On the Motivations for Seeking a Theory of Quantum Gravity

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Abstract. While there are some empirical problems that could suggest the need for a theory of quantum gravity, most of these are not standardly taken as motivations for seeking a new theory. Rather, the quest for a theory of quantum gravity has been primarily motivated, guided, and constrained by philosophical and theoretical concerns. A critical examination of these can help us better understand what the theory is supposed to achieve—and, further, what it *should* be expected to achieve. On the other hand, there are various approaches towards finding a theory of quantum gravity, with different aims, methods, and starting-points—they disagree on what the theory is supposed to be like. A relevant question is then: what is it that unites these approaches such that we classify them as approaches to quantum gravity? This paper argues that a basic characterisation of the theory can be given in terms of the minimal shared motivation across these different approaches, and that this itself can be seen as motivated by various other problems that have been appealed to as reasons for seeking a theory of quantum gravity.

1. Introduction

When physicists search for a new theory, it's typically because something has been observed that cannot be explained by current theories. For instance, the development of quantum mechanics began with the anomalous experimental phenomena of the spectrum of blackbody radiation and the photoelectric effect; and the development of special relativity was supported by the Michelson-Morley experiment, and by Kaufmann's 1902 experiments which contradicted Newton's laws of motion by showing that a constant force does not produce constant acceleration in an electron as it approaches the speed of light. Now, however, physicists are searching for a new fundamental theory, known as quantum gravity, largely unprompted and unconstrained by novel observational results. Although the theory is potentially related to some empirical problems—such as dark energy, and dark matter, as well as the problems described in §6, below—the main motivations for seeking quantum gravity are conceptual and theoretical problems. It is also these types of concerns that primarily guide and constrain the search for the new theory.

There are various different approaches (research programs) towards finding quantum gravity, characterised by different aims and methods, but also by their differing assumptions and use of various principles. They disagree on what the relevant problems are that quantum gravity should solve, and what the theory should be like. Yet, there are some assumptions, motivations and constraints that the approaches have in common. And it is via these that we recognise the various research programs as being approaches to *quantum gravity*. Perhaps one of the reasons for difficulty in finding a theory of quantum gravity is due to some faulty assumptions about

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what the theory is supposed to achieve, or our prejudices about what the theory should be like. A minimal characterisation of the shared motivations for quantum gravity can help give a general definition of the theory, and an exploration of the other general motivations may help reveal new insights into the key assumptions underlying the search for the theory. These can then be subject to philosophical examination. The aim of this paper is not to complete this project, but merely to incentivise it.

What is the minimal characterisation of the shared motivation of the various approaches to quantum gravity? The usual answer refers to 'two pillars' of fundamental physics: general relativity (GR), providing our best understanding of gravity, and quantum field theory (QFT), our best understanding of matter. Both these frameworks are supposed to be *universal*: unrestricted in their domains of applicability. In practice, however, it is only necessary to use these frameworks in particular, reasonably well-defined domains, which are disparate from one another. Yet, it is thought that there are domains where both theories are required—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 in these domains, which 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.

The problem, then, is apparently to find a new theory that describes the domains where both GR and quantum theory are supposed to be necessary, *and* which somehow captures (or 'takes into account') the lessons of *both* GR and quantum theory. Let us call this the *Primary Motivation* upon any acceptable theory of QG—although it is very imprecisely defined as stated, and ignores the 'third pillar' of fundamental physics, thermodynamics. The most straightforward attempts at constructing a theory that fulfils the Primary Motivation—by quantizing GR, treating gravity in the framework of QFT, or otherwise 'combining' GR and quantum theory—are beset by various conceptual and technical problems, which have led to their dismissal as unable to fulfil the expectations of a theory of quantum gravity. For example, *canonical quantization* of GR leads to the infamous 'problem of time'; the treatment of gravity in the framework of perturbative QFT is divergent, and thus typically viewed as internally inconsistent; while *semiclassical gravity*, which couples classical gravity to quantum matter fields, also leads to divergences, and has been accused of paradox in various thought-experiments.

Each of these problems could be referred to as 'the problem of quantum gravity', since they are obstacles that prevent the acceptance of each approach as a contender for QG. These problems are damning, however, only to the extent that they prevent these approaches from satisfying the Primary Motivation on quantum gravity. Beyond this, the criticisms of the various approaches reveal interesting prejudices we have about the nature of physical theories, and expectations about what quantum gravity is to achieve.

The main general motivations for seeking quantum gravity that appear in the literature[1] include:

- *The Primary Motivation*: 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;
- *Incompatibilities between GR and QFT*: To have a theory that provides a coherent picture of the world;
- *Unification*: i. [Minimally] to have GR and quantum theory accounted for by a common framework; ii. [Full] to have a unified theory of all forces, including gravity, as stemming from a single interaction;

[1] See, e.g., Held (2019); Loll et al. (2022); Kiefer (2007b); Rickles (2008).

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- *Putative inconsistency of semiclassical and other 'hybrid' approaches to QG*: i. Claims that a theory with quantum matter coupled to a classical spacetime is inconsistent, and thus unable to serve in place of a full theory of QG; ii. Claims that perturbative GR is inconsistent because it is non-renormalizable;
- *Singularity resolution or explanation*: i. To have a theory that addresses the singularity theorems of GR, particularly to describe black holes and the cosmological 'big bang' singularity, ii. To have a theory that 'cures' the divergences and other mathematical inconsistencies in QFT;
- *Black hole thermodynamics*: To have a theory that describes the evolution of black holes, particularly black hole evaporation as suggested by theoretical work on *black hole thermodynamics*;
- *Complete cosmology*: i. To have a theory that describes the initial conditions of the universe; ii. To have a theory that solves the cosmological constant problem;
- *Hierarchy problem*: To have an explanation for why the gravitational force is so weak compared to the other fundamental forces.
- *The measurement problem of QM*: To have a more fundamental framework that explains the origin of this problem, and is free of it;
- *The problem of becoming in GR*: To have a more fundamental framework that explains the passage of time.

This paper will explore a selection of these motivations in the hopes of clarifying them at a general level, to better understand what is meant by 'quantum gravity', and to begin to evaluate how these motivations might serve as constraints or desiderata for the theory sought, across the various approaches. The aim is to inspire more critical scrutiny of the theoretical and conceptual problems which motivate the theory, in order to reveal some of the principles or prejudices which may underlie these problems.

