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The singular case of spacetime singularities in quantum gravity

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Abstract
Spacetime singularities are expected to disappear in quantum gravity. Singularity resolution prima facie supports the view that spacetime singularities are mathematical pathologies of general relativity. However, this conclusion might be premature. Spacetime singularities are more accurately understood as global properties of spacetime, rather than things. Therefore, if spacetime emerges in quantum gravity – as it is often claimed – then so may its singular structure. Although this proposal is intriguing, the attempt to uphold that spacetime singularities may be emergent fails. I provide three arguments in support of this claim, drawing upon different views on spacetime emergence.

1. Introduction

What kind of entities are spacetime singularities? A naive characterization of spacetime singularities is that of points at which some physical quantity goes to infinity (e.g. curvature, density, etc.), or of missing points in spacetime that abruptly interrupt the wordlines of what ‘falls into them’. As we will see afterward (§3), these intuitive descriptions are inaccurate. Still, they capture some important traits of spacetime singularities. In particular, the link with infinities is one of the main reasons why singularities are frowned upon by many physicists and philosophers (Ellis et al., 2018).

The predominant view is that spacetime singularities are just mathematical pathologies of general relativity (GR) which ensue due to the limits of the theory. In other words, singularities are thought of as signals that GR breaks down in certain circumstances and is not trustworthy anymore. However, this is not the only stance. More tolerant attitudes towards singularities have been proposed in the literature (Earman, 1996; Crowther and Haro, 2022).

Despite the general abhorrence of spacetime singularities, they extensively appear in models of GR. Several theorems show (e.g. Penrose 1965; Hawking 1965, 1966; Hawking and Penrose 1970; Geroch 1970) that singularities are unavoidable in GR under some physically reasonable conditions. While this result seems to suggest that spacetime singularities should be considered physically seriously since they are predictions of one of our best-established physical theories (Earman, 1996), it has also prompted the opposite reaction. Singularity theorems have sometimes been taken to indicate that GR “contains the seeds of its own destruction” (Bergmann and Woolf, 1980, 186).

This stance is prima facie supported by research at the frontiers of physics. Spacetime singularities are generally expected to disappear in quantum gravity (QG). Singularity resolution is used as an umbrella term to indicate the various mechanisms that permit the avoidance of some types of spacetime singularity in theories of QG. There are at least two good reasons to assume that singularity resolution is a feature of the (yet-to-come) definitive theory of QG. First, this assumption is supported by several works in different research programs in QG (e.g. Bojowald 2001; Ashtekar et al. 2006; Rideout and Sorkin 1999; Mathur 2005). Second, the disappearance of spacetime singularities in QG is suggested by analogy with other physical theories in which the classical singularities vanish upon quantization.[1] Although, as will also be mentioned in §3, the analogy with the singularities of other theories must be taken gingerly.

I argue that, upon the reasonable assumption of singularity resolution in QG, spacetime singularities should not be considered physical entities, if not in a very weak sense. In other words, QG provides good reasons to maintain that spacetime singularities do not exist.[2] In this work, I provide an example of singularity resolution in QG (§2.1) and put forward an argument to the effect that singularities are just mathematical pathologies of GR (§2.2). Then, I consider an objection to the argument based on the idea that singularities may be emergent (§3). Finally, I present three arguments against that idea and reply to possible objections (§4).

2. Singularity resolution

2.1. Bouncing models in loop quantum cosmology

The vanishing of the Big Bang singularity in loop quantum cosmology (LQC) provides a case study of singularity resolution. Loop quantum gravity (LQG) carries out a canonical quantization of relativistic spacetime to get to a quantum spacetime. In order to do this, GR is reformulated as a Hamiltonian system with constraints. While the kinematical structure of the theory is well-established, there is no consensus on how to deal with the dynamics. Loop quantum cosmology does so by restricting the space of admitted models. More precisely, LQC is a symmetry-reduced version of LQG that covers the cosmological sector of the full theory by studying simplified models.[3,4]

In LQC, cosmological singularities are solved thanks to the fundamental discreteness of the quantum geometry.[5] Because of the underlying quantum geometry, the relevant physical observables are normally represented by bounded operators, whose expectation

[1] This does not mean that *every time* that quantum physics is involved singularities are avoided. Well-known counterexamples are UV-divergencies in quantum fields theory.

