When theory breaks down outside of the laboratory
Considering (two of) the motivations for quantum gravity

Karen Crowther

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Driven neither by experiment nor anomalous observation, physicists are seeking a new fundamental theory of gravity—motivated, guided, and constrained by purely theoretical and philosophical concerns. Here, I briefly consider two of these issues: dreams of unification, and the resolution of spacetime singularities. The discussion in this essay is based on a forthcoming book for the *Cambridge Elements in Philosophy of Physics* series, titled 'Why do we want a theory of quantum gravity?' Please keep an eye out for it (hopefully) later this year!

The search for a new scientific theory is typically prompted by an encounter with something in the world that cannot be explained by current theories: we find observations that do not accord with predictions, or predictions that do not accord with observations. Eventually, a new theory is developed that is empirically adequate for describing the anomalous phenomena. In such cases, observations and experiment go hand-in-hand with the theoretical work: motivating, guiding, and constraining it. For quite a while, however, fundamental physics has worked without encountering any such anomalous phenomena: our current best theories are extremely good at describing the empirical world within their own domains, leaving no mismatch between prediction and observation that is taken (by the scientific community) to suggest the need for a new fundamental theory.[1] And yet, there is an ongoing—*century long*—search for a new theory, thought necessary to replace our current ones in describing parts of the world that we *cannot* observe.

This long-sought theory of fundamental physics goes by the title *quantum gravity.* Disconnected from novel empirical observations, the search for quantum gravity has been primarily motivated, guided, and constrained, by theoretical and philosophical considerations. There are several different different research programs, or *approaches*, towards finding quantum gravity, of varying degrees of completeness. These begin from different starting points, utilise different theoretical tools, and are characterised by the

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[1] There are some open problems related to observations. For instance, you are now probably asking, "But what about the problems of dark energy and dark matter?" Good question. Although the problems of dark energy and/or dark matter may point to the need for a new, more fundamental theory of quantum gravity, they are not standardly treated as such.

priority of different principles—in short, they disagree on what it is they are looking for, what the theory is supposed to be like.

What is it that unites these different approaches such that we classify them as approaches to *quantum gravity*? What is the minimal characterisation of their shared motivation? The usual answer refers to 'two pillars' of fundamental physics: *general relativity* (GR), providing our best understanding of gravity (spacetime), and *quantum field theory* (QFT), our best understanding of matter. Both these frameworks are supposed to be *universal*: unrestricted in their domains of applicability, i.e., both are supposed to describe everything in the universe. In practice, however, we typically only *need* to use GR to describe 'big stuff' (the universe at large distance scales), and quantum theory to describe 'small stuff' (matter and forces at short distance scales, or, equivalently, high-energy scales). Yet, there are domains of the universe ('parts of the world') where both GR and QFT are thought to be necessary—where we cannot get away with just using one or the other theory, or any known combination of both. This means that we lack an account of what the universe is actually like here. These domains are characterised by extreme densities or temperatures (potentially as high as 10^{93} grams per cubic centimetre, or 10^{32} degrees Celsius), and include the cores of black holes (within the Planck length 10^{-35} m), cosmological singularities such as the 'big bang', and the first instants of early universe cosmology.[2] The desire for a description of these—unobserved and experimentally inaccessible—domains is part of the primary motivation for seeking the new theory of quantum gravity.[3] The *Primary Motivation* for quantum gravity can be roughly stated as: To have a theory that describes the domains where both GR and QFT are supposed to be necessary, *and* which somehow 'takes into account' the lessons of both GR and quantum theory.[4]

There are several other motivations for the theory which go beyond the minimal characterisation offered by the Primary Motivation, and which also warrant philosophical scrutiny. One of these is the desire for theoretical *unification.*

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[2] It's difficult to appreciate how small the Planck length is at 10^{-35} m. The diameter of the entire observable universe is also difficult to fathom at 10^{26} m. The geometric mean of these distances, 120 μm, is the size of the human egg cell, which is slightly bigger than the average diameter of a strand of human hair (which, at 100 μm, is the size of the smallest objects visible to the naked eye). Thus, the size of the Planck length compared to a human egg cell is the same as that of the egg cell to the entire observable universe. That probably doesn't help you much with visualisation. To help, I recommend playing with this tool, `https://htwins.net/scale2/` which, as an added bonus, will also help you appreciate your insignificance in the universe.

[3] A common mischaracterisation of the Planck length is that it is the smallest possible distance; while this is an implication of a natural way of combining GR and QFT, it is not necessarily the case. For now, we take it that we need a theory of quantum gravity in order to describe physics at the Planck scale, and then we can ask that theory whether there is a minimal length or not.

[4] The requirement of 'taking into account' the lessons of both theories is explained in more detail in the forthcoming book.