The Primary Motivation is expounded in a little more detail in §2, highlighting several areas where it may be questioned. The principle of consistency is explored in §3, explaining its role in motivating the Primary Motivation, as well as briefly outlining some prominent cases of inconsistency that arise in the search for QG. The principle of unification is considered in §4, where it is argued to not be necessary for motivating the Primary Motivation. The resolution of spacetime singularities is explored as a motivation in §5, articulating the sense in which this motivates the Primary Motivation. Finally, some of the empirical problems that could be relevant in motivating (and/or constraining) the search for QG are considered in §6. Before all this, however, it is worth explaining the difference between motivations, constraints, and desiderata in the search for a new theory.

1.1. Motivations, constraints, desiderata

The motivations for quantum gravity are the reasons for seeking a theory that satisfies the Primary Motivation: answers to the question 'why do we want this theory in the first place?'

Broadly, motivations can be translated into either:

(i) *Heuristics* or *guiding principles*: these are desirable or useful features that can aid in the discovery of the theory by leading to new insights, but which may or may not actually be retained in the resulting theory; they are non-necessary *desiderata*: features that it would be nice if the theory possessed, and which would make us more inclined to accept the theory; or,

(ii) *(Strong) constraints* or *criteria of theory acceptance*: the new theory should not be accepted if it is incompatible with the principle (unless there is strong evidence in favour of the

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theory, and/or the principle is shown to be violated under the relevant conditions); when a motivation is adopted as a constraint, it typically is taken to form part of the definition of the new theory.

Not all of the constraints on quantum gravity come from its motivations, nor do all desiderata motivate the need for a new theory. Typically, the non-motivational constraints are not taken to define the theory, as the motivational ones are. Some examples of constraints on QG that are not motivations include those principles coming from current theories within their domains of applicability (e.g., predictions should not violate Lorentz invariance in the domains where we know this symmetry holds). There is also the requirement that the new theory *explain* the success of the theories it replaces, in the domains where we know those theories work well. This constraint is related to the *Generalised Correspondence Principle*—roughly: that the old theory (or a corrected version thereof) be derivable from the newer one in the appropriate domain (Post, 1971; Radder, 1991). This principle also plays a significant role in ensuring the new theory satisfies certain empirical constraints, namely those observations that are explained by current theories, and is one of the few agreed-upon constraints upon any theory of quantum gravity. Also, some of the non-motivational constraints, in spite of being non-motivational, can nevertheless still also be heuristically useful. Examples of desiderata that are not motivational include unexpected explanation of (theoretical or empirical) problems that are not hitherto thought to be quantum-gravitational (Dawid, 2013). As with any physical theory, the most important guides and constraints come from empirical results.

Motivations, constraints, and desiderata can all play important roles as *means of confirmation* or as indicators of *pursuit-worthiness* of a program: compatibility with the principle (or empirical result) serving to increase credence in the theory, or as being suggestive of the theory's potential future success and/or theoretical fruitfulness, if it were to be developed. [2]

2. The Primary Motivation

Above, the Primary Motivation for quantum gravity was stated very roughly: 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. Three points require more elaboration: 'describes', 'domains', and 'taking into account'.

2.1. 'Describes'

To say that a theory *describes*, or *applies to*, a particular domain usually means that the theory gives predictions in that domain which have been tested and not falsified. In the case of the domains of quantum gravity, this presents a challenge. We might require, more minimally, that the theory is physically predictive in these domains, as well as that it satisfies the other constraints that we expect for quantum gravity—most importantly, the Generalised Correspondence Principle, which would ensure that the predictions of the new theory approximately agree with those of GR and quantum theory in the domains where we know these theories are good descriptions of the world (Crowther, 2018). If the predictions of the new theory are correct in the domains where we can test, we can take this as inductive support for its predictions in untested domains also being correct.

2.2. 'Domains'

Quantum gravity, like GR and quantum theory, should be a universal theory: not restricted to particular domains. Properly, the motivation for quantum gravity is to describe domains where quantum-gravitational effects cannot be neglected—where the predictions of the theory

[2] See, e.g., Achinstein (1993); Crowther (2021); McGrew (2003); Shaw (2022); Whitt (1990).

are thought to differ from those of GR and QFT. This is supposed to include: the Planck scale, the interior of black holes and the very early universe. I describe the reasoning behind each of these in turn.

The Planck scale is obtained by dimensional analysis: combining both the characteristic constants of GR and quantum theory to form a new set of characteristic constants. Planck, in 1899, showed that there is a unique way (apart from numerical factors) to combine the speed of light c, the gravitational constant (Newton's constant) G, and the quantum of action (the reduced Planck's constant), $\hbar$, to arrive at the Planck length, l_{P}, the Planck time t_{P} and the Planck mass (equivalently, the Planck energy) m_{P}, respectively:[3]

$$l_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.62 \times 10^{-35}\mathrm{m} \tag{1}$$

$$t_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^5}} \approx 5.40 \times 10^{-44}\mathrm{s} \tag{2}$$

$$m_{\mathrm{P}} = \sqrt{\frac{\hbar c}{G}} \approx 1.22 \times 10^{19}\mathrm{GeV} \tag{3}$$

In cosmology, we also refer to the Planck temperature T_{P}, and Planck density ρ_{P}, (where k_{B} is Boltzmann's constant),

$$T_{\mathrm{P}} = \frac{m_{\mathrm{P}} c^2}{k_{\mathrm{B}}} \approx 1.41 \times 10^{-32}\mathrm{K} \tag{4}$$

$$\rho_{\mathrm{P}} = \frac{m_{\mathrm{P}}}{l^3{}_{\mathrm{P}}} \approx 5 \times 10^{93}\mathrm{g/cm}^3 \tag{5}$$

In spite of the popularity of the Planck scale as characterising the domains of QG, the dimensional analysis that gives us the Planck scale is heuristic: it does not establish that this is the characteristic scale of QG. The relevance of the Planck scale can be criticised as a naive general estimate. Nevertheless, it is possible to make the case that the Planck scale is the relevant scale at which to expect new physics, based on arguments from both particle- and gravitational-physics which may be taken to suggest that our current picture of familiar 'large scale' (i.e., energies lower than the Planck energy) physics is complete (Held, 2019). Such a conclusion, however, neglects the problems of dark matter and dark energy (the cosmological constant Lambda), which may be considered as part of QG phenomenology.

