Quantum Gravity: Motivation and Alternatives

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Abstract

The mutual agreeance of incompatibility between Quantum Mechanics and General Relativity is seen as the forefront drive for the motivation of the development of a theory for Quantum Gravity. It leads to the discussion that if gravity is a fundamental interaction and Quantum Mechanics is globally valid then the gravitational field will have to be quantized because of the inconsistency of semi-classical theories of gravity. The aim of a theory of Quantum Gravity would 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 space-time metric has to be taken into account. The quantization has to be adequate which means especially the resulting quantum theory has to be background independent. This means it cannot be achieved by theoretical procedures of quantum field. More realistic strategies like ***Loop Quantum Gravity*** will have to be applied in this scenario.

One of the basic requirements for a quantization attempt is that the quantum theory has a classical limit identical to General Relativity. However, gravity isn't a fundamental but a residual interaction that could very well be a classical phenomenon. If Quantum Mechanics is to be universally valid then we have to assume a quantum substrate from which gravity would result as an emergent phenomenon and there would be zero conflict with the argument against semi-classical theories, because there would be no gravity at all on a substrate level. The gravitational field wouldn't have any quantum properties to be captured by a theory of Quantum Gravity, and a quantization of General Relativity wouldn't lead to any functional theory. The 'objective' of a theory of Quantum Gravity would be the identification of the quantum substrate from which the gravity results. The requirement that the substrate theory has General Relativity as a classical limit – that it reproduces at least the known phenomenon – would remain the theory.

This paper gives an overview over the main options for theoretical construction in the field of Quantum Gravity. Because of the still unclear status of Gravity and Space-Time, it pleads for the necessity of a plurality of a conceptually different approach to Quantum Gravity.

Keywords: Quantum Theory, String Theory, Quantum Gravity, Loop Quantum Gravity, Semi-Classical Theories and General Relativity.

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 Incompatibility of General Relativity and Quantum Field Theory / Quantum Mechanics

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

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.

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.

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.

References for current sections:

Under which conditions this conceptual incompatibility has to be seen as real or as only apparent, as well as what follows from each of these possibilities, will have to be discussed later. See section 2. All other fields as well as matter are also treated classically by General Relativity. See sections 2. And 3.1. Cf. Kiefer (1994, 2004, 2005), Peres / Terno (2001), Terno (2006), Callender / Huggett (2001a, 2001b).

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 cannot 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 cannot 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 at a description of the black hole event horizon going beyond the classical picture.

References for current sections:

Cf. Earman (2006, 2006a). Cf. Earman (1986, 1989, 2002, 2006, 2006a), Earman / Norton (1987), Norton (1988, 1993, 2004). It is again the active diffeomorphism invariance of General Relativity that leads not at least to the Problem of Time. Cf. Belot / Earman (1999), Earman (2002), Pons / Salisbury (2005), Rickles (2005), Rovelli (1991a, 1991b, 2001, 2002, 2006), Isham (1993), Unruh / Wald (1989). Cf. Hawking (1974, 1975), Bardeen / Carter / Hawking (1973). 11 Cf. Bekenstein (1973, 1974, 1981, 2000, 2001, 2003), Wald (2001), Bousso (2002). See also section 2.

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 are still no relevant empirical data that point 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 (or does it emerge from) a quantum substrate or rather something completely different? Has 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?

if 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 (unlike all other interaction fields) 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. But this does not exclude the possibility that gravity – in contrast to the intuition leading to the assumption of quantum properties of the gravitational field – could be an intrinsically classical phenomenon, emerging from a quantum substrate without gravitational degrees of freedom. It is at least not completely unreasonable to take this possibility into account. Then, gravitation would not be a fundamental interaction; it would be a residual interaction, caused by non-gravitational interactions and their corresponding degrees of freedom. This would not lead to any conflict with the arguments against semi-classical theories, because, on the fundamental level, there would be only the quantum substrate, governed by fundamental quantum interactions, to which gravity would not belong.