The "physicist's tale"...

A traditional guiding principle in physics, unification is often viewed as means of producing successful theories. Familiar examples (representing various different ideas, and degrees, of unification) include Maxwell's theory of electromagnetism, which unified light as well as the electric and magnetic forces; the electroweak theory, which unified the electromagnetic force and the weak nuclear force; and even GR, with its identification of inertial mass with gravitational mass, and spacetime with gravity. There is a tendency to view the history of physics as a history of unification, and the path forward as one of continuing this trajectory to its ultimate end in a final, unified theory: Salimkhani (2018) calls this the "physicist's tale", following Maudlin (1996), who states that it "has become so pervasive as to rank almost as dogma". It is illustrated in Fig. 1, below. For those inclined towards unification, the current situation in physics—the split picture of the world it presents—is unsettling, and calls us to question the fundamental nature of both GR as well as the framework of QFT (and the Standard Model of particle physics, formulated within the framework of QFT).

What is meant by unification? Maudlin (1996) argues that there are several degrees (or levels) of unification that exist between a lower and upper bound. The lower threshold states that unification is something more than having two (or more) theories be consistent with one another, or sharing a common dynamics, or having a law-like connection (nomic correlation) between physical forces. The upper bound represents *perfect unification*. Here, the idea is not just that there be a single theory describing all phenomena, but that it describe all phenomena as *the same*—as fundamentally stemming from a single origin, e.g., as manifestations of a single entity or interaction (a notion that echoes the Parmenedian "All is One"). And,"it is this deeper sense of unification, the idea that all the physical forces are at base one and the same, which contemporary physicists invoke when they speculate on the theories to come" (Maudlin, 1996, p. 132). Morrison (2000) refers to this type of unification—where two phenomena hitherto thought to be distinct are identified—as *reductive* unification.[5] An example of such a unificationist goal is found—albeit imperfectly—in an approach to quantum gravity known as *string theory*, which seeks to describe all fundamental particles and forces (including gravity) in terms of one basic type of entity: 'strings'. (Additionally, this approach aspires for a final 'theory of everything', whereas quantum gravity, as I've defined it here via the Primary Motivation, need not be a final theory, nor a 'theory of everything').[6] Most approaches to quantum gravity, though, do not in fact aim at perfect unification.

The demand of the Primary Motivation for a theory that 'takes into account' both GR and QFT does not require that quantum gravity be a unified theory, even in a lower sense than perfect unification. And, indeed, there are reasons for resisting the compulsion towards unification (and thus objecting to the picture offered by the

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[5] It is just one of 13 different forms of unification described in Morrison (2000).

[6] For a discussion of what is meant by a 'final theory' in physics, see Crowther (2019), and for a discussion of quantum gravity as a final theory, see Crowther and Linnemann (2019); Dawid (2013b).

"physicist's tale" in Fig. 1). One of these depends on how we interpret GR: the 'canonical picture' of GR is a geometrical one, according to which gravity is not actually a force at all, but the curvature of spacetime. As Maudlin (1996, p. 133) puts it,

> In the general theory [of relativity], gravity and inertia are reduced to a single structure: the metrical structure of space-time. One may retain Newton's first law, but only if one recognizes that *there is no force of gravity at all.* Phenomena formerly understood as effects of gravitational forces are now explained as effects of the influence of matter on the affine structure of space-time. The equality of inertial and gravitational mass, as evidenced by free fall in a gravitational field, is reinterpreted as the common response of all matter to inertial structure. Objects do not couple to the gravitational field, they merely exist in space-time.

On this view, then, seeking to unify gravity with the fundamental forces described by QFT, is simply misguided. To frame this worry more starkly: QFT is a theory of dynamical quantum fields formulated on a fixed background spacetime—i.e., spacetime geometry is specified 'by hand' *for* the theory, rather than described *by* the theory, and it is non-dynamical. QFT then describes the forces as the exchange of particles (which are pointlike excitations of the corresponding quantum fields) within this given, static spacetime 'stage' (or 'backdrop'). GR, on the other hand, is a theory *of* spacetime, and describes gravity as a dynamical field: spacetime itself (the theory tells us what the geometry is, we just need to solve for it). Attempts to unify QFT and GR—even when not aiming at perfect unification—run into various problems, usually diagnosed as owing to this conflicting treatment of spacetime. Infamous among these is the nest of issues referred to as the *problem of time*, which may be grossly presented as indicating that time 'disappears', or 'does not exist' in quantum gravity.