[2] In this work, I often use interchangeably the claim that spacetime singularities are not physical and the claim that they do not exist. However, I do not want to take any specific stance on the existence of non-physical things (e.g. mathematical objects). When I say that singularities do not exist, what I mean is that they do not have actual physical existence. What *this* means is not easy to state exactly. For the moment, we can settle for the idea that something has physical existence if it is unavoidably involved in physical explanations or successful empirical predictions/observations.

[3] Flat isotropic homogeneous models.

[4] See Bojowald (2011) for a detailed but accessible introduction to LQC.

[5] This presentation is based on Bojowald (2001), Ashtekar et al. (2006), Ashtekar (2009), and Huggett and Wüthrich (2018).

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values remain finite even in the regime in which they classically diverge and become singular. The classical equations are modified accordingly. The resulting quantum evolution predicts an effective repulsive force when density and curvature approach the Planck scale. Unlike the classical situation, in which density and curvature go to infinity and result in the Big Bang singularity, this effective repulsive force overcomes the gravitational attraction and makes the universe expand again. The initial singularity is thus replaced by a bounce. In this way, LQC provides a non-singular description of the early universe.

This generic example of singularity resolution exhibits some interesting characteristics. First, the modified classical equations are such that allow for an effective spacetime description, i.e. the relevant GR solutions are recovered in the appropriate classical limit (Ashtekar et al., 2008; Ashtekar and Singh, 2011; Singh, 2014). This shows that GR is a good approximation of the more fundamental theory at low energies and curvature. Secondly, it is possible to rigorously compute – also through the use of computer simulations (Ashtekar et al., 2006) – the quantum evolution at the bounce. In particular, it has been shown that the bounce occurs when energy density reaches a maximum value $\rho_{max} \approx 0.41\rho_{Pl}$. Finally, the quantum evolution remains well-defined through the bounce, while the classical description breaks down. As a consequence, the quantum geometry acts as a 'quantum bridge' joining the pre-bounce and post-bounce structures in the Planck regime. Although these two structures have a spatiotemporal interpretation as classical universes,[6] no spatiotemporal interpretation is available for the region in the deep quantum regime (Huggett and Wüthrich, 2018; Brahma, 2020).

2.2. A simple argument against singularities

The naive reasoning on how the debate on the status of singularities changes in light of singularity resolution goes as follows. In GR, although the prevailing view is that singularities are just mathematical pathologies, singularity theorems show that spacetime singularities are unavoidable under physically reasonable conditions. However, this hurdle is overcome in QG: spacetime singularities disappear. Then, singularity resolution seems to vindicate the prevailing view that spacetime singularities are only mathematical pathologies of GR.

Let me try to structure this reasoning into a rigorous argument.

(1) Spacetime singularities are avoided in QG.
(2) If spacetime singularities are avoided in QG, then spacetime singularities do not exist fundamentally.
(3) Spacetime singularities do not exist fundamentally.
(4) If spacetime singularities do not exist fundamentally, then they are mathematical pathologies of GR.
(C) Spacetime singularities are mathematical pathologies of GR.

Is the argument sound? The first premise is the main assumption of this work. The third one is obtained by modus ponens from the first and the second. Thus, my main focus is on (2) and (4). The justification for (2) is the following:

[6] They can be interpreted either as one contracting and the other expanding, or as both expanding in opposite directions (in which case there is no bounce). See Huggett and Wüthrich (2018) and Wüthrich (2021) for a defense of the latter option.

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(i) If a more fundamental theory avoids the singularities present in a less fundamental theory, then those singularities do not exist fundamentally.
(ii) The (yet-to-come) definite theory of QG is more fundamental than GR.
(2) If spacetime singularities are avoided in QG, then spacetime singularities do not exist fundamentally.