A theory describing the dynamics of the gravitational field would be an effective theory describing the intrinsically classical dynamics of collective degrees of freedom that result from a completely different quantum substrate; this classical theory would have to be recovered from the fundamental theory by means of a statistical approximation over the (more) fundamental degrees of freedom of the substrate. However, should gravity indeed be a fundamental interaction (and should Quantum Mechanics be universally valid), then we had to expect for the gravitational field, as a fundamental entity, quantum properties, not yet taken into account in the classical picture provided by General Relativity. The gravitational field would have to be 'quantized' – like the electromagnetic field, but very probably not with the model-theoretical apparatus used in Quantum Electrodynamics, because of the fixed background spacetime necessarily required in Quantum Field Theory.

Should General Relativity be the adequate classical theory to be quantized and should it capture the relevant classical features of gravity, then its identification of gravity with properties of a dynamical geometry would probably mean that a quantization of the gravitational field corresponds to a quantization of dynamical spacetime. The quantization of gravity would lead to a quantum geometry. At least on first sight, one could suspect that a (conceptually and empirically successful) quantization of General Relativity – should it be achievable – would lead to a theory describing the metric of spacetime as an expectation value of a quantum variable; furthermore one would probably expect something like uncertainties of spacetime, or quantum fluctuations of the spacetime metric, of spacetime geometry, possibly even of the spacetime topology.

But this strategy for the development of a theory of Quantum Gravity, i.e. constructing it by means of a (direct) quantization of General Relativity, intended to identify and capture the quantum properties of gravity and spacetime, will only be successful if gravity is indeed a fundamental interaction, if the gravitational field (as well as spacetime) has indeed quantum properties. If gravity is an intrinsically classical phenomenon, this strategy will simply lead to a quantization of the wrong degrees of freedom: macroscopic collective degrees of freedom resulting from a totally different substrate, governed by totally different fundamental degrees of freedom, which then should be the original subject of a theory of 'Quantum Gravity' – supposed that one has the intention to keep up this name for the theory by means of which we would get over the conceptual incompatibility between General Relativity and Quantum Mechanics, irrespective of the question if it is a factual or only an apparent incompatibility. So, under consideration of the possibility that gravity could either be a fundamental interaction or an intrinsically classical phenomenon – which means to take all possibilities into account – 'Quantum Gravity' would (irrespective of the details) be the name of the theory by means of which we are able to explain the dynamics (and possibly the emergence) of gravity (and spacetime) in a way that gets over the (factual or only apparent) conceptual incompatibility between General Relativity and Quantum Mechanics.

It would be a theory describing the substrate of gravity (and spacetime). And this substrate may either contain (quantum) gravitational degrees of freedom or not. The options are still open: fundamental or emergent gravitational interaction, fundamental or emergent spacetime, quantum geometry or intrinsically classical spacetime, substantial or relational spacetime, etc. Taking all options seriously, the theory of 'Quantum Gravity' we are searching for should be a quantum theory (in the broadest sense), which – and this is the most basic requirement for any such theory – reproduces the phenomenal content of General Relativity (at least approximately and without conflict with known empirical data; possibly as a classical, macroscopic, low-energy limit), and which should be able to explain the empirical and conceptual successes of General Relativity. Additionally, at least on the long run, such a theory has to lead to specific own prediction that go beyond those of its precursor theories, leading thereby to specific and differential forms of experimental testability. This minimum definition (and broad conception) of 'Quantum Gravity' leads to a wide spectrum of options for theory development.

The already existing approaches differ especially with regard to the specific conceptual and model-theoretical components of the precursor theories they take to be essential for Quantum Gravity or as indispensable for its modalities of theory construction. But, here again, it has to be emphasized that the probably inevitable inclusion of conceptual elements derived from the precursor theories is not completely unproblematic. The well-established precursors and their conceptual implications could just point towards the wrong direction.

