 14

above T_C that will result in the same E at temperatures below T_C. The particular microstate of B is thus underdetermined given only the E state.

8.1 Geometrogenesis

Pregeometric approaches to QG describe spacetime emergent in a phase transition known as *geometrogenesis*. There are several approaches of this type, but here I consider just one simple example, *quantum graphity*.[21] The fundamental structure described by this approach is represented as a graph: points represent events, which are causally related if there is a connection (link) between them. This system is quantum-mechanical, and its dynamics is represented as a change in the connections between the points. The connections, represented by the links of the graph, are able to be in two states 'on' or 'off', and, being quantum-mechanical, the generic states are superpositions of both 'on' and 'off'.

In the early universe, prior to the phase transition, space does not exist. At the micro-level, this is depicted as a maximally connected graph: every point is connected to every other point (t_1 in Fig. 7). This means that everything in the universe is adjacent to every other event, and so there is no notion of geometry or locality. In this state, the dynamics is invariant (symmetric) under permuation of the events (they cannot be distinguished by their connections). As the universe cools and condenses, it undergoes a phase transition in which many of the connections switch off. The system at low-energy (i.e. at its ground state) is a graph with far fewer edges (t_2 in Fig. 7): the permutation invariance breaks, and instead translation invariance arises. At this stage locality is able to be defined and we gain a sense of relational geometry. The idea is that geometry emerges in this phase transition, known as *geometrogenesis*. This is illustrated in Fig. 7.

Note that, in these approaches, there is a notion of time at the fundamental level, that connects the pre- and post-geometric phases. Spacetime is supposed to be associated with the geometric phase, such that the post-geometric phase is a finer-grained (lower-level) description of GR spacetime (being the higher-level phenomenon). But flat emergence concerns only a single level; here we consider the system just at the more-fundamental level of the discrete structures, rather than the 'phenomenal' spacetime. So, the emergence basis B is taken as the model describing the pre-geometric phase (t_1 Fig. 7), and the emergent model E describes the geometric phase (t_2 Fig. 7).

The Dependence condition can be understood as flat supervenience, since there is no change in the E state unless there is a change in the B state, and not vice-versa. This is ensured by the temporal aspect of these models, such that the B state causally precedes the E state via the theory's evolution equation, and the two states are supposed to be of the same system, being the entire universe. The Novelty condition is satisfied given the different symmetries characterising the two states: B is permutation invariant, while E is not permutation invariant (but is translation invariant). Finally, the Autonomy condition is plausibly satisfied, since E depends only on the broken symmetry pattern that the system instantiates, rather than the details of B.

Thus, there is a plausible sense in which spacetime could potentially be flatly emergent on these models (one which would arguably also apply to any symmetry-breaking phase transition). But there is also a sense of hierarchical emergence here. Unlike in more familiar cases

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[21] For details: Konopka, Markopoulou, and Severini (2008); Markopoulou (2009). Another active approach to geometrogenesis is in group field theory, see Oriti (2009, 2014).

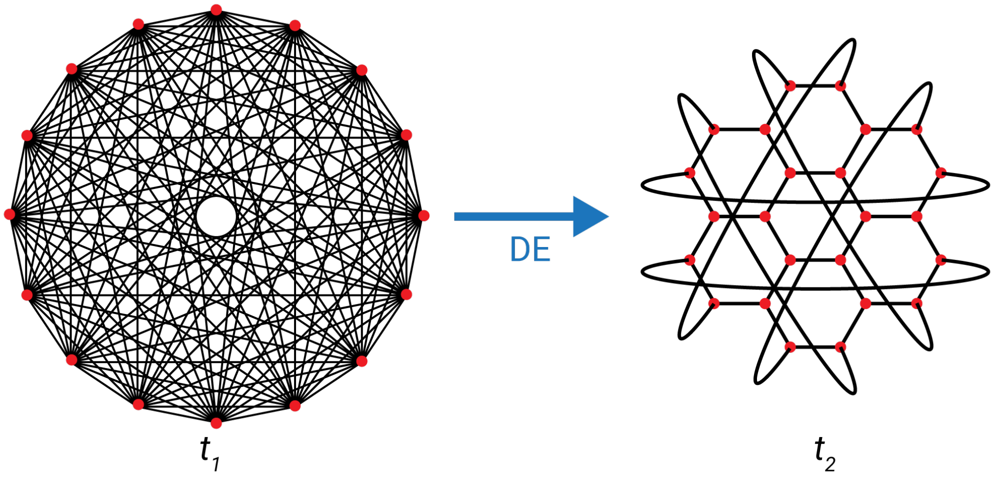

Figure 7: Geometrogenesis as flat emergence (DE). (t_1) High-energy (pre-geometric) phase of quantum graphity, in which every point is connected to every other point. (t_2) Low-energy (geometric) phase of quantum graphity, in which there are fewer connections between the points, resulting in the emergence of a conception of locality. Figure adapted from Markopoulou (2009).