Perhaps stronger than the heuristic arguments for the relevance of the Planck scale is the argument that the Planck scale is where 'low energy quantum gravity' (LEQG) breaks down. This is a theory of gravity in the path integral formalism of QFT, including fluctuations treated using the background field method (Wallace, 2022). While it could be seen as a theory of quantum gravity, since it describes quantum-gravitational phenomena (i.e., self gravitating objects whose description also requires quantum theory), LEQG is an *effective field theory*: it is not predictive at high energies, and is thought not to describe Planck scale physics. Because of this, we need a new theory precisely to describe this regime, and it is this new—unknown—theory which is properly called quantum gravity. It is worth noting, however, that the new theory sought, though it is motivated by the need to provide a description of the high-energy regimes where LEQG fails, need not itself be a UV-complete theory, valid to arbitrarily high energies (Crowther and Linnemann, 2019). All that is required to fulfil the Primary Motivation is to describe the Planck regime, as well as the other domains where quantum gravity is necessary.

[3] See, e.g., Kiefer (2007a), §1.1.3.

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The other domains that characterise QG are the interior of black holes and the very early universe. This is motivated by the idea that GR 'breaks down' in the vicinity of curvature singularities because of the neglect of expected quantum effects in these domains (described below, §5). Another reason for thinking a new theory of QG is required to describe the interior of black holes comes from the desire to explain the theoretical predictions of *black hole thermodynamics*. These results are derived in the framework of semiclassical gravity (described below, §3), which already represents an attempt to bring together GR and QFT, and which is standardly considered an approximation to LEQG in the situations where quantum fluctuations of the spacetime geometry can be ignored. Following Hawking's prediction that black holes radiate (Hawking, 1974, 1975), this framework has delivered a tantalising suggestion that black holes are ordinary thermodynamic objects. This may, for instance, mean that black hole thermodynamics is underpinned by a statistical-mechanical 'micro-theory', as ordinary thermodynamic systems have an underlying description in terms of statistical mechanics. Indeed, that particular approaches to QG manage to calculate the statistical-mechanical entropy for black holes, in agreement with the predictions of black hole thermodynamics, has been presented as a desideratum and means of confirmation for these approaches. It is often also viewed as a criterion of acceptance for any theory of QG.[4] Another problem that arises in the context of black hole thermodynamics, and whose solution is expected to necessitate QG, is the 'information loss paradox'.[5]

While the results of black hole thermodynamics are taken seriously as indicators for QG, it is worth emphasising that semiclassical gravity is not well-confirmed empirically. Furthermore, the framework suffers from plethora of theoretical and conceptual difficulties—*even when* considered as an approximation, rather than a fundamental theory of QG. Because of this, the amount of trust in black hole thermodynamics as offering insights into the nature of QG seems a striking—perhaps even suspicious—situation.[6]

2.3. 'Takes into account both QM and GR'

The second main condition of the Primary Motivation is that the theory *take into account both quantum theory and GR*. This condition is motivated by the success of GR and QM as universal theories. In spite of this, it is a condition that requires further critical evaluation and explanation: after all, both theories are thought not to apply in the domains where quantum gravity is necessary. Here, I do not undertake such an evaluation, but seek merely to explicate the condition as it is currently understood. 'Taking into account both GR and quantum theory' means: 1) that QG feature one or more of the principles employed in GR and one or more of the principles of quantum theory, and 2) to the extent that QG differs from GR and QFT, the new theory should 'recover' GR and QFT as approximations in the domains where we know them to be successful descriptions of the world. These are the two necessary aspects required to satisfy the condition, as currently understood. Note, that this is not to say that these aspects cannot, or should not, be challenged, but simply that they are necessary for defining what the consensus takes to be 'the problem of QG'.

There are two main ways of understanding this condition, representing different viewpoints on the problem of quantum gravity. The *Standard Perspective* on the problem takes the

[4] Various approaches to QG have managed to reproduce this result, for different types of black holes, and to varying levels of precision, including in loop quantum gravity (Meissner, 2004; Rovelli, 1996), and in the context of the AdS/CFT duality (Witten, 1998; Aharony et al., 2004) and in string theory, (Strominger and Vafa, 1996). For more details on the interpretation of the string theory result, see De Haro et al. (2020); van Dongen et al. (2020); Wallace (2018b).

[5] See, e.g., Unruh and Wald (2017) for a review, and Dulani (202); Wallace (2020) for recent philosophical evaluation.

[6] See Curiel (2023); Wallace (2018a,b); recent physics reviews: Almheiri et al. (2021); Harlow (2016).

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fundamentality of quantum theory seriously, but seeks to modify GR.[7] According to this perspective, we need a need a quantum theory at high energies from which the classical theory of GR is recovered in its domain of success. For instance, Loll et al. (2022, p. 16) expresses the sentiment that the "universality of quantum theory" is one of the fundamental principles of modern physics: the physical world at the fundamental level is governed by quantum laws, and that the classical picture is only an approximation, valid at sufficiently low energies and on sufficiently large scales.

An alternative way of viewing the problem, which we may call the *New-Framework Perspective*, holds that both GR and quantum theory will need to be modified in some way. This perspective is nonstandard, but can be read, e.g., in Ashtekar and Geroch (1974), in a passage where the authors state that GR and QM each can be understood as a distinct "body of universal rules", which means that the quantization of gravity is essentially different from quantizing the electromagnetic field: "From this viewpoint, then, the problem is to obtain a new body of rules which suitably encompasses the essential features of those of quantum mechanics and of general relativity." (Ashtekar and Geroch, 1974, p. 1214).

Here, I will not argue for one view or the other, but will at least suggest that the fundamentality of quantum theory is an assumption that has perhaps not been questioned seriously enough in the search for QG. The problem of QG may well be that we require a whole new framework that could 'explain' the success of quantum theory just as it would explain the success of GR.

There are more-specific ways of satisfying the 'takes into account' condition of the Primary Motivation. (Butterfield and Isham, 2001, §3.1.3), describes four different types of approach to QG: 1) quantize GR, 2) GR as the low-energy limit of a quantization of a different classical theory, 3) GR as the low-energy limit of a theory that is not a quantization of a classical theory, 4) start *ab initio* with a radically new theory. Approaches 1-2 represent the Standard Perspective, approach 4 represents the New-Framework Perspective, while approach 3 could represent either perspective, depending on whether or not the theory is formulated in the framework of quantum theory as we currently understand it. Any of these approaches could produce a theory that accords with the condition of 'taking into account' both GR and quantum theory, if it satisfies the two necessary aspects described above. Nevertheless, the by-far dominant approach is 1, where not only is QG supposed to be a quantum theory, but one in which gravity is quantized.