Taking these precursor theories more or less uncritically as constitutive components of a starting point for an attempt to eradicate their mutual conceptual incompatibility – the dominant attitude at least for the direct quantization approaches – could possibly lead into dead ends. A careless extrapolation of elements from the precursor theories might be fatal and should at least not be taken as the only option for the theory development in Quantum Gravity. On the other hand, too speculative approaches, far from the conceptual basis of the precursor theories, bear without doubt their own risks. Only a pluralistic strategy in theory construction will be adequate to make these different risks of every single approach more controllable. All reasonable alternatives should be taken into account, even those alternatives that, on first sight, seem to be eccentric in comparison with the standards of our well-established theories. Such eccentric alternatives could nonetheless be able to reproduce the implications of these precursors as low-energy approximations and lead to specific new predictions – and, thereby, to empirical testability.

There is still something that was not yet mentioned with regard to the prerequisites of a possible starting point for the theory development in the field of Quantum Gravity, something that could nonetheless be of specific heuristic significance in this context. The statement made at the beginning of this section, that General Relativity and Quantum Mechanics are still delivering the only concrete conceptual elements for a starting point with regard to the attempts to get over their mutual conceptual incompatibility, is not quite correct. Additionally, there are conceptions and ideas that are motivated sufficiently well within the context of our established theories, but do not belong any more fully to this context – something that could be called 'elements of transition'. What makes these 'elements of transition' interesting and relevant for Quantum Gravity, is that they already constitute bridges going over the frontiers between the otherwise conceptually incompatible established theories. A paradigmatic example of such an 'element of transition', conceptually going beyond the context of our established theories, concerns the Bekenstein-Hawking entropy of black holes. It results from considerations that combine implications of General Relativity, Quantum Mechanics, Thermodynamics and Information Theory. And it is this combination that makes black hole entropy interesting and relevant for Quantum Gravity. The Bekenstein-Hawking entropy of black holes, and the Covariant (or Holographic) Entropy Bound20 which can be motivated within the thermodynamics of black holes, point directly to a discrete substrate at the Planck level. This can be taken as an indication either of a discrete spacetime structure – if spacetime should be fundamental – or of a discrete structure from which spacetime emerges.

In any case, it is pointing directly to a substrate with a finite number of degrees of freedom per spacetime region – irrespective of the question, if this spacetime region is part of the fundamental level or emergent, i.e. if the fundamental degrees of freedom are (quantum) geometric or 'pregeometric'. Additional, but much more indirect indications of such a discrete structure come from the singularities that General Relativity predicts (but which transcend its model-theoretical apparatus: differential geometry) and from the divergences that occur in Quantum Field Theory for small distances / high energies. Both could be artifacts of the continuum assumption with regard to spacetime or of the assumption of an infinity of the relevant degrees of freedom respectively.

Interestingly, almost all existing approaches to a theory of Quantum Gravity lead to indications either of a discrete spacetime structure – for those approaches that take spacetime to be a fundamentally entity whose quantum properties have to be revealed in the context of a theory that goes beyond General Relativity in exactly this point t – or of a discrete ('pregeometric') substrate structure from which spacetime results. What is of specific significance, is that these indications of a discrete substructure are not only present in the more radical approaches, but also in those approaches that take the fundamentals of General Relativity as well as those of Quantum Mechanics to be essential for a theory of Quantum Gravity.

This is most astonishing, because the assumption of a spacetime continuum and of an infinite number of physically relevant degrees of freedom is an inevitable ingredient of General Relativity (differential geometry presupposes the continuum) as well as of Quantum Mechanics and Quantum Field Theory (fields are defined on a classical continuous background space). The best example of a very sophisticated, but at the same time very conservative approach to Quantum Gravity that takes the conceptual basis of General Relativity as well as that of Quantum Mechanics very seriously as essential part of its conceptual strategy, but nonetheless leads directly to a discrete structure when General Relativity is quantized, is *Loop Quantum Gravity*.