of phase transitions, however, this is identical with the flat emergence in geometrogenesis. This is because there is no macro state corresponding to the pre-geometric phase of the universe. The emergent macro state of the universe is associated with the post-geometrogenesis phase. These models can be seen as simulataneously representing both the 'diachronic' (flat) emergence of spacetime from the (state replacing the) 'Big Bang' as well as the 'synchronic' (hierarchical) emergence of spacetime from its 'atoms'. In other words, the content (spacetime) is emergent along with the context (the conditions required for the geometrogenesis phase transition).

9 Collapsing the Distinction

So far, I have presented two different accounts of emergence, applicable to different scenarios: the case of spacetime emergent from some more-fundamental 'atoms' is a possible example of hierarchical emergence, while spacetime emergent from some 'prior' non-spatiotemporal state (replacing the Big Bang singularity) is a possible example of flat emergence. But in the case of spacetime, it may be more natural to think of them as representing the same situation. The conditions we encounter as we extrapolate backwards in cosmological time, and see the universe contracting to a very high-energy state, are the same conditions required to move to the 'lower-level', finer-grained picture of the 'atoms' of the universe (the most fundamental structures). This is the connection between cosmology and high-energy particle physics. Understanding these two senses of emergence as lacking a distinction in the case of spacetime is not exemplified in the case of LQG and LQC, as presented here. But it is more apparent in the case of geometrogenesis, which illustrates the possibility of collapsing the two conceptions of emergence: it is a case where both types of emergence obtain simultaneously.

Collapsing the distinction may seem natural, too, given how difficult it is to accommodate the more standard conceptions of emergence in the case of spacetime. The distinction between flat and hierarchical emergence is intuitive, but loses this motivation when we are forced to abstract away from spatiotemporal notions. We had to define the 'micro' and 'macro' levels in hierarchical emergence not by reference to length scales, in spite of the connotations of the labels 'micro' and 'macro'. On the other hand, we run into problems understanding the Dependence condition in flat (diachronic) emergence without a notion of time, and rely on a non-temporal sense of causation, or flat supervenience, to link the emergent state to its 'prior' basis. Representing the flat and hierarchical emergence of spacetime as the same scenario from the outset may be a simpler way of envisioning spacetime emergence. For instance, it might help us solve the problem of Dependence in flat emergence: the 'prior' or basis state may be identified as the one lacking a macro state, which emerges *along with* the emergent micro state, as in geometrogenesis.

Arguably, the more general conception of emergence, presented in §5, is suitable for capturing the relevant sense of 'collapsed' or 'no levels' emergence. This account is supposed to be a balance of prescriptive and descriptive: to potentially be useful for understanding the unique case of spacetime emergence, while still attempting to capture enough of what is usually meant by 'emergence' in philosophy. But an alternative may be to develop a more radical account of emergence, that departs further from resemblance to more standard accounts of emergence in philosophy. For instance, we might explore abandoning the asymmetry typically required for emergence, by removing the Dependence condition. Such a conception would then be more readily applicable to the case of LQC, as an example, and we could say that the model of §7.1 does actually represent *both* the emergence and dissolution of spacetime.

10 Conclusion

Understanding emergence in QG is difficult because we do not have a fully-developed theory. We are trying to interpret fragmentary pieces of theories that may not even be meaningful to speculate about at this stage. Nevertheless, philosophical exploration can still be interesting here, and potentially useful in anticipating what spacetime emergence may be like, and perhaps for suggesting new avenues to explore.

Standardly, there are two different senses in which spacetime is thought to emerge according to QG, and QG cosmology. I've recommended a positive conception of emergence, based on other case studies in physics, that can be framed to fit either the hierarchical case, of spacetime emergent from some more fundamental structures, or the flat case, of (a 'micro' structure corresponding to) spacetime emergent from some 'prior' non-spatiotemporal state, as described by models of QG cosmology. But splitting this conception of emergence into the two specific accounts may not be necessary—it may be more natural to collapse the distinction between flat and hierarchical emergence in the case of spacetime, given that the way these two accounts are normally distinguished is by reference to spatiotemporal notions, and the possibility of QG models where the 'micro dynamics' responsible for the appearance of spacetime is the same in the early universe as it is at a high-energy, finer-grained description of our universe 'now'. It is a case where, possibly, *content* emerges along with *context*.

Acknowledgements

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