It is possible that QG take into account QM without itself being a (purely) quantum theory. The most familiar way of thinking about this is along the lines of semiclassical gravity (§3) or other 'hybrid' approaches, which attempt to couple the classical and the quantum as a sort of 'amalgamation' (as opposed to a unification) or 'mongrel gravity' theory (a term borrowed from Mattingly (2009); cf. Tilloy (2018) for discussion of some other hybrid theories). The New-Framework Perspective countenances the possibility that the framework of QM—as it stands—is not applicable in QG, and gets modified somehow (in which case QG would be more fundamental than both GR and QM, but need not be a full unification of GR and QM §4).

One motivation for considering the modification (or replacement) of quantum theory is the measurement problem. Most promiently, Penrose believes that the measurement problem of QM points to the need for QG, and that the unitarity of QM will be modified, so that QM will become a non-linear theory at the Planck length. More recently, the unitarity of QM has been called into question in the context of quantum cosmology, where Cotler and Strominger (2022) replace linear unitary time evolution with linear isometric time evolution (note: this is very different from the quite radical proposal of Penrose). Other recent work in the New-Framework Perspective is the hybrid, 'post-quantum classical gravity' theory which modifies both GR and QM (Oppenheim, 2023). This approach is motivated by problems with semiclassical gravity

[7] Which is not to say that GR fails to embody some principles, e.g., background independence, that are thought to be fundamental.

and as well as perceived inadequacies to mainstream responses to the black hole information loss paradox.

2.4. Three pillars perspective

An increasingly significant perspective upon the problem of QG is that it involves bringing together not just GR and QM, but also the third pillar of modern physics: thermodynamics (also including statistical mechanics). There are several approaches to QG that tie gravity to the thermodynamic concept of entropy. For instance, Jacobson (1995) argues that the Einstein Field Equations can be derived from the proportionality of entropy and black hole horizon area together with the first law of thermodynamics. Padmanabhan (2004, 2010) and Verlinde (2011, 2017) also present arguments for gravity being an emergent phenomenon of entropic origin. According to the 'emergent gravity' approaches, spacetime is an effective thermodynamic entity; as such, a quantization of gravity (the metric field) would not lead us to the 'micro' degrees of freedom which we seek to describe by a more fundamental theory of QG (Linnemann and Visser, 2018). These micro degrees of freedom, however, could themselves be described by a quantum theory, and so these approaches need not represent the New-Framework Perspective. The link between GR, QFT and thermodynamics is motivated, and further revealed, through the theoretical results of black hole thermodynamics (Wallace, 2018a,b).

3. Consistency

Consistency is the most basic constraint motivating QG through the Primary Motivation. QFT and GR offer two different pictures of the world which seem to fundamentally conflict with one another, and we seek a single, consistent description of nature. The motivation here is a problem of *external inconsistency*, where the two theories are apparently inconsistent with one another as they stand. Straightforward attempts to combine these theories lead to approaches, such as semiclassical gravity, which are apparently *internally inconsistent*. Additionally, both QFT (or, rather, particular QFTs) and GR have been accused of internal inconsistency, related to various types of singularities associated with these theories, and this prompts the search for a more fundamental theory which should itself be internally consistent.

While inconsistency is taken as a signal that something is wrong, philosophers have pointed out that scientists do not, and should not, reject inconsistent theories—such theories are unproblematic so long as we are not doxastically committed to them (Vickers, 2013). In the case of QG, this means treating GR and QFT as approximately true in certain domains, but not believing they are fundamental (or universal) theories. In order to have a consistent picture of the world, we need to modify one or both of the theories in the domains where quantum-gravitational effects cannot be ignored, which means developing a new theory in accordance with the Primary Motivation. While QG is motivated by the principle of consistency, it is interesting to ask whether, and in what ways, consistency need be a constraint on QG.

As formulated, the Primary Motivation does not require that QG be an internally consistent theory: the theory can be inconsistent in this sense so long as the inconsistency does not prevent it from fulfilling the Primary Motivation, particularly in regards to it yielding physically reasonable predictions in the requisite domains. Nevertheless, if QG were not internally consistent, this would prevent it being accepted as a fundamental theory, and physicists would continue their search (Crowther, 2019). External consistency—between QG and GR, and between QG and QFT—is a constraint on QG, which is to be demonstrated through satisfaction of the Generalised Correspondence Principle. As described above, satisfaction of this principle also helps ensure empirical consistency, in the domains where QFT and GR are well-confirmed.

The rest of this section briefly outlines some apparent inconsistencies between GR and QFT, and in semiclassical gravity. The goal is to encourage more thorough investigation into the role of consistency in motivating QG. (§5 & 6 also concern consistency).

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Quantum mechanics is not a theory, but a framework within which particular theories are formulated; similarly, QFT is also a framework—one which combines QM and special relativity. Basically, it extends QM to to fields, i.e., systems with an infinite number of degrees of freedom, defined on a fixed, flat, continuum spacetime of SR. The framework uses spacetime, but it does not *describe* spacetime. Theories formulated in this framework, such as the Standard Model of particle physics, are said to be *background dependent*, because the spacetime serves as a 'background' in the theory. The framework treats all matter as composed of particles, which are understood as local excitations of quantum fields; the fundamental forces are themselves represented by quantum fields, whose corresponding excitations interact locally with the other particles, depending on their type. Any dynamical field, according to QFT, is quantized. Incorporating gravity into this framework would entail treating gravity as a field whose force is mediated by a particle called the *graviton*.

By contrast, GR is a theory *of* spacetime; the equivalence of gravitational and inertial mass means we can understand gravity as a property of spacetime itself, rather than a field propagating on a fixed spacetime background. It stands in contrast to QFT for several reasons. Most basically, GR says that spacetime is a dynamical field rather than a fixed, static background structure. It is a *nonlinear* theory (while QM is a linear theory), in that spacetime 'reacts' to matter and energy, and in turn, the behaviour of matter and energy are affected. But, from the perspective of GR, we could say that gravity is not really a force at all–it does not 'act' on objects (Maudlin, 2012). Objects simply exist in spacetime, and GR tells us that an object's inertial path is determined by the curvature of spacetime (rather than, e.g., conceiving of gravity as a field that deflects objects from their inertial paths).[8]

The formalism of GR can be defined by the Einstein-Hilbert action[9],

$$S_{EH} = \frac{c_4}{16\pi G}\int_{\mathcal{M}} d^4x\sqrt{-g}(R-2\Lambda) - \frac{c^4}{8\pi G}\int_{\partial\mathcal{M}} d^3x\sqrt{h}K \tag{6}$$

where g is the determinant of the metric, R is the Ricci scalar, and Λ is the cosmological constant. The first integral is over a spacetime region $\mathcal{M}$ (a four-dimensional manifold of spacetime points, encoding the topology and differentiable structure), and the second integral is defined on the boundary, $\partial\mathcal{M}$, of this region. This term is required for a consistent variational principle; here, h is the determinant of the three-dimensional metric, and K is the trace of the second fundamental form. We also consider a 'matter action', S_m, for non-gravitational fields, which give rise to the energy-momentum tensor,