Both (i) and (ii) are commonly accepted claims. (i) is based on the idea that what exists fundamentally is determined by our fundamental physical theories. (ii) is a basic condition for theories of QG.

The fourth premise of the main argument is the most problematic. Why should the conclusion that singularities are just mathematical artifacts follow from the fact that they do not exist fundamentally? To make the argument work, additional strong metaphysical assumptions are necessary. Without them, there seems to be a way out of the argument: spacetime singularities may be emergent.

3. A new hope for singularities

Spacetime singularities are not to be easily sentenced. The above argument against singularities can be attacked by rejecting the fourth premise: spacetime singularities may be emergent. To defend this view, it is necessary to delve into two further aspects concerning singularities and QG: the definition of spacetime singularities and spacetime emergence.

First, consider the task of defining spacetime singularities in GR. Part of the confusion on their nature derives exactly from the difficulty in providing a satisfying definition, as testified to by several analyses of this issue (Geroch, 1966; Earman, 1995, 1996; Curiel, 1999). The source of the problem has to do with the misleading inclination to treat singularities as localizable things. However, spacetime singularities are neither localizable things nor points of spacetime (Hoefer and Callender, 2002, 187). This does not mean that it is *in principle* impossible to provide a rigorous definition of singularities-as-things, i.e. a local definition. But one would need to do so by characterizing them as boundary points of singular spacetimes and equipping them with a certain topological structure (Earman, 1996, 625). No such definition has been successfully provided so far and might not be possible *in practice*.[7] Therefore, actual definitions deal with singular spacetimes instead of singularities.[8]

Among the different proposals on what it takes for a spacetime to be singular, the standard one is in terms of geodesic incompleteness. A spacetime is singular if and only if it is geodesically incomplete, that is to say, if and only if it contains a maximally extended timelike or null geodesic that terminates after a finite lapse of proper time. It is important to highlight that geodesic incompleteness is a global property of spacetimes (Curiel, 1999, 138).[9] This is so because there is no point at which a geodesic comes to an end any more than there is a point at which the spacetime is singular. Therefore,

[7] See Curiel (1999, §4) for an analysis of attempts to construct boundary points.

[8] This highlights an important dis-analogy between spacetime singularities and those of other physical theories. In other theories, singularities can be treated locally since we can always resort to the background space(time) to specify their location, whereas this is not possible for spacetime singularities. The requirement of a global treatment is a unique feature of spacetime singularities.

[9] A property P on a spacetime is local if, given any two locally isometric spacetimes, one has P if and only if the other has P. A property on a spacetime is global if and only if it is not local (Manchak, 2009, 55).

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actual definitions reinforce the idea that there might be no way to study singular behavior locally. To be properly understood, the singular structure must be conceived as a global property of spacetime (Geroch and Horowitz, 1979, 296).

The shift of perspectives from considering a singularity a localizable thing to regarding it as a property plays a crucial role in the attempt to object to the argument in §2.2. I should specify that the singularities typically solved by QG are strong curvature singularities (e.g. the Big Bang and black hole singularities) and other cosmological singularities. However, the definition in terms of geodesic incompleteness is more general and includes also other singularities not affected by QG. Given that the focus of this paper is on the singularities solved by QG, I will not discuss the status and plausibility of the other types of singularities.[10]

The other key element to formulate the objection is the emergence of spacetime. Singularity resolution shows that spacetime singularities vanish at the fundamental level. In addition, even spacetime itself is said to disappear in QG (Huggett and Wüthrich, 2013; Crowther, 2016; Oriti, 2021; Baron, 2019, 2021b). In other words, spacetime might not exist fundamentally. However, it has been argued that spacetime must be recovered at a derivative level to avoid the threat of empirical incoherence (Huggett and Wüthrich, 2013).[11] The idea of spacetime emerging from a fundamental non-spatiotemporal structure is widespread in QG and different accounts of spacetime emergence have been proposed, as we will see in the next section.

