# Quantum Gravity: Motivations and Alternatives
## A Review

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A B S T R A C T

The mutual conceptual incompatibility between General Relativity and Quantum Mechanics is generally seen as the most essential motivation for the development of a theory of Quantum Gravity. It leads to the insight that, if gravity is a fundamental interaction and Quantum Mechanics is universally valid, the gravitational field will have to be quantized, not at least because of the inconsistency of semi-classical theories of gravity. The objective of a theory of Quantum Gravity would then be to identify the quantum properties and the quantum dynamics of the gravitational field. If this means to quantize General Relativity, the general-relativistic identification of the gravitational field with the spacetime metric has to be taken into account. The quantization has to be conceptually adequate, which means in particular that the resulting quantum theory has to be background-independent. This can not be achieved by means of quantum field theoretical procedures. More sophisticated strategies, like those of Loop Quantum Gravity, have to be applied. One of the basic requirements for such a quantization strategy is that the resulting quantum theory has a classical limit that is (at least approximately, and up to the known phenomenology) identical to General Relativity. However, should gravity not be a fundamental, but an induced, residual, emergent interaction, it could very well be an intrinsically classical phenomenon. Should Quantum Mechanics be nonetheless universally valid, we had to assume a quantum substrate from which gravity would result as an emergent classical phenomenon. And there would be no conflict with the arguments against semi-classical theories, because there would be no gravity at all on the substrate level. The gravitational field would not have any quantum properties to be captured by a theory of Quantum Gravity, and a quantization of General Relativity would not lead to any fundamental theory. The objective of a theory of 'Quantum Gravity' would instead be the identification of the quantum substrate from which gravity results. The requirement that the substrate theory has General Relativity as a classical limit – that it reproduces at least the known phenomenology – would remain.

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## 1. **Motivations**

The most essential motivations for the development of a theory of Quantum Gravity are generally supposed to be based on two probably interrelated types of problems: (i) the mutual conceptual incompatibility between General Relativity on the one hand and Quantum Mechanics and Quantum Field Theory on the other hand, and (ii) specific physical problems, unsolved within the framework of the established theories and resulting at least partially from the fact that General Relativity predicts singularities: spacetime points for which it loses its validity.

### 1.1 *The Mutual Concept incompatibility of General Relativity and Quantum Mechanics*

The following three points should elucidate some of the crucial aspects of the conceptual incompatibility between General Relativity and Quantum Mechanics / Quantum Field Theory:

(1) General Relativity, today our best theory of gravity as well as of spacetime, treats the gravitational field as a classical dynamical field, represented by the (pseudo-) Riemannian metric of spacetime. But, according to Quantum Mechanics, dynamical fields have quantum properties. So, if Quantum Mechanics is taken to be universally valid, it seems reasonable to assume the necessity of a (direct or indirect) quantization of the gravitational field. – An additional motivation for the quantization of gravity comes from rather conclusive arguments against semi-classical modifications of the Einstein field equations, i.e. a formalism treating gravity classically and everything else quantum mechanically.

(2) In General Relativity the gravitational field is represented by the metric of spacetime. Therefore, a quantization of the gravitational field would correspond to a quantization of the metric of spacetime. The quantum dynamics of the gravitational field would correspond to a dynamical quantum spacetime. But Quantum Field Theories presuppose a fixed, non-dynamical background space for the description of the dynamics of quantum fields. They are conceptually inadequate for a description of a dynamical quantum geometry. An attempt to find a quantum description of dynamical geometry by means of a theoretical approach that necessarily presupposes a background space with an already fixed metric will scarcely be successful. A quantum theory of the gravitational field can scarcely be a Quantum Field Theory, at least not one in the usual sense. – But it is not only the dynamical character of general relativistic spacetime that makes traditional background-dependent quantum theoretical approaches problematic. It is

foremost the active diffeomorphism invariance of General Relativity that is fundamentally incompatible with any fixed background spacetime.

(3) In General Relativity, time is a component of dynamical spacetime. It is dynamically involved in the interaction between matter/energy and the spacetime metric. It can be defined only locally and internally; there is no external global time parameter with physical significance. Quantum Mechanics, on the other hand, treats time as a global background parameter, not even as a physical observable represented by a quantum operator.