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g^{\mu\nu}} \tag{7}$$

which acts as a 'source' of the gravitational field. From the variation of $S_{EH} + S_m$, we obtain the Einstein Field Equations (EFE),

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{8}$$

where $g_{\mu\nu}$ the Lorentzian metric tensor, encoding the geometry and $R_{\mu\nu}$ is the Ricci curvature tensor. A model (i.e., a spacetime) of GR is specified as $\mathrm{M} = \langle\mathcal{M}, g_{\mu\nu}, T\rangle$ where the two tensors $g_{\mu\nu}$ and $T_{\mu\nu}$ satisfy the EFE (eq. 8).

So, on the one hand, we have GR describing classical geometry as a dynamical field coupled to classical matter, and on the other hand, we have QFT which uses a fixed, non-dynamical classical geometry, and which describes quantum matter, saying that all dynamical fields should

[8] For other formal compatibility issues, see §3.6.3 of Rickles (2006).
[9] Here, following the presentation in Kiefer (2007a).

be quantized. A natural way to combine GR and quantum theory, then, is to attempt to quantize the gravitational field, similar to the way in which the electromagnetic field was quantized. This approach is in line with the Standard Perspective on the problem of QG, but faces extraordinary conceptual and theoretical difficulties, as described in Weinstein and Rickles (2021). The quantization of the electromagnetic field in quantum electrodynamics (QED) results in a theory of quantum fluctuations of the electromagnetic field against a well-defined classical spacetime background. The attempt to quantize gravity, however, means subjecting some of the properties of spacetime to quantum fluctuations. We thus run into trouble in giving a mathematical characterisation of the quantization procedure itself without a well-defined background spacetime. Even if we are able to achieve this, we then face trouble in giving a physical account of the theory that results—for example, a fluctuating metric would seem to imply a fluctuating causal structure and spatiotemporal ordering of events, which makes it difficult to define equal-time commutation relations in the quantum theory.

Additionally, by contrast to QED, gravity treated in the framework of perturbative QFT is *non-renormalizable* according to a standard, heuristic criterion known as the power-counting method (see, for example, Kiefer, 2007a, §2.2.2). This means that the theory diverges at high-energies—namely, at the Planck scale. This is often interpreted as the theory being mathematically inconsistent. Here, however, it is not mathematical inconsistency that motivates a new theory of QG in accordance with the Primary Motivation, but rather the fact that this approach is not predictive at the Planck scale Crowther and Linnemann (2019).

Another straightforward option to combine GR and quantum theory is to modify (eq. 8) to take into account the quantum nature of matter, by replacing $T_{\mu\nu}$ with the expectation value of the *quantum energy-momentum tensor operator*, $\left\langle \hat{T}_{\mu\nu} \right\rangle$, to obtain,

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \left\langle \hat{T}_{\mu\nu} \right\rangle \tag{9}$$

These are the *semiclassical Einstein equations*, where gravity stays classical while the other fields are quantum. Note that the quantum energy-momentum tensor operator is not only difficult to compute mathematically, but its expectation value is also difficult to understand physically.[10] Nevertheless, it is an operator that acts on states $|\psi\rangle$ of a material quantum system, and thus obeys the Schrödinger equation, with Hamiltonians describing both the dynamics of matter with itself, and with gravity,

$$\mathrm{i}\partial_t|\psi\rangle = \hat{H}_{\text{matter + gravity}}|\psi\rangle \tag{10}$$

A system described by equations (eq. 9-10) is referred to as semiclassical gravity. While the semiclassical Einstein equations may be of value as approximations, leading to insights into the low-energy regime of QG, they face several serious conceptual and theoretical difficulties if treated as exact equations at the fundamental level of QG.[11]

More generally, the basic intuition that semiclassical gravity is inconsistent can be appreciated by analogy with the case of electromagnetism: Bohr and Rosenfeld (1933) analysed an equation akin to the 'semiclassical' equation for electromagnetism and demonstrated that the electromagnetic field had to be quantized in order to be consistent with the quantized matter it couples to.[12] The basic idea is usually taken as the uncertainty relations in the quantized system spread to ('infect') the coupled non-quantized system. In the case of semiclassical gravity, the uncertainty in the position of a quantized gravitating object would lead to quantum uncertainty

[10] Cf. Huggett et al. (2023); Kiefer (2007a); Wald (1994).
[11] While Großardt (2021, 2022) discusses "three little paradoxes" of semiclassical gravity, Erik Curiel describes a "panopticon of problems" with semiclassical gravity and black hole thermodynamics. See also Kiefer (2007a).
[12] (Butterfield and Isham, 2001, §3.1.2.), Huggett and Callender (2001).

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in the gravitational field, so the gravitational field itself should be quantized. Although such arguments are heuristically very powerful, the consensus is they cannot by themselves compel the quantization of gravity.[13]

A prominent point of contention between GR and QM has to do with the superposition principle of QM (Weinstein and Rickles, 2021). It seems, firstly, that superpositions conflict with general relativity's fixed causal structures: it is difficult to see how we could understand superposed causal structures of GR. Possibly relevant for this, however, are recent 'quantum switch' experiments, which show quantum superposition of causal structure (Chiribella, 2020; Goswami et al., 2020). Furthermore, as (Penrose, 2004, §30.10-30.11) argues, using a thought experiment called 'Schrödinger's lump', there may be a conflict between the superposition principle of QM and the principle of general covariance of GR.[14] Penrose (2014) uses this as part of an argument for the "gravitization of quantum theory", as opposed to the quantization of gravity.

The superposition principle has also, however, been used to argue for the quantization of gravity. This argument comes from Feynman, who considers a Stern-Gerlach type experiment in which a spin-1/2 particle is guided to two counters. The counters are connected to an indicator which is either up when the particle arrives at counter 1 or down when it arrives at counter 2. The indicator itself is a ball of macroscopic dimensions (1 cm), which would then be in a superposition of being in two positions. Since the ball is macroscopic, its gravitational field would also be in a superposition. "We would then use that gravitational field to move another ball, and amplify that, and use the connections to the second ball as the measuring equipment. We would then have to analyze through the channel provided by the gravitational field itself via the quantum mechanical amplitudes. Therefore, there must be an amplitude for the gravitational field." (Feynman, quoted in Zeh (2011), p. 66).[15] The idea is that the gravitational field itself must be described by quantum states subject to the superposition principle. As (Kiefer, 2013, p. 2), states, this is not an argument that demonstrates the necessity of quantizing gravity, but rather "is an argument based on conservative heuristic ideas that proceed from the extrapolation of established and empirically confirmed concepts (here, the superposition principle) beyond their present range of application. It is in this way that physics usually evolves".