We can now see how spacetime emergence combined with the understanding of singularity as a global property of spacetime can be articulated to reject the fourth premise. If spacetime emerges in QG, then singular spacetimes emerge as well. This suggests that the status of singularities can be restored in the same sense in which that of spacetime is in QG. Thus, against the received view, singular structure may be considered an emergent property.

4. Do singular spacetimes emerge?

To assess whether or not singular spacetimes can emerge, we should look at how spacetime emergence works in QG. In this section, I put forward three arguments against the proposal presented in the previous section. Each argument is based on a different view on spacetime emergence defended in the literature.

4.1. The argument from eliminativism

The hope of recovering the singular structure together with spacetime in QG relies on the assumption that spacetime emerges from an underlying non-spatiotemporal structure. However, according to spacetime eliminativism, the lesson from QG is not only that spacetime does not exist fundamentally but also that it does not exist at all: spacetime does not emerge (Baron, 2019, 2021a). Under this view, the idea that the singular structure enjoys the same ontological status as spacetime in QG goes against the hope

[10] Still, it is worth mentioning that these other singularities are often believed to be solved or prohibited in other ways.

[11] A theory is empirically incoherent if the truth of the theory undermines our empirical justification for believing it to be true (Huggett and Wüthrich, 2013, 277).

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of (re)instating singularities. According to spacetime eliminativism, spacetime does not exist, so neither does its singular structure.

It could look like the claim that spacetime does not exist clashes with the idea that QG must recover relativistic spacetime in the domains in which GR is successful. However, a distinction needs to be made between spacetime as a mathematical entity (ME), i.e. a model of GR, and spacetime as a physical entity (PE), i.e. the four-dimensional entity we refer to when we say, for example, that spacetime is relational rather than absolute.[12] This distinction helps to clarify the content of spacetime eliminativism: this view maintains that spacetime (PE) does not exist, without denying the possibility of a formal, mathematical derivation of GR from QG. Some spacetimes (ME) are expected to be recovered as limit cases of QG, independently of whether or not spacetime (PE) is said to emerge. Henceforth, spacetime emergence always refers to spacetime as a physical entity. If one believes that spacetime eliminativism is the correct approach to the question of spacetime emergence, then the hope of restoring singularities quickly sinks.

4.2. The argument from composition

The general notion of emergence used in the philosophy of quantum gravity involves at least novelty and dependence (Butterfield and Isham, 2000; Butterfield, 2011*a*; Crowther, 2016), and it is usually compatible with reduction (Butterfield, 2011a,b; Crowther, 2016; Huggett and Wuthrich, 2025). The dependence condition establishes asymmetry between the basis and the emergent phenomenon. The novelty condition ensures that the relation captures some important qualitative differences, e.g. a novel behavior or property that is not exhibited by the basis.[13] The case of spacetime arising from theories of QG seems to satisfy both conditions. The spacetime structure emerges from the more fundamental degrees of freedom, on which it depends, by manifesting strikingly novel features in the domains in which GR works (i.e. low-energy regimes). But how can the emergence of spacetime be understood more specifically?

Recent papers (Le Bihan, 2018; Baron and Bihan, 2022*a*,b) analyse it in terms of composition. Drawing upon the proposal in Paul (2002, 2012), the mereological approach to spacetime emergence appeals to a notion of *logical* composition. According to this notion, the relation of composition can apply inter-categories and is topic-neutral. On this basis, it is argued that spacetime and spatiotemporal relations are composed of non-spatiotemporal parts. The only requirement for the topic-neutral parthood relation is to satisfy the basic mereological axioms and definitions.

The mereological approach maintains that non-spatiotemporal entities of QG compose spacetime. However, the fundamental degrees of freedom do not always give rise to spacetime. Theories of QG contain models without any emergent spacetime and other models with domains without an emergent spacetime (Wüthrich, 2021). “Only when the structure is of the right type, where that means that it is governed by the right laws, will spacetime emerge” (Baron and Bihan, forthcoming, 23). This means that composition does not always occur. “Composition occurs when, and only when, we may map an entity from the spatial structure onto a plurality of entities that are parts of the non-spatial structure” (Le Bihan, 2018, 13). There is no precise answer to the question

[12] This is a *conceptual* distinction. In GR, it sometimes collapses *in practice* given that (at least some) mathematical models are supposed to provide a complete description of the physical entity.