References for current sections:

Cf. Hawking (1976, 1982, 2005), Belot / Earman / Ruetsche (1999). (cf. Earman (1986, 1989, 2002, 2006, 2006a), Earman / Norton (1987), Norton (1988, 1993, 2004); Cf. Bekenstein (1973, 1974, 1981, 2000, 2001), Wald (1994, 2001), Bousso (2002). See also section 1.2. Cf. Bekenstein (1981, 2000, 2001), Bousso (2002), Pesci (2007, 2008).

3. Strategies for the Development of a Theory of Quantum Gravity

3.1 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. The quantum theory has at least to 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.

3.1.1 Covariant Quantization

The Covariant Quantization of General Relativity consists in the attempt to construct a Quantum Field Theory of gravity, which means: a Quantum Field Theory of the metric field, in the manner of Quantum Electrodynamics, the Quantum Field Theory of the electromagnetic field. But Quantum Field Theories in this orthodox sense need a background space time with a fixed metric for the definition of its operator fields. Consequently, Covariant Quantization uses a standard perturbation-theoretical approach on this background to be treated quantum mechanically. This leads to a Quantum Field Theory of the fluctuations of the metric. The corresponding field quanta of gravity, called 'gravitons', are massless and have spin 2 – as a consequence of symmetry arguments and of the properties of classical gravity (long-range, exclusively attractive). They are assumed to represent the quantum properties of spacetime and to behave according to standard Feynman rules on a fixed background spacetime. But Covariant Quantization with its perturbation expansion of the fluctuations of the spacetime metric turns out to be non-renormalizable. This is a direct consequence of the self-interaction of the graviton, which, in turn, is nothing else than a quantum-field-theoretical expression of the nonlinearity of classical gravity. Gravity couples to mass and, because of the mass-energy equivalence, to every form of energy. Therefore the self-interaction contributions to gravity increase for decreasing distances or increasing energies. So, the contribution of virtual particles with increasing energies dominates the higher orders of the perturbation expansion. This leads to uncontrollable divergences of the expansion and to its non-renormalizability. No quantitative predictions can be achieved. This makes the theory irrelevant as a fundamental description of spacetime.

3.1.5 Theory Extension before or after the Quantization of General Relativity

An additional option that could be considered as a possible road to an adequate theory of Quantum Gravity consists in a weakening of the directness of a quantization of General Relativity by means of an extension: One can either extend General Relativity before its quantization or extend the quantum theory resulting from a quantization of General Relativity. Usually, the symmetries of the theory are taken to be the main object of such an extension. To this context belongs a theory called Supergravity42 – a supersymmetric and, because of consistency requirements, eleven-dimensional extension of a quantum version of General Relativity. In the seventies and eighties, Supergravity was taken very seriously as a promising option for a theory of Quantum Gravity. This perspective vanished with the discovery of conceptual problems and increasing doubt with regard to the renormalizability of the theory. Finally, it came to a resurrection of the approach as an effective theory; Supergravity aroused the interest of string theoreticians, who found a new role for it as part of the web of dualities between the perturbative string theories.

3.2 Conditions that could result in the Inadequacy of a Quantization of General Relativity

As already mentioned in section 2, there is the possibility that gravity could be an intrinsically classical, macroscopic phenomenon. As also mentioned before, an intrinsically classical gravity does not lead to conflicts with the arguments against semi-classical theories of gravity, if it is an emergent phenomenon, resulting from a quantum substrate that does not contain any gravitational degrees of freedom. The arguments against semi-classical theories of gravity presuppose that gravity is a fundamental interaction. They lose their validity if gravity is not fundamental, if gravity does not even appear in a fundamental quantum description of nature. Then, on the fundamental level, there would be no semi-classical hybrid dynamics that leads to conceptual inconsistencies. So, if gravity is an intrinsically classical phenomenon, it cannot be a fundamental interaction. It has to be an induced or residual effect, caused by a quantum substrate dominated by other interactions.