We can question whether unification need properly be understood as a goal of physics at all. Salimkhani (2021) points out that unification can be seen as an external imposition upon theory development in physics, driven by metaphysical, metatheoretical, or epistemological considerations. Opposing this view, Salimkhani argues that, rather, unification naturally arises in physics as a consequence—a 'by product'—of the more basic (or genuine) aims and methods of physics, such as empirical adequacy and theoretical consistency. This is not, however, to deny the heuristic value of unification in guiding theory development, as described by Kao (2019), nor to condemn its use as a theoretical virtue in conferring support, or providing justification, for a theory (note that this can be the case even without requiring or implying the metaphysical assumption that the world itself is unified). Epistemic virtues such as this take on much more weight in the absence of experiment, serving as a means of *non-empirical confirmation* (increasing credence in the theory, without necessarily implying that it is correct), or indicators of *pursuit-worthiness* (giving us reason to think the approach is 'on the right track', likely to lead to a successful theory in the future, or at least giving us interesting problems to work on).[7]

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[7] Non-empirical confirmation has been much discussed following Dawid (2013a), which offers an

Just as we might view the aim of unification as driven by factors external to physics properly understood, we can view the unification of GR and QFT as an *external motivation* for quantum gravity. By this I mean that it is, in a sense, a problem of our own making: it is not compelled by our best current physics, where we consider the theories separately, on their own terms. Likewise, the numerous theoretical and conceptual difficulties that arise from attempts to unify—or even to otherwise combine aspects of—GR and QFT are not problems we would be grappling with otherwise. Rather, these problems—conceptually interesting, philosophically tantalising, and theoretically stimulating as they are—derive from various incomplete and untested approaches towards finding a new theory: one that is supposed to replace our theory of spacetime at a more fundamental level, far beyond the reach of our sense-organs and scientific instruments.

I've characterised the external motivations for quantum gravity as being those problems that signal the need for a more fundamental theory of gravity, but which are not problems with our current best theories of physics when considered as they actually are. *Internal motivations*, by contrast, are features of our current theories—when considered individually, on their own terms—that give us reason to believe that these theories are not fundamental. While the external motivations for quantum gravity are more numerous, and (I'd say) more compelling, there are some internal motivations as well. The most widely-cited of these is the appearance of particular *spacetime singularities* in GR, which are taken, by physicists, as indications that the theory *breaks down*. Philosophers, however, have difficulty making sense of this.

The theory contains the seeds of its own destruction...

Spacetime singularities are pathologies typically interpreted as signalling the breakdown of spacetime—e.g., an 'end', 'edge', or 'missing point' of spacetime—and there are various ways in which a spacetime may be singular. Most familiar are black hole singularities and the initial 'Big Bang' singularity, which, to the popular imagination evoke ideas of everything in the vicinity of such a cosmic horror being ripped apart by incredibly strong tidal forces in the process of being dragged in, before being crushed to an infinitely dense point and simply disappearing from spacetime itself. To physicists, these pathologies are standardly interpreted as indicating the failure of the theory to describe some domain and the need for a new theory in order to describe what actually happens in that domain. This is bad news, because as theorems by Penrose and

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insightful philosophical exploration in the context of string theory; but note that Dawid's idea of non-empirical confirmation is more specific than the one I am using, and his arguments for it more nuanced (i.e., he does not mean it to refer to satisfaction of particular theoretical virtues as I—and several others—do). Distinct from the idea of non-empirical confirmation, the topic of pursuit-worthiness has also recently become quite popular in philosophy of science more generally, and I encourage interested MA students to look into this.

Hawking demonstrate, spacetime singularities arise unavoidably in GR under very reasonable conditions (Penrose, 1965; Hawking, 1972). For this reason, it's often remarked that GR *contains within itself the seeds of its own destruction.*

Trying to formulate a precise, general definition of a spacetime singularity has not been an easy task for physicists or philosophers, and even the more specific definitions of the different types are not without problems.[8] Here, following Crowther and De Haro (2022), I consider the two main types of spacetime singularity: geodesic incompleteness, and curvature singularities. We find that it is not straightforward to label the former as problematic for GR, while the latter serve as a stronger motivation for quantum gravity.

The most common way of identifying a spacetime as being singular is its featuring an *incomplete geodesic.* A geodesic is a 'worldline'—a path through spacetime—traced out by a freely moving particle, i.e., a particle not subject to any external forces. An *incomplete* geodesic is one that ends within a finite proper time (the time as measured by a clock following that path) and cannot be further extended. Rather disturbingly, this means that "particles could pop in and out of existence right in the middle of a singular spacetime, and spacetime itself could simply come to an end, though no fundamental physical mechanism or process is known that could produce such effects" (Curiel, 1999, p. S140).