[13] The robustness of emergent features to changes in the basis is also sometimes mentioned.

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of when exactly the non-spatiotemporal building blocks compose spacetime. Further developments in physics are necessary to advance an answer since a satisfying explanation requires an established theory of QG and depends on how the details of its relation with GR are worked out.[14] However, it seems possible to identify a minimal condition for spacetime composition: spacetime is composed only in the domains in which GR applies, that is to say, in which GR is a good approximation of the fundamental theory.

So, why should we expect the property of being singular to emerge? As shown by works on singularity resolution, GR and theories of QG have radically different predictions concerning singular behavior.[15] Take, for instance, LQC and the early universe. In §2.1, we have seen that a quantum bounce replaces the classical singularity in models of LQC. The quantum geometry bridging the two effective spatiotemporal phases at the bounce does not have a spatiotemporal interpretation. So, spacetime composition does not occur at the bounce. In other words, given that composition occurs only in the domains in which GR applies and singularity resolution indicates one of the domains in which GR does not apply, the singular structure does not emerge by composition.

4.3. The argument from functionalism

According to the functionalist accounts of spacetime emergence (Lam and Wüthrich, 2018; Lam and Wüthrich, 2021), the functionally relevant features of relativistic spacetimes are recovered by having their roles fulfilled by entities belonging to the fundamental ontology. The functionalist approach does not claim that the *full* spacetime must be functionally recovered. Rather, only *some* spatiotemporal features emerge from underlying non-spatiotemporal states. How this can be achieved is spelled out in a two-step process (Lam and Wüthrich, 2018). First, the functional roles of the relevant spatiotemporal properties must be specified. Secondly, the fundamental entities that can fill these functional roles are individuated, and it is provided an explanation of how they manage to do so.

A preliminary argument against the emergence of the singular structure can be framed as follows. Being singular is a *global* property of spacetime, which means that it is a property of the whole spacetime taken together. As such, it applies to the entire spacetime. However, according to the functionalist account, relativistic spacetime does not fully emerge but only some of its features do. So, there is no entire spacetime that can instantiated this global property. Therefore, the status of singularities cannot even be that of an emergent global property.

A red flag immediately rises. Some undesired consequences seem to follow from a generalization of this argument. On the same ground on which the global property of being singular is ruled out, all the other global properties of spacetime should be ruled out as well. Thus, there could be no emergent global spacetime properties. This is problematic because we want to say that *some* global properties can emerge. However, this objection is not fatal for functionalism. In a functionalist fashion, one could argue that some global properties can emerge without applying to the full spacetime structure but

[14] Moreover, it could be that composition never occurs: the mereological approach to spacetime emergence as a whole might turn out to be inappropriate.

[15] Note that it is not even a matter of recovering the successful predictions of the classical theory but of *correcting* them, analogously for example to the ultraviolet catastrophe in the context of black-body radiation.

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simply by having their functional role fulfilled by the fundamental degrees of freedom. But then, another worry arises: why cannot the property of being singular functionally emerge?

The answer is that the property of being singular does not have any physically salient spacetime role. Although a lack of a precise account of physical salience in QG, it should involve at least physical explanations and successful empirical predictions. In light of singularity resolution, neither of these applies to the property of being singular. The latter point about predictions is especially compelling given the disagreement with results from QG.

One could still try to argue that there is a way to assign a functionally relevant spacetime role to singularities, even in light of singularity resolution. The strategy consists in finding a functional role based on some observable phenomena. For example, one could try to characterize it by referring to gravitational and tidal forces, which are arguably physically significant phenomena. However, there is a serious mismatch between what is functionally characterized and its suggested functional characterization: one is a global property, while the other is based on local effects. Even more baffling, different observers in different states of motion can experience radically different tidal forces in the same region (Curiel, 1999, 126-29). A functional characterization of this kind is inadequate since it cannot capture the global aspect of the property it is supposed to characterize. Therefore, even this strategy turns out not to be very promising for defenders of singularities.