4. Unification

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 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 (Maudlin, 1996; Salimkhani, 2018). Along these lines, unification is a way of motivating QG: 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 quantum theory and the Standard Model of particle physics.

What is meant by unification? Maudlin (1996) argues that there are several degrees (or levels) of unification, which exist between a "lower bound" that falls short of unification, and an

[13] Other examples of such arguments include Eppley and Hannah (1977); Peres and Terno (2001), and have been much-discussed, Großardt (2021, 2022); Huggett and Callender (2001); Kent (2018); Mattingly (2005, 2006); Oppenheim (2023); Rydving et al. (2021); Tilloy (2018); Wüthrich (2005).
[14] Cf. Penrose (2014); Weinstein and Rickles (2021).
[15] The original report is from 1957 and republished in Dewitt and Rickles (2011).

"upper bound" that represents *perfect unification*. The lower threshold states that unification is not merely that two (or more) theories are consistent with one another, or that they share a common dynamics, or that there exists a law-like connection (nomic correlation) between physical forces. The upper bound of perfect unification requires that there be a single theory that describes all phenomena as *the same*—as fundamentally stemming from a single origin, e.g., as manifestations of a single entity or interaction ("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) identifies 13 different forms of unification, and refers to this type of unification—where two phenomena hitherto thought to be distinct are identified—as *reductive* unification.

As described, unification is an external motivation for QG (the desire to unify two separate frameworks), but it can also be considered as an internal motivation (within a single framework), if the lack of unification *within* the Standard Model of particle physics is taken as a problem motivating QG. Although the Standard Model can be written as a single theory, it appears as a disjointed amalgam of separate (particle) fields, rather than a unified theory in Maudlin's sense, and this drives many physicists to seek a more unified theory beyond. But why unification? Unification is generally regarded as an epistemic virtue, conferring support for a theory, and being used as a means of justification of a theory (note that this can be the case even without requiring or implying the metaphysical assumption that the world itself is unified); several authors have given Bayesian analyses of unification as an epistemic virtue (Myrvold, 2003). Unified theories have also been argued as being more explanatory, testable, falsifiable, and successful than non-unified (or less-unified) ones (Schindler, 2018, §1.1.4). (Additionally, unification can be used *heuristically* in guiding theory-development, as described by Kao (2019).)

String theory is often promoted as being a unified theory, as well as being a 'theory of everything', since it treats gravity as on par with the fundamental forces of the Standard Model, and all stem from the same basic physics (the behaviour of strings). Yet, QG is not necessarily a unified theory, nor a 'theory of everything'. In the first case, it may be a semiclassical or hybrid theory, which is a non-unified combination of GR and QFT, and in the second case, it may just be a quantum theory of gravity, and not a theory that combines gravity with the Standard Model forces.

There may be reasons for not wanting to unify gravity with the forces of the Standard Model of QFT, depending on how one interprets GR. The typical interpretation of GR is a geometrical one, according to which gravity is not properly a force at all, but the curvature of spacetime. This interpretation of GR stands in contrast to the 'particle physics perspective' which drives string theory. Instead, it—along with the principle of *background independence*—motivates approaches to QG which primarily aim at a consistent quantum description of (more fundamental physics responsible for the low-energy existence of) spacetime, such as loop quantum gravity and causal set theory. In such approaches the principle of background independence is prioritised over the principle of unification.[16]

Perfect unification of GR and QM is not a standard motivation for QG. If it were, this would mean that both GR and quantum theory (as a framework) are not fundamental, but must somehow be recovered from QG—using appropriate limiting procedures and approximation techniques—in the regimes where they are known to be successful. If any approach to QG could not demonstrate that this can be achieved, then its acceptance would be unlikely. But, this is not what most approaches aim at; in line with the Standard Perspective, they aim to essentially retain the framework of quantum theory, rather than reduce it to a more basic theory. Arguably, even unification in a weaker sense is not properly called the problem of QG, if we

[16] For discussion of background independence, see Read (2023).

would be satisfied with a 'hybrid' approach to QG, or an approach such as asymptotic safety, which treats GR in the framework of QFT (Niedermaier and Reuter, 2006).

Salimkhani (2018) adopts the particle physics perspective and argues that the problem of QG is not the need to unify—nor even to combine—GR and QM. He uses results by Weinberg to argue that GR can be reduced to (derived from) the combination of SR and QM (i.e., QFT), and that we have LEQG; thus that the problem is that we need to find the correct theory at high energy scales. More generally, Salimkhani (2021) argues that unification need not be understood as a goal of physics at all. Unification is considered an external influence on physics—*external* here meaning that it is driven by philosophical assumptions, such as metaphysical, metatheoretical, or epistemological considerations that are imposed on physics. Against this, Salimkhani argues that, instead, unification naturally arises in physics as a consequence of the more basic (or genuine) aims and methods of physics, i.e., factors properly *internal* to physics itself, such as empirical adequacy and theoretical consistency.

While the Primary Motivation for QG is to find a theory that describes the domains where both GR and QFT are supposed to be necessary, and which somehow combines GR and QM, it seems we should not understand the problem—as it currently stands—as to find a unified theory. This is not to say, however, that the goal of unification may not be heuristically useful, or that unification could not be an epistemic virtue, or a means of confirmation for a theory of QG.

5. Singularity resolution

Widely-cited as a motivation for QG is the need to resolve particular spacetime singularities in GR. Spacetime singularities are pathologies of a spacetime, and there are various ways in which spacetimes can be singular.[17] Here, largely following Crowther and De Haro (2022), I discuss the two most common categories of spacetime singularity: incomplete geodesics, and curvature singularities.[18] Theorems of Penrose and Hawking (Penrose, 1965; Hawking and Ellis, 1973), show that singularities (incomplete geodesics) are unavoidable in GR under very general, physically reasonable conditions. A common interpretation of these singularities is that they represent the 'breakdown' of spacetime, thus motivating the need for a theory that *resolves* the spacetime singularities—meaning that it should both be non-singular (in any physically problematic way), as well explain 'what happens' in those domains where GR is thought to break down. Yet, it is not clear exactly if, how, or why, the spacetime singularities in GR signal a 'breakdown' or incompleteness of GR—and thus, whether, or how, they in fact serve as motivations, or constraints, for QG.