### 1.2 *Unsolved Physical Problems*

Although it is commonly assumed that gravity is a universal interaction and that Quantum Mechanics is universally valid, most physical problems can be captured either by General Relativity (e.g. celestial mechanics, GPS positioning) or by Quantum Mechanics (e.g. hydrogen atom, electromagnetic radiation). However, there are specific physical situations, in which both of these mutually incompatible conceptual frameworks – General Relativity and Quantum Mechanics – would be necessary to get to an adequate description. But such a description can not be achieved because of their mutual incompatibility. Here a theory of Quantum Gravity, by means of which we could get over the mutual incompatibility of General Relativity and Quantum Mechanics, seems to be inevitable. The most prominent of those problematic cases are black holes (Hawking radiation , Bekenstein-Hawking entropy) and the presumed high-density initial state of the universe ('big bang', physics of the early universe, quantum cosmology).
In both cases General Relativity predicts singularities; but, because of the breakdown of the equivalence principle for the singularities themselves, the theory becomes inapplicable for these points in spacetime. The fact that General Relativity predicts singularities – points for which it loses its validity – indicates that it can not be a universal theory of spacetime. According to common wisdom, a successful, adequate theory of spacetime should be able to describe what happens in those cases in which General Relativity predicts singularities.
Such a theory – conventionally subsumed under the label *'Quantum Gravity'*, irrespective of the concrete details – should capture the presumed quantum properties of the gravitational field and of dynamical spacetime. Or it should be able to explain how gravity and/or spacetime as possibly emergent, intrinsically classical phenomena with no quantum properties could be compatible with – and result from – a quantum world consisting of quantum matter and quantum interactions. It should also explain which microstates are responsible for the Bekenstein-Hawking entropy of black holes; in the classical case, black holes are described by only a few physical quantities that can scarcely be responsible for their (immense) entropy.
And a theory of Quantum Gravity should describe the details leading to the Hawking radiation of black holes – the details beyond the intuitive quantum field theoretical picture. In particular, it should clarify if Hawking radiation leads to a breakdown of the unitarity of Quantum Mechanics – and thereby to an information paradox. And finally it should describe what happens in the final

stages of an eventually complete evaporation of a black hole. For all that, it will very probably be inevitable to reach a description of the black hole event horizon going beyond the classical picture.

## 2. Conceptual Considerations

The well-established, empirically well-confirmed precursor theories – General Relativity and Quantum Mechanics together with the already existing empirical data that confirmed these theories, are still the only concrete elements that constitute a reasonable starting point for the different attempts to construct a theory of Quantum Gravity, intended to get over their mutual conceptual incompatibility. There is still no relevant empirical data that points without doubt beyond those precursors.

In this situation, the most fundamental requirements for theory construction in Quantum Gravity are, on the one hand, conceptual coherence and consistency. On the other hand it is the necessity to reproduce at least the empirical basis of the well-established theories – their phenomenology which means that theoretical approaches in Quantum Gravity have to reproduce those precursors at least as approximations or low-energy implications. The freedom left for theory development, after taking into account (or at least having the intention to take into account) those basic requirements, is usually filled by (sometimes rather problematic) metaphysical assumptions. Which basic conceptual (or model-theoretical) elements of the established precursor theories – beyond their phenomenology – are taken to be essential for the development of the new theoretical approaches depends primarily on the assessment of those elements with regard to their relevance for Quantum Gravity. Because of the conceptual incompatibility of the precursor theories it has necessarily to be a selection. And there are no objective a priori criteria for this selection. Idiosyncratic convictions enter at this point. *Is the background-independence of General Relativity indeed to be seen as a basic conceptual requirement for Quantum Gravity? Is spacetime fundamental or emergent? Is it a substance or a relational construct? If it is a substance, does it have quantum properties? Is spacetime based on a quantum substrate or rather something completely different? Is the theory of 'Quantum Gravity' necessarily to be a quantum theory? Has the fundamental theory to be a nomologically or ontologically unified theory? So, with this caveat in mind, what could be reasonable elements of a starting point for the development of a theory of Quantum Gravity? What should be taken as at least heuristically relevant? Which conceptual elements of the precursor theories constitute presumably essential physical insights that will probably survive the next step in the development of a coherent and empirically adequate picture of physical reality? What should at least be taken into account?*