Moreover, even supposing – for the sake of argument – that being singular can be somehow included among the relevant spacetime functions, the possibility of its functional emergence is doubtful. The avoidance of singularities in QG indicates that there is nothing in the fundamental theory that can fulfill the function of being singular, i.e. the second step of the functionalist account cannot be completed. Consider the curvature blow-up in the example regarding the Big Bang singularity in LQC. The disappearance of the singularity arises from the properties of the operators, such that no blow-up occurs and the quantum evolution through the bounce is non-singular. The physics at the Planck regime does not have any elements that can be functionally connected to curvature blow-up, i.e. that can play such a role.

But how can this apply to the more general singular behavior exhibited by geodesic incompleteness?[16] Referring again to the example of LQC, several results (Ashtekar and Singh, 2011; Singh and Vidotto, 2011; Singh, 2014) show that the solution of singularities provides us with modified classical equations such that the effective spacetime is geodesically complete.[17] So, we can hope that emergent spacetimes always turn out to be geodesically complete. Unfortunately, this is not so straightforward. In GR, generally, there can be spacetimes without blow-up but still with incomplete geodesics.[18] As specified above, not all the singularities are solved by QG. However, if the claim is just that there can be geodesic incompleteness even once we achieve singularity resolution

[16]Given the lack of classical trajectories, there is no unambiguous notion of geodesic available in the purely QG context. Therefore, trivially, there is also no geodesic incompleteness.

[17]Curiously, these papers also show that LQC does not solve the so-called ‘weak singularities’, such as sudden singularities which exhibits a divergence in pressure but do not disrupt the path of geodesic so that spacetime remains geodesically complete. Given that these cases do not fall under the definition of singularities as geodesic incompleteness, they are not relevant to the question here considered.

[18]See Earman (1996).

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in QG, it does not compromise the conclusion that (at least) the singularities solved by QG do not give rise to an emergent singular structure.[19]

A different objection is based on the claim that the emergent spacetime may be singular – even if nothing plays the role of a strong curvature singularity and there are no other sources of singular behavior – simply because the singular structure might still be readable in some limit cases from the equations describing spacetime in low-energy approximations. However, in light of the above discussion, such a feature would not be functionally emergent but merely mathematically derivable. In other words, the property of being singular may be assigned to some models of GR, but it does not emerge in QG. This suggests that it should be considered a property of spacetime as a mathematical entity (i.e. of models of GR) but not of the emergent spacetime.

Under a more permissive understanding of physicality, there is a weak sense in which such a property could be considered physical, namely that of being a signal for something else, i.e. pointing to fertile ground for new physics. Still, this position is compatible with the conclusion that singular spacetimes do not emerge according to the main views on spacetime emergence in QG.

5. Conclusion

The fate of spacetime singularities in QG is often taken for granted. In this work, I hope to have shown that the debate on the nature of singularities widespread in GR carries over into QG, in another form. Singularities are not part of the basic ontology of theories of QG, but they could be emergent. Therefore, there are still meaningful and interesting questions to ask about their nature and status.

The main contribution of this paper is to refine the standard view against spacetime singularities in light of singularity resolution in QG. I structured the prevailing opinion about spacetime singularities in QG in a precise argument. Then, I considered a way out: singularities may be emergent. Finally, I provided three arguments based on different views on spacetime emergence to show that this way out turns out to be a dead end. I conclude that if singularity resolution were to be borne out we would have good reasons to consider spacetime singularities not to be physical, if not in a weak sense.

[19] In these cases, the singular behavior is to ascribe to some other feature of spacetime (e.g. exotic patching of different metrics). I plan to discuss their physicality and plausibility in future works.

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References

Ashtekar, A. (2009). Singularity Resolution in Loop Quantum Cosmology: A Brief Overview. *Journal of Physics: Conference Series 189*, 012003. arXiv:0812.4703 [gr-qc].