Geodesic incompleteness could thus mean that the theory is incomplete, since it leads to a lack of predictability and determinism (Earman, 1995, §2.6). A failure of determinism, in general, means that even if we know the complete state of the world at a given time (e.g., the positions, momenta and other relevant properties of all the objects we are describing), plus the laws of nature, we would not be able to predict the state of the world at all other times: the theory would fail to give us a definite, or unique, answer in one or more regimes. In GR physics, a putatively necessary condition for determinism is that the spacetime models of the theory possess a particular causal structure called *global hyperbolicity* (though I won't go into the details of this here).

The problem here is not with indeterminism *per se* (more on this below), but *inconsistency*: laws set up to describe an apparently deterministic universe reveal that we actually have an indeterministic one. If the breakdown of determinism were visible to external observers, "then those observers would be sprayed by unpredictable influences emerging from the singularities" (Earman, 1992, p. 171). This would represent a nasty form of inconsistency—as Earman puts it, the laws would "perversely undermine themselves".

In order to avoid such a scenario, Penrose (1979) proposed his *strong cosmic censorship hypothesis.* There are various formulations of this, but the idea is to ensure that an observer, perhaps an astronaut, on a geodesically incomplete worldline would detect nothing unusual up until—and presumably after—her disappearance. Accordingly, the truth of this conjecture—which is still very much an open question—would render any singularities (incomplete geodesics) harmless in regards to determinism, and avoid the

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[8] See, e.g., Curiel (2021); Earman (1996).

inconsistency that would otherwise be introduced. As Dafermos and Luk (2017, p. 5) states, "The singular behaviour of Schwarzschild [a particular type of black hole spacetime], though fatal for reckless observers entering the black hole, can be thought of as epistemologically preferable for general relativity as a theory, since this ensures that the future, however bleak, is indeed determined". Thus, strong cosmic censorship may be able to save GR from the charge of incompleteness.

There are two issues which have bothered philosophers about this discussion, however. The first regards the nature of the spacetime singularities themselves: a singularity is not *located* at a point somewhere in spacetime—if it could be given spacetime coordinates, then it would not be a breakdown of spacetime, but something that exists within the spacetime. For this reason, Curiel (1999, 2021) emphasises that a singular spacetime does not have any "missing points". (Accordingly, Curiel and others stress the *global*, rather than local nature of singularities). Since there are no missing points of spacetime, there is *nowhere* where the laws of GR fail to apply, and the theory cannot be accused of incompleteness: of failing to give predictions in some parts of the universe (where exactly *are* these 'parts' of the universe that the theory fails to describe?) This argument is put forward by Earman (1995, 1996), who uses it against those who suggest that the initial 'Big Bang' singularity, and the final cosmological 'Big Crunch' singularity imply that GR is incomplete: unable to tell us what happens before the Big Bang or after the Big Crunch. In response, Earman (1996, pp. 631–632) says that, by the lights of GR, talk about "before" the Big Bang and "after" the Big Crunch is physically meaningless, and "GR does not stand convicted out of its own mouth of raising meaningful questions it cannot answer".[9]

Earman generally advocates a "tolerance for spacetime singularities"—maintaining that we can treat them as *predictions*, rather than pathologies of GR (Earman, 1995, 1996). Nevertheless, he believes there is one way in which the charge of incompleteness may be justified. This is the idea, described above, that if strong cosmic censorship does not hold, then the determinism of GR is undermined. Earman ties the determinism of GR to spacetime models that are globally hyperbolic. The problem with this, however, is a "dirty open secret", that determinism in GR fails without help by fiat—i.e., the imposition of *ad hoc* constraints that simply rule out those spacetimes that do not satisfy this condition.

This leads to the second issue that has philosophers scratching their heads—whether, or in what sense, GR is a deterministic theory, as well as whether all models (solutions) of the theory represent physically possible spacetimes. These questions are explored in Smeenk and Wüthrich (2021), which also highlights a tension between the "philosopher's conception" of determinism and the physicist's focus on global hyperbolicity. Doboszewski (2019, 2020) also discusses the problems of defining determinism in GR, with the former paper arguing for a pluralistic conception. These complexities in regards to determinism in GR may take the bite out of the worry that geodesic

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[9] Cf. Smeenk (2013), who makes a similar argument in regards the Big Bang singularity: that the laws of GR apply throughout the entire spacetime, and there is no obvious incompleteness.

incompleteness without strong cosmic censorship is a problem motivating quantum gravity: if GR is not a deterministic theory, then the indeterminism associated with geodesic incompleteness may not represent inconsistency. (Though, if you're deeply bothered by the indeterminism itself, that's another matter...) Thus, the status of spacetime singularities as an internal motivation for quantum gravity is not yet clearly established: geodesic incompleteness may not represent an incompleteness of GR, depending on the status of the strong cosmic censorship conjecture and/or the assessment of (in)determinism of GR.