5.1. Geodesic incompleteness

The definition of spacetime singularities in terms of *geodesic incompleteness* states that a spacetime is singular if and only if it contains an incomplete, inextendible timelike geodesic. Such a geodesic is the worldline of a freely falling test object; the property that makes it singular is that the worldline ends within finite proper time and cannot be further extended. While this definition forms the basis of the Penrose and Hawking singularity theorems, it is not without problems (see Curiel, 2023, §1.1). 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

[17] See, e.g., Curiel (1999); Earman (1996) for a discussion of different types.

[18] 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.

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spacetime singularities (Curiel, 2023, §1.1). 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.

Geodesic incompleteness leads to a lack of predictability and determinism[19], and 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). Arguably, it is not the lack of predictability and determinism *per se* that is the problem, though, but rather that the theory itself has been constructed based on these principles (i.e., it is predicated on the fact that we do not observe such influences). 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). Earman says that this would represent a nasty form of inconsistency—the laws would "perversely undermine themselves".

The breakdown of determinism inside black holes occurs beyond the *Cauchy horizon*: beyond this surface, the Einstein equations no longer give a unique solution. In response, Penrose (1979) proposed *strong cosmic censorship* (SCC), which postulates that the appearance of the Cauchy horizon in Schwarzschild black holes is non-generic, and that the interior region of these black holes is in some way unstable (under small perturbation of initial data) in the vicinity of the Cauchy horizon. Any passing gravitational waves would prevent the formation of Cauchy horizons, meaning that instead, spacetime would terminate at a 'spacelike singularity', across which the metric is inextendable.

SCC—*if it holds*—would ensure that no violations of predictability are detectable even by local observers (i.e., an astronaut on a geodesically incomplete worldline would detect nothing up until, and presumably after, her disappearance), and so, the truth of this conjecture would render any singularities (incomplete geodesics) harmless in regards to determinism. As (Dafermos and Luk, 2017, p. 5) states, "The singular behaviour of Schwarzschild, 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, SCC may be able to save GR from the charge of inconsistency.

In what sense does geodesic incompleteness signal an incompleteness of GR? Here there are two issues of relevance that have been discussed in the philosophy literature. The first regards the nature of the spacetime singularities themselves: (essential) singularities are not located at a *point* of spacetime.[20] Thus, a singular spacetime does not have any "missing points" of spacetime: the gravitational field is defined and differentiable of the manifold—as Earman (1995, 1996) emphasises, there are no singular points where the laws of GR fail to apply.[21] Smeenk (2013) makes the same argument in regards to the big bang singularity: that the laws of GR apply throughout the entire spacetime, and there is no obvious incompleteness. If GR is the correct final theory, "then there is nothing more to be said in regards to singularities" (p. 634).[22] This means that GR is not incomplete in the sense of failing to describe any events.

Although Earman generally advocates a "tolerance for spacetime singularities"—arguing that we can treat them as *predictions*, rather than pathologies of GR—he nevertheless believes there is one way in which the charge of incompleteness may be justified. This is the idea, described

[19] In GR, physicists typically take determinism to hold if the spacetime admits of a well-posed initial value formulation. Cf., Doboszewski (2019); Smeenk and Wüthrich (2021) for recent work on the problems of defining determinism in GR.

[20] If a singularity is located at a point in spacetime, then this is indicative of having a non-essential singularity, i.e., one that can be removed, in the case of incomplete geodesics, by extending the geodesics beyond that point.

[21] For this reason, Curiel (1999, 2023) and others have stressed the *global*, rather than local nature of singularities.

[22] While Smeenk does not view spacetime singularities as motivation for seeking QG, he states that there are other reasons for doubting that GR is the correct final theory, and good reasons to expect that the successor to GR will have novel implications for singularities.

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above, that if SCC does not hold, then the determinism of GR is undermined (Earman, 1995, 1996). Earman ties the determinism of GR to spacetime models that are globally hyperbolic and thus admit of a globally well-posed initial value formulation. 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 admit a globally well-posed initial value formulation).

This leads to the second issue discussed in the philosophy literature—whether GR is a deterministic theory, and whether all models 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 conditions needed for having a well-posed initial value formulation in GR physics. Doboszewski (2019, 2020) also discusses the problems of defining determinism in GR, with the former paper arguing for a pluralistic conception. These issues with determinism in GR may take the bite out of the worry that geodesic incompleteness without SCC is a problem motivating QG (though, of course, this depends on one's convictions regarding the need for a deterministic theory).

5.2. Curvature singularities

According to the definition of curvature singularities, a spacetime is singular if the curvature, especially the scalar quantities constructed by contracting powers of the Riemann tensor, grows without bound in some region of the spacetime.[23] This gives rise to various problems, such as unbounded tidal forces and the lack of consistency of the semiclassical approximation. The semiclassical approximation being referred to here treats GR as an effective field theory, with the Einstein-Hilbert action supplemented with additional higher-curvature terms that represent the quantum corrections to the theory.[24] If we take a model M of GR with a curvature singularity, and then check whether it is an approximate solution of the equations with the quantum corrections, we find that in general, M may be a good solution far away from the singularity, but as we approach the singularity, the higher-order (high curvature) terms will start to dominate over the lowest order term (Einstein tensor). Because of this, M will not be a model of the quantum-corrected theory. This shows how the curvature singularities can be used to predict that GR 'breaks down', since it reveals an inconsistency between GR and (expected) QG effects that manifest at high curvature in the region close to the curvature singularity.

This is a standard argument found in the physics literature, and physicists tend to find the curvature singularities more concerning than geodesic incompleteness, which has been the focus in the philosophy literature. Notice, however, that here it is not the singularity *itself* that is the problem (depending on the outcome of the charge of indeterminism described above), but the *expected quantum effects* in regimes of high curvature—it is this that motivates the need for a new theory, in accordance with the Primary Motivation for QG.

6. Empirical problems

Although QG is primarily motivated by non-empirical concerns, the need to be consistent with empirical observations is still a principle that is used extensively in the search for QG. Three different types are employed: empirical observations that *are not* explained by current theories; empirical observations that *are* explained by current theories; future empirical observations. I briefly describe each in turn.