One of the most fundamental insights of General Relativity – our empirically well-confirmed classical theory of gravitation and of spacetime – is that it is the metric of spacetime which represents the gravitational field. If we take this geometrization of gravity seriously, that means that the gravitational field is not a field defined on spacetime, but rather a manifestation of spacetime itself. Consequently, it is not possible to describe the dynamics of the gravitational field on an already predefined (or fixed) background spacetime. As long as there are no better, well-founded reasons, a theory of Quantum Gravity has to take into account this background-independence; it has to describe the dynamics of the gravitational field without recourse to an already existing spacetime (metric). Additionally, under extrapolation of the conceptual implications of General Relativity, one could suspect, at least for the time being, that a successful theory of Quantum Gravity will probably not only be a theory describing a dynamical spacetime, rather it will be based on a relational conception of spacetime – or it will even lead to an emergent spacetime scenario. If we take Quantum Mechanics seriously as our fundamental (and presumably universally valid) theory of the dynamics of matter and fields, it seems to be reasonable (at least at first sight) to assume that the gravitational field – like all other dynamical fields – should have quantum properties. Much more clearly than this intuition, the arguments against semi-classical theories of gravitation exclude the possibility of a fundamental non-quantum gravitational interaction in a quantum world.

## 3. Development of a Theory of Quantum Gravity - Quantization of General Relativity

Considering the direct quantization of General Relativity as a reasonable strategy to overcome its apparent conceptual incompatibility with Quantum Mechanics and Quantum Field Theory, one has to remember that the most essential requirement for a theory of Quantum Gravity consists – besides conceptual consistency and coherence – in its ability to reproduce General Relativity after its quantization as a classical limit or low-energy approximation of the quantized theory. Quantum theory has to at least reproduce the macroscopic phenomenology of its classical starting point up to the exactitude of the already existing empirical data. We will see in the following that this requirement is not necessarily or automatically fulfilled.

A quantization of General Relativity does not necessarily lead back to it. But the way back is the essential requirement for a theory of Quantum Gravity – and not that it was constructed by a quantization of the empirically well confirmed classical theory. If one tries nonetheless to follow the direct quantization strategy, one has to decide which quantization procedure should be applied; there are different methodological options, even when the classical theory is well-known and well-defined. Furthermore one has to decide which physical magnitude has to be quantized. In the case of General Relativity, it could be the metric, or topology, or even the causal structure. And for all these decisions the question remains how to take into account the background-independence of the classical theory during quantization.

As we will see, all existing direct quantization approaches start from a quantization of the metric or of physical magnitudes on the same descriptive level: connections, holonomies. Their most striking difference is to be found in their respective attitude with regard to background-independence and its formal realization.

## 4. Beyond Quantum Gravity

### 4.1 *A Fundamental Theory without the Quantum*

The question remains if the already mentioned approaches to a theory of Quantum Gravity, finally, are sufficient or radical enough to get over the possibly only apparent conceptual incompatibility between General Relativity and Quantum Mechanics / Quantum Field Theory, and if at least one of these approaches has the potential to attain at the same time an empirically adequate description of nature, consistent also with future empirical data that go beyond those on which the established theories are based. The more orthodox, mainstream approaches to Quantum Gravity, like String Theory and Loop Quantum Gravity, seem to lead to severe conceptual problems and are unable, at least at the moment, to reproduce the phenomenology of our established, but apparently mutually incompatible theories. And the less orthodox approaches – especially the emergent gravity / emergent spacetime scenarios, like the Quantum Causal Histories approach – are at the moment only more or less developed conceptual ideas, far from a full theoretical framework. Almost all of these approaches, orthodox or less orthodox, presuppose Quantum Mechanics. They either suppose that there are quantum properties of gravity and spacetime, or they start with a quantum substrate from which gravity and spacetime result as emergent, intrinsically classical phenomena. Some people think that such attempts at a construction of a theory of Quantum Gravity are not radical enough, that not only gravity and spacetime, but also the quantum could be an emergent phenomenon. According to those people, the still unknown fundamental theory could quite perfectly be a non-quantum theory, describing a substrate from which gravity, spacetime and the quantum emerge.

### 4.2 *No Fundamental Theory - Patchwork Physics*

Should all attempts to get rid of the conceptual incompatibility between our established fundamental theories – General Relativity and Quantum Mechanics / Quantum Field Theories – remain without success on the long run, the last option would consists in the view that a unified, conceptually coherent physical description of nature can possibly not be achieved. Maybe physical theories can only be seen as theoretical instruments with a limited explicatory scope. Maybe they do not lead to a coherent, unified description of nature. Then all attempts to reach at a fundamental physical description of nature, to reach at a unified theory describing an ultimate substrate dynamics, would probably be conceptually inadequate extrapolations of our nomological ambitions. The assumption of a fundamental unity of nature would be simply wrong, at least as far as it concerns its reflection within our theoretical and methodological apparatus of physics.

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