The definition of singularities in terms of geodesic incompleteness forms the basis of the Penrose and Hawking singularity theorems. It is the most widely-discussed definition, and the one philosophers have focused on. According to Earman (1995, p. 59), this choice of definition "seems to have been guided by expediency: this is the sense that most easily lends itself to proofs of the existence of singularities". But it may be too narrow to serve as a standard definition; it can be argued that this definition counts some pathological spacetimes as being non-singular, and thus does not allow us to address the full range of problems associated with spacetime singularities (Curiel, 2021, §1.1). Very recently, Kerr (2023) has argued that Penrose and Hawking's theorems are insufficient to establish that the spacetimes which those theorems identify as singular, are actually singular. Kerr (1963), 60 years before this recent scathing condemnation, published the first solution to Einstein's GR equations which describes a rotating black hole spacetime (previous solutions had only described non-rotating black holes, which are less physically-realistic). He now argues that the definition in terms of geodesic incompleteness does not prove that these spacetimes are actually singular.

The second main way of identifying a singular spacetime is through unbounded (infinite) curvature, and although it has been less-discussed by philosophers, it is arguably no less difficult to appeal to as a definition of spacetime singularities (Curiel, 1999, 2021).[10] Basically, it states that a spacetime is singular if its curvature grows without bound in some region—spacetime curvature 'blows up' towards an infinite value. *Curvature singularities* lead to various problems, including unbounded tidal forces. (Tidal forces are a direct consequence of spacetime curvature, though we typically think of them as generated by the difference in intensity of the gravitational field at neighbouring points of spacetime—so, for instance, when you are standing on Earth, your feet feel a stronger pull of gravity than your head, which is ever-so-slightly further away from the Earth's centre of mass. As you can imagine, then, it's a pretty dangerous prospect if there are regions of the universe where the strength of tidal forces increase without limit). Nevertheless, it is standardly thought that GR is not reliable in such extreme regimes, due to its neglect of quantum effects that are supposed to become important here. The existence of curvature singularities is thus treated as an external

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[10] What is the relation between curvature singularities and geodesic incompleteness? According to Earman (1996), curvature singularities lead to geodesic incompleteness, whereas the opposite is not true. Curiel (1999, §1.1) argues that the two notions are actually independent, i.e., it's possible to have curvature singularities that do not lead to geodesically incomplete trajectories, and geodesically incomplete spacetimes where no components of the curvature are unbounded.

motivation for quantum gravity, as a theory thought necessary in order to describe these regimes of extreme curvature.

Finding meaning in failure

Spacetime singularities may seem like cosmic abominations, but, as stated, physicists standardly view them as unphysical—symptoms of the theory's failure to describe reality in all regimes. These singularities are thus typically seen as helpful horrors: their dreadful appearance in GR not only provides motivation to seek a new theory, but also some guidance as to what the new theory should be like, in the absence of experimental guidance. It is generally thought that the new theory of quantum gravity should *resolve* the problematic singularities, which means that it should itself be singularity-free, and also—ideally—explain why singularities pop up in general-relativistic spacetimes (which would themselves be treated as low-energy or 'large distance' approximations to the more-fundamental physics described by quantum gravity). Singularity resolution is thus taken as an important guide to quantum gravity, and an indication of pursuit-worthiness when it features in various quantum gravity approaches. It could potentially serve in stronger roles as well: as a means of non-empirical confirmation, or even potentially as a criterion of theory-selection (meaning that any potential theory of quantum gravity must satisfy this condition in order to be accepted).

There are numerous proposals for how the various singularities may be resolved in quantum gravity. I mention only a few of the possibilities here. One example is the 'Big Bounce' model in an approach known as *loop quantum cosmology*: here, the Big Bang singularity is replaced by a quantum bounce, so that the quantum evolution remains non-singular through this regime. For the Big Bang cosmology, if we imagine rewinding a video tape of the expansion of the universe back towards the beginning, we would see the universe becoming hotter and hotter, denser and denser, and eventually we'd expect the video to stop at the Big Bang singularity (or, rather, your video tape would start emitting smoke and your VCR blow up at some point approaching the singularity). In the Big Bounce case, though, we could imagine rewinding the tape right through the part in the video where the Big Bang would otherwise appear, and watch as the universe contracts to a state of maximal, but finite density, and then re-expands. The universe on the other side of the Big Bounce that we would see as we were watching the rewinding video would correspond to a universe that existed before our own.[11]

Another way in which singularities might be resolved is through the introduction of a minimal length in quantum gravity. This minimal length could simply be an *operational* minimal length, meaning that while spacetime itself is continuous, it may be that—according to some approaches to quantum gravity—it is impossible to probe the universe at arbitrarily short distances (for instance, if we had an extended probe, such