Ashtekar, A., A. Corichi, and P. Singh (2008). Robustness of key features of loop quantum cosmology. *Physical Review D 77*(2), 024046. arXiv:0710.3565 [gr-qc, physics:hep-th].

Ashtekar, A., T. Pawlowski, and P. Singh (2006). Quantum nature of the big bang. *Physical Review Letters 96*(14), 141301. https://doi.org/10.1103/PhysRevLett.96.141301.

Ashtekar, A. and P. Singh (2011). Loop quantum cosmology: a status report. *Classical and Quantum Gravity 28*(21), 213001. http://dx.doi.org/10.1088/0264-9381/28/21/213001.

Baron, S. (2019). The curious case of spacetime emergence. *Philosophical Studies 177*(8), 2207–2226. https://doi.org/10.1007/s11098-019-01306-z.

Baron, S. (2021a). Eliminating spacetime. *Erkenntnis 88*(3), 1289–1308. https://doi.org/10.1007/s10670-021-00402-z.

Baron, S. (2021b). Parts of spacetime. *American Philosophical Quarterly 58*(4), 387–398. https://doi.org/10.2307/48619322.

Baron, S. and B. L. Bihan (2022a). Composing spacetime. *Journal of Philosophy 119*(1), 33–54. https://doi.org/10.5840/jphil202211912.

Baron, S. and B. L. Bihan (2022b). Quantum gravity and mereology: Not so simple. *Philosophical Quarterly 72*(1), 19–40. https://doi.org/10.1093/pq/pqab016.

Baron, S. and B. L. Bihan (forthcoming). Causal theories of spacetime. *Noûs*. https://doi.org/10.1111/nous.12449.

Bergmann, P. and H. Woolf (1980). Some strangeness in the proportion. In *A Centennial symposium to celebrate the achievements of Albert Einstein, Addison-Wesley, Reading, Massachusetts*.

Bojowald, M. (2001). Absence of singularity in loop quantum cosmology. *Physical Review Letters 86*(23), 5227–5230. https://doi.org/10.1103/PhysRevLett.86.5227.

Bojowald, M. (2011). *Quantum Cosmology: A Fundamental Description of the Universe*. Lecture Notes in Physics. New York: Springer-Verlag.

Brahma, S. (2020). Emergence of time in loop quantum gravity. In Huggett, Matsubara, and Wüthrich (Eds.), *Beyond Spacetime: The Foundations of Quantum Gravity*, pp. 53–78. Cambridge University Press.

Butterfield, J. (2011a). Emergence, reduction and supervenience: a varied landscape. *Foundations of Physics 41*(6), 920–959. https://doi.org/10.1007/s10701-011-9549-0.

Butterfield, J. (2011b). Less is different: Emergence and reduction reconciled. *Foundations of Physics 41*(6), 1065–1135. https://doi.org/10.1007/s10701-010-9516-1.

Butterfield, J. and C. Isham (2000). Spacetime and the philosophical challenge of quantum gravity. In *Physics Meets Philosophy at the Panck Scale*. Cambridge University Press.

Crowther, K. (2016). *Effective Spacetime*. Springer International Publishing.

Crowther, K. and S. D. Haro (2022). Four attitudes towards singularities in the search for a theory of quantum gravity. In A. Vassallo (Ed.), *The Foundations of Spacetime Physics: Philosophical Perspectives*, pp. 223–250. Routledge.

Curiel, E. (1999). The Analysis of Singular Spacetimes. *Philosophy of Science 66*, S119–S145. https://doi.org/10.1086/392720.

Earman, J. (1995). *Bangs, Crunches, Whimpers, and Shrieks: Singularities and Acausalities in Relativistic Spacetimes*. Oxford University Press USA.

Earman, J. (1996). Tolerance for spacetime singularities. *Foundations of Physics 26*(5), 623–640.

Ellis, G., K. Meissner, and H. Nicolai (2018, 07). The physics of infinity. *Nature Physics 14*. https://doi.org/10.1038/s41567-018-0238-1.