Empirical results not explained by current theories can serve as motivations, but may or may not be constraints on QG. The most prominent open problems related to observations include

[23] There are also curvature singularities whereby some of the physical components of the Riemann tensor do not have a limit, see, (Earman, 1995, p. 37).
[24] See Crowther and De Haro (2022), §2.3 for full details.

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the problems of dark matter and dark energy. Although these problems may be related to QG—and to each other—they are not standardly treated as such. The observations associated with dark matter, for instance, are instead generally taken to motivate searches for new particles beyond the Standard Model—though other candidates, such as primordial black holes, do not require new physics. Additionally, most approaches to QG have not taken these anomalies as empirical evidence motivating the need for a more-fundamental theory of QG. There are some exceptions to this 'traditional' position, however—and, indeed, there are a growing number of papers related to QG that treat the solution to these problems as a guiding principle, means of confirmation, or indicator of pursuit-worthiness for a theory of QG.[25] This raises interesting questions as to how, or whether, the solutions to the problems of dark energy and dark matter should be used in the search for QG. Perhaps these empirical anomalies *should* motivate the search for a more fundamental theory of matter and spacetime, and be counted as part of 'the problem of QG'?

Empirical results explained by current theories are not motivations for QG, but are constraints. It is a criterion of acceptance that QG reproduce the empirical results explained by current theories, in accordance with the Generalised Correspondence Principle. As stated above, the main specific form of this principle in QG is as the requirement that GR be appropriately derivable from QG in the domain where GR is known to be successful. This correspondence between QG and GR has overwhelmingly dominated as a constraint of interest, shared amongst all approaches.

Novel empirical results can serve as motivations and constraints on QG. These results come from *QG phenomenology*: a unique field of research that aims to reciprocally connect QG to observable phenomena, by building models that bridge the considerable gap (many orders of magnitude) between them. So far, there has not been any philosophical work dedicated to exploring QG phenomenology in general, in spite of the importance of the field, and its offering intriguing connections to philosophy of scientific modelling and experiment. QG phenomenology has led to numerous results, including tight empirical constraints on any possible violation of Lorentz invariance.

While QG phenomenology typically connects with cosmological and astrophysical observations, it can also potentially connect with laboratory experiments, such as 'tabletop' Gravitationally Induced Entanglement experiments, which may provide a 'witness' of the underlying quantum nature of gravity in the non-relativistic limit, using superpositions of Planck-mass bodies.[26]

7. Delimitations

The Primary Motivation is supposed to represent the minimal definition of QG: any approach that does not (attempt to) satisfy it would not be accepted, by the current mainstream consensus, as an approach to QG. The definition thus serves to delimit what would 'count' as an acceptable theory, and necessarily excludes alternative possibilities. It is worth bearing in mind that there may be other solutions to the problems listed above, which are overshadowed if we take them exclusively as problems that motivate QG (as a theory that satisfies the Primary Motivation). Examining the particular motivations in more detail, as I have begun here, can help us also to explore the other possibilities for their resolution, or reconsider the need to resolve them at all.

This is nicely illustrated by the example of spacetime singularities. Crowther and De Haro (2022) shows, through a survey of the physics literature, that there are four different attitudes

[25] The most prominent is Verlinde (2017), but see also Calmet and Latosh (1998); Kastner and Kauffman (2018); Oriti and Pang (2021).

[26] These include Bose et al. (2017); Marletto and Vedral (2017); philosophical exploration in Adlam (2022); Huggett et al. (2023).

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one may take towards singularities in GR (and also, analogously, for divergences in particular quantum field theories). Briefly, the four attitudes in the case of spacetime singularities are:

1 The singularities are to be resolved classically, or 'at the level of GR', rather than pointing to QG.

2 The singularities are to be resolved by QG; (this is the attitude that dominates the physics literature, and which I have focused on here, as it is the only attitude that motivates QG).

3 Tolerance for spacetime singularities, which means not resolving them at any level, because we have reason to keep them.

4 Indifference to spacetime singularities: they are not of any significance.

Crowther and De Haro (2022) finds examples of each of these attitudes in the literature, and argues that the choice of which attitude to take depends on the singularity being considered. We can—and should—adopt different attitudes towards different singularities. In general, singularities in current theories do not automatically point to the need for a new theory. And, in the cases where the (particular) singularities do motivate a new theory, it is not certain that these point to the need for QG rather than a different theory formulated 'at the level of current theory' (i.e., a new classical theory of gravity such as a modification of GR).

As suggested, there is the possibility that other motivations for QG may also be addressed by reconsidering our current best theories. This possibility is considered, for instance, in Avril Styrman's contribution to this conference proceedings, in the context of motivating Dynamic Universe theory as an alternative to GR. Such a possibility is contra to QG as a theory satisfying the Primary Motivation as defined here. In particular, it clashes with the two aspects of the 'takes into account' condition described above. One of these aspects requires that the new theory employ one or more principles of GR. The Dynamic Universe perspective questions the principles of GR even in the regimes where GR is well-tested. But, a separate criticism of this aspect in the context of QG (rather than Dynamic Universe), might be to question why, given that we expect GR to be incorrect in the domains where QG is necessary, that we should retain any of its principles in the domains of QG. In this context, we would need further arguments as to why, e.g., background independence is an important principle to retain at the level of QG (this has been discussed, see, e.g., Read (2023); Smolin (2006)).

The second of these aspects relates to the Generalised Correspondence Principle as requiring the 'recovery' (derivation) of GR as an approximation in its domains of success, and has been taken as a constraint on QG. In this context it is interesting to consider the motivations for this constraint, and its implications. It is possible that some of the motivations for imposing this principle could be satisfied in other ways than derivation—e.g., the motivation of ensuring no 'Kuhn losses' of predictions (or explanations) could be satisfied by showing that the replacement theory delivers approximately the same predictions as GR in the domains where GR is known to be successful (or that it does not leave unexplained anything that was previously explained) in ways other than by derivation of GR as an approximation in these domains. For other motivations for this principle, in the form of derivation, see Crowther (2020).

8. Conclusion

If we are to better understand what a theory of QG should be like, we need to examine the motivations that drive us to search for it in the first place. This paper has attempted to provide a characterisation of the primary motivation behind the current (consensus) approaches to QG, in the hopes of not just better understanding what it is that we mean by a 'theory of QG', but also of stimulating further critical exploration of it, by highlighting some weaknesses and delimitations, as well as some avenues that have been less-explored. There are various motivations that have been appealed to in the search for QG—some of these motivate what I

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have characterised as the Primary Motivation, while others do not. This paper has started to question how the principles of consistency, unification, and singularity resolution are problems that motivate—or fail to motivate—the Primary Motivation.

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