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[11] Careful, however, since these models are not always so straightforward to interpret, see, e.g., Huggett and Wüthrich (2018).

as a string). Alternatively, according to other approaches to quantum gravity, the minimal length may actually be a physical shortest-possible distance. In this case it would mean that spacetime itself, as a continuum, is not fundamental, but ‘breaks down’ at this minimal length (and time) scale, beyond which the universe is not spatiotemporal. This allows us to avoid the curvature singularities and other infinities, by ‘cutting off’ spacetime at some very small, but finite, distance so that the offending quantities cannot blow up to infinity (as they otherwise would if spacetime were continuous, i.e., infinitely divisible).[12] Some approaches to quantum gravity describe discrete ‘atoms’ of spacetime—‘atoms’ here referring to the original meaning of the word, as a smallest possible, indivisible unit of some substance. These atoms would themselves not exist in spacetime (so, for instance, we cannot imagine them as being *located* anywhere), but are supposed to themselves collectively ‘compose’ spacetime (analogous to how ordinary physical objects, such as tables and chairs, are composed of atoms at smaller scales, in spite of their material appearing continuous to us at familiar scales).[13]

Alternative attitudes

While the dominant attitude towards spacetime singularities is that they signal the need for a new theory of quantum gravity, this is not the only attitude we could take. Perhaps the spacetime singularities need not bother us. Perhaps we could be more tolerant, or even accepting, of these beasts. Or perhaps we could get rid of them, but without needing to resort to a new theory of quantum gravity. Crowther and De Haro (2022) describe these three alternative attitudes, based on examples found in the physics and philosophy literature. Importantly, we emphasise that it is possible—and indeed, sensible—to adopt different attitudes towards different types of singularities.

We might be *indifferent* to particular singularities, for instance, if we believe that they are of no physical significance and that we will not learn anything by resolving them. One reason we might be unbothered by spacetime singularities is the “no missing points” argument by Curiel (1999): that singularities are not a problem for GR, because they are not part of the spacetime manifold, they are not part of the theory. So, no worries. Another example is a particular scenario in *string gas cosmology*, which is a model of the evolution of the very early universe based on aspects of string theory. In this particular scenario, Brandenberger and Vafa (1989) uses some aspects of the physics of strings to argue that, even though a cosmological Big Bang singularity is

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[12] E.g., Ellis et al. (2018) states there is a widespread sentiment among QG physicists, that the singularities associated with infinities in GR and QFT are due to the assumption of a spacetime continuum. For more on the minimal length, see Hossenfelder (2013).

[13] Exactly how we can think of the non-spatiotemporal atoms as ‘composing’ spacetime is an interesting question in metaphysics of quantum gravity, see, e.g., Baron and Bihan (2022). Also related is the much-discussed question of spacetime ‘emergence’, see, e.g., Crowther (2016); Oriti (2021); Wüthrich (2019).

present, it is of no consequence for the theory, whose behaviour near the singularity is completely regular: the string does not 'see' the singularity.

While indifference is a neutral attitude, another possibility is to take a positive attitude towards particular singularities: to be *tolerant* or accepting of them. We might adopt this attitude in cases where we have reasons for wanting to keep particular singularities in our theories. A tolerance towards spacetime singularities is advocated by Earman (1996), who, following Misner (1969), argues that they might be considered *predictions* rather than pathologies of spacetime—as "seeds of definitive confirmation" in GR, rather than seeds of its own destruction. What exactly does this mean, though? Because singularities are not localisable in spacetime, determining whether spacetime singularities actually occur involves determining whether or not spacetime has some large-scale or global properties. Such a determination, however, may not be impossible in principle, according to Earman.

Physicists who are hostile towards infinities as predictions typically maintain that infinities are unverifiable *in principle* and are thus unscientific—scientists are finite beings with finite measuring instruments and abilities, after all.[14] Spacetime singularities (e.g., geodesic incompleteness) do not all involve some quantities becoming infinite, but the curvature singularities do, so this seems like a problem—at least if you accept the naive, positivistic-sounding argument just given. Earman (1996, p. 630) responds,

> How, for example, could it be verified that the spacetime we inhabit is timelike geodesically incomplete? Even if some volunteer could be found to sacrifice himself for the sake of scientific knowledge, how could he tell the difference between a case where his geodesic (let us suppose) world line is in principle inextendible beyond a certain finite proper time because, say, it encounters unbounded curvature vs. a case where his world line is extendible in principle but not in practice because of curvature that is bounded but so strong as to terminate any physical measuring instrument? The short answer is that our self-sacrificing scientist can't tell the difference and, thus, cannot definitely verify the singular nature of his spacetime. But by the same token he cannot verify predictions about the temperature at the core of the sun. The interesting issue is not whether we can definitively verify predictions about the temperature of the core of the sun or the singularity structure of spacetime but whether observation and previously accepted theory can combine to give us reasonable beliefs about such matters. There are skeptics who will give a negative answer for both cases. I have no response to hardline skeptics. My claim is only that to the extent that it is reasonable to form beliefs about nonverifiable theoretical assertions in physics, then assertions about the singularity structure of spacetime will be among them.