Geroch, R. (1966). Singularities in Closed Universes. *Physical Review Letters 17*(8), 445–447.

Geroch, R. (1970). Singularities. In M. Carmeli, S. I. Fickler, and L. Witten (Eds.), *Relativity*, pp. 259–291. Boston, MA: Springer.

Geroch, R. P. and G. T. Horowitz (1979). Global structure of spacetimes. In *General Relativity: An Einstein Centenary Survey*, pp. 212–293.

Hawking, S. W. (1965). Occurrence of Singularities in Open Universes. *Physical Review Letters 15*(17), 689–690.

Hawking, S. W. (1966). Singularities in the Universe. *Physical Review Letters 17*(8), 444–445.

Hawking, S. W. and R. Penrose (1970). The singularities of gravitational collapse and cosmology. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences 314*(1519), 529–548.

Hoefer, C. and C. Callender (2002). Philosophy of space-time physics. In P. Machamer and M. Silberstein (Eds.), *Blackwell Guide to the Philosophy of Science*, pp. 173–198.

Huggett, N. and C. Wüthrich (2013). Emergent spacetime and empirical (in) coherence. *Studies in History and Philosophy of Modern Physics 44*(3), 276–285. https://doi.org/10.1016/j.shpsb.2012.11.003.

Huggett, N. and C. Wuthrich (2025). *Out of Nowhere: The Emergence of Spacetime in Quantum Theories of Gravity*. Oxford University Press.

Huggett, N. and C. Wüthrich (2018). The (a)temporal emergence of spacetime. *Philosophy of Science 85*(5), 1190–1203. https://doi.org/10.1086/699723.

Lam, V. and C. Wüthrich (2018). Spacetime is as spacetime does. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 64*, 39–51. https://doi.org/10.1016/j.shpsb.2018.04.003.

Lam, V. and C. Wüthrich (2021). Spacetime functionalism from a realist perspective. *Synthese 199*, 335–353. https://doi.org/10.1007/s11229-020-02642-y.

Le Bihan, B. (2018). Space emergence in contemporary physics: Why we do not need fundamentality, layers of reality and emergence. *Disputatio 10*(49), 71–95. https://doi.org/10.2478/disp-2018-0004.

Manchak, J. B. (2009). Can we know the global structure of spacetime? *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 40*(1), 53–56. https://doi.org/10.1016/j.shpsb.2008.07.004.

Mathur, S. D. (2005). The fuzzball proposal for black holes: an elementary review. *Fortschritte der Physik 53*(7-8), 793–827. https://doi.org/10.1002/prop.200410203.

Oriti, D. (2021). Levels of spacetime emergence in quantum gravity. In C. Wüthrich, B. L. Bihan, and N. Huggett (Eds.), *Philosophy Beyond Spacetime*, pp. 16–40. Oxford University Press.

Paul, L. A. (2002). Logical parts. *Noûs 36*(4), 578–596. https://doi.org/10.1111/1468-0068.00402.

Paul, L. A. (2012). Building the world from its fundamental constituents. *Philosophical Studies 158*(2), 221–256. https://doi.org/10.1007/s11098-012-9885-8.

Penrose, R. (1965). Gravitational Collapse and Space-Time Singularities. *Physical Review Letters 14*(3), 57–59.

Rideout, D. P. and R. D. Sorkin (1999). Classical sequential growth dynamics for causal sets. *Phys. Rev. D 61*, 024002. https://doi.org/10.1103/PhysRevD.61.024002.

Singh, P. (2014). Loop quantum cosmology and the fate of cosmological singularities. *arXiv: General Relativity and Quantum Cosmology*.

Singh, P. and F. Vidotto (2011). Exotic singularities and spatially curved loop quantum cosmology. *Physical Review D 83*(6). https://doi.org/10.1103/physrevd.83.064027.

Wüthrich, C. (2021). One time, two times, or no time? In A. Campo and S. Gozzano (Eds.), *Einstein Vs. Bergson: An Enduring Quarrel on Time*, pp. 209–230. De Gruyter.

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