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[14] See, e.g., Ellis et al. (2018), and also Hossenfelder's take at `https://backreaction.blogspot.com/2020/12/is-infinity-real_5.html`.

This is certainly an interesting passage to discuss, as is the general idea of treating singularities as predictions, though I won't do so here (future paper).

Finally, we might take the attitude that particular singularities do need to be resolved, but that we do not need a theory of quantum gravity in order to do this, and in fact that the singularities need not tell us anything about quantum gravity. (Of course, however, one might hold this attitude and still believe we need a theory of quantum gravity for other reasons). In the case of spacetime singularities in GR, the idea is to find a way of removing them without appealing to quantum effects—they can be resolved at the classical level, rather than at the level of a more fundamental theory. Here, I mention two examples.

One example of a purely classical mechanism that can resolve black hole singularities is through the introduction of small extra dimensions. Ordinary spacetimes in GR are four-dimensional (three spatial dimensions and one time dimension). Gibbons et al. (1995) show that some particular black hole spacetimes that look singular in four-dimensions could actually "descend from" classical solutions of a higher-dimensional theory of *supergravity* that are completely non-singular. "Descending from higher dimensions" means that the extra spatial dimensions are *compactificatified*, existing on length scales so small that they are invisible to us, and each one points in a direction that does not exist in the three-dimensional space that we inhabit. These higher-dimensional spacetimes evade the singularity theorems of Penrose and Hawking because they do not feature one of the properties that is assumed by those theorems. This proposal is interesting, but does not offer a general mechanism for avoiding spacetime singularities, only holding for particular cases.

Another example is a conjecture about an alternative to black holes: Astronomical objects called 'gravitational vacuum stars', or 'gravastars' for short (Mazur and Mottola, 2001). These look similar to black holes from the outside, except they have no singularity and no event horizon. Instead, they are composed of a form of dark energy encapsulated by a thin shell of regular matter. A new model of gravastars has very recently been proposed: A novel solution of Einstein's GR equations describing a 'nesting' of gravastars, with one shell inside the other, like a matryoshka doll. The authors call this a 'nestar', but acknowledge that there is no likely scenario that could produce such objects (Jampolski and Rezzolla, 2024).

In general, singularities in our current fundamental theories (yes, they feature in QFT as well, though that's a whole other story) do not automatically point to the need for a new theory. When they do point to the need for a new theory, this theory may not be a more fundamental one. However, the curvature singularities in GR do seem to require not only a new theory, but a more-fundamental theory of quantum gravity. This is because they represent regions of extreme curvature where quantum effects cannot be neglected—these singularities do seem to signal the breakdown of our classical description of gravity.

Keeping theorists, and philosophers, busy

Theoretical physicists make problems outside of the laboratory. In the future we will probably have experiments and other tests for quantum gravity, but so far the whole enterprise has relied on theoretical and philosophical motivations and constraints. As I hope to have demonstrated, there are plenty of interesting and important philosophical questions to explore here at the frontier of physics. I close by suggesting a few more.

Concerning metaphysics, we can ask: What do the various particular approaches to quantum gravity suggest about the nature of reality? What could it mean for spacetime to emerge from something non-spatiotemporal? What would be the implications of a non-spatiotemporal fundamental reality for questions about causation and laws of nature?

Concerning epistemology, and the philosophy of science: Why are we seeking this theory, and what is it supposed to achieve? To answer this we can undertake a critical examination of particular assumptions and principles guiding it. We can ask about inter-theory relationships in theory-change, the role and status of the theoretical virtues, as well as different indicators of pursuit-worthiness and the status of non-empirical confirmation in science in general. We can also ask what it means for a theory to break down.

References

Baron, S. and Bihan, B. L. (2022). Composing spacetime. *Journal of Philosophy*, 119(1):33–54.

Brandenberger, R. H. and Vafa, C. (1989). Superstrings in the early universe. *Nuclear Physics B*, 316(2):391–410.

Crowther, K. (2016). *Effective Spacetime: Understanding Emergence in Effective Field Theory and Quantum Gravity.* Springer, Heidelberg.

Crowther, K. (2019). When do we stop digging? Conditions on a fundamental theory of physics. In Aguirre, A., Foster, B., and Merali, Z., editors, *What is 'Fundamental'?* Springer.

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

Crowther, K. and Linnemann, N. (2019). Renormalizability, fundamentality, and a final theory: The role of uv-completion in the search for quantum gravity. *British Journal for the Philosophy of Science*, 70(2):377–406.

Curiel, E. (1999). The analysis of singular spacetimes. *Philosophy of Science*, 66:S119–S145.

Curiel, E. (2021). Singularities and black holes. *Stanford Encyclopedia of Philosophy*, Spring 2021 Edition.

Dafermos, M. and Luk, J. (2017). The interior of dynamical vacuum black holes I: The c°-stability of the Kerr Cauchy horizon. *arXiv:1710.01722*.

Dawid, R. (2013a). *String Theory and the Scientific Method*. Cambridge University Press.

Dawid, R. (2013b). Theory assessment and final theory claim in string theory. *Foundations of Physics*, 43(1):81–100.

Doboszewski, J. (2019). Relativistic spacetimes and definitions of determinism. *European Journal for Philosophy of Science*, 9(24):1–14.

Doboszewski, J. (2020). Epistemic holes and determinism in classical general relativity. *British Journal for the Philosophy of Science*, 71(3):1093–1111.

Earman, J. (1992). Cosmic censorship. *PSA: Proceedings*, 2:171–180.

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

Earman, J. (1996). Tolerance for spacetime singularities. *Foundations of Physics*, 50(26):623–640.

Ellis, G. F., Meissner, K., and Nicolai, H. (2018). The physics of infinity. *Nature Physics*, 14:770–772.

Gibbons, G. W., Horowitz, G. T., and Townsend, P. K. (1995). Higher-dimensional resolution of dilatonic black-hole singularities. *Classical and Quantum Gravity*, 12(2):297–317.

Hawking, S. W. (1972). Black holes in general relativity. *Commun. Math. Phys.*, 25:152–166.

Hossenfelder, S. (2013). Minimal length scale scenarios for quantum gravity. *Living Reviews in Relativity*, 16:2–90.

Huggett, N. and Wüthrich, C. (2018). The (a)temporal emergence of spacetime. *Philosophy of Science*, 85(December):1190–1203.

Jampolski, D. and Rezzolla, L. (2024). Nested solutions of gravitational condensate stars. *Classical and Quantum Gravity*, 41(6):065014.

Kao, M. (2019). Unification beyond justification: A strategy for theory development. *Synthese*, 196(8):3263–3278.

Kerr, R. P. (1963). Gravitational field of a spinning mass as an example of algebraically special metrics. *Phys. Rev. Lett.*, 11:237–238.

Kerr, R. P. (2023). Do black holes have singularities? *arxiv.org/abs/2312.00841*.

Maudlin, T. (1996). On the unification of physics. *Journal of Philosophy*, 93(3):129–144.

Mazur, P. O. and Mottola, E. (2001). Gravitational condensate stars: An alternative to black holes. *arXiv:gr-qc/0109035*.

Misner, C. (1969). Absolute zero of time. *Physical Review*, 186(5):1328–1333.

Morrison, M. (2000). *Unifying Scientific Theories: Physical Concepts and Mathematical Structures*. Cambridge University Press, Cambridge.

Oriti, D. (2021). Levels of Spacetime Emergence in Quantum Gravity. In *Philosophy Beyond Spacetime: Implications from Quantum Gravity*. Oxford University Press.

Penrose, R. (1965). Gravitational collapse and space-time singularities. *Phys. Rev. Lett.*, 14:57–59.

Penrose, R. (1979). Singularities and time-asymmetry. In Hawking, S. and Israel, W., editors, *General Relativity: An Einstein Centenary Survey*, pages 581–638. Cambridge University Press.

Salimkhani, K. (2018). Quantum gravity: A dogma of unification? In Christian, A., Hommen, D., Retzlaff, N., and Schurz, G., editors, *Philosophy of Science. European Studies in Philosophy of Science, Vol 9.*, pages 23–41. Cham: Springer.

Salimkhani, K. (2021). Explaining unification in physics internally. *Synthese*, 198(6):5861–5882.

Smeenk, C. (2013). Philosophy of cosmology. In Batterman, R., editor, *Oxford Handbook of Philosophy of Physics*, pages 607–652. Oxford: Oxford University Press.

Smeenk, C. and Wüthrich, C. (2021). Determinism and general relativity. *Philosophy of Science*, 88(4):638–664.

Wüthrich, C. (2019). The emergence of space and time. In Gibb, S., Hendry, R. F., and Lancaster, T., editors, *The Routledge Handbook of Philosophy of Emergence*. Routledge.

Figure 1: The "physicist's tale" of unification. Here, quantum gravity is depicted as a final 'theory of everything', though I argue that quantum gravity need not be a final theory, nor a unified one.