Therefore, if gravity should indeed be an emergent, intrinsically classical, macroscopic phenomenon, and not a fundamental interaction, it would not have to be quantized to make it compatible with Quantum Mechanics. Resulting as a classical phenomenon from a quantum substrate, it would already by compatible with Quantum Mechanics. Moreover, it would not only be unnecessary to quantize gravity –it would rather be completely nonsensical to try to quantize gravity. A quantization of gravity would be a quantization of collective, non-fundamental, emergent, macroscopic degrees of freedom. A quantization of General Relativity would be the quantization of an effective theory describing the dynamics of these collective degrees of freedom. It would be as useful as a quantization of the Navier-Stokes equation of hydrodynamics. The resulting 'theory of Quantum Gravity' would be analogous to something like 'Quantum Hydrodynamics': an artificial, formal quantization of a classical theory describing collective, macroscopic degrees of freedom, without any implications for, or any clarifications with regard to, an underlying quantum substrate. It would be simply the wrong degrees of freedom, which are quantized.

So, the option that gravity could be an emergent, intrinsically classical phenomenon would explain very well the problems of all attempts to quantize gravity: conceptual problems as well as those with the reproduction of an adequate classical limit. A quantization of gravity is only (but not necessarily) a reasonable strategy for the construction of a theory of Quantum Gravity if gravity is a fundamental interaction. If it is not a fundamental interaction, the adequate strategy for the development of a theory of Quantum Gravity – then understood primarily as a theory that would dispel the only apparent incompatibility between General Relativity and Quantum Mechanics –consists in the search for the quantum substrate, and for a theory that would explain how the dynamics of the quantum substrate leads to an emergent level with gravitational degrees of freedom.

But, what about spacetime? – If gravity should be an intrinsically classical, residual or induced, emergent phenomenon, without any quantum properties, and if General Relativity gives an adequate description of this intrinsically classical phenomenon, the general relativistic relation between gravity and spacetime, i.e. the geometrization of gravity, should be taken seriously, at least as long as no better reasons make this questionable. General Relativity would have to be seen as a classical, low energy, long-distance limit to a searched-for theory describing the quantum substrate from which gravity and spacetime results. The substrate itself would neither contain gravity, nor would it presuppose spacetime, at least not the continuous, dynamical spacetime of General Relativity into which the gravitational field is encoded as metric field. The spacetime of General Relativity – we would have to expect – would be, like gravity, an emergent phenomenon. It would not be fundamental, but the macroscopic result of the dynamics of a non-spacetime ('pregeometric') substrate.

However, if gravity and spacetime should be emergent phenomena, from which structure do they emerge? Of what entities and interactions does the substrate consist? Does matter (and do other quantum fields) also emerge from the substrate? – Meanwhile, there exist a lot of different, more or less (mostly less) convincing scenarios that try to answer these questions; some are conceptually interrelated and some are completely independent. Some of these scenarios take General Relativity as an adequate description of gravity and spacetime – as an effective theory for the macroscopic, low-energy regime –, keep to the general relativistic relation between gravity and spacetime, and treat them as emerging together from a pregeometric substrate. Others take General Relativity as a theory with limited validity, even for the classical, macroscopic regime – especially with regard to its geometrization of gravity –, and try to describe the emergence of gravity from a substrate that already presupposes spacetime. Some are pregeometric with regard to space, but not with regard to time, which is presupposed, either as a continuous parameter, or in form of discrete time steps. Most of the scenarios presuppose the validity of Quantum Mechanics on the substrate level, but a few try also to explain the emergence of Quantum Mechanics from a (sometimes deterministic) pre-quantum substrate.

3.2.5 Spacetime and Gravity as Phenomenological Results of a Computational Process

One of the advantages of the idea that spacetime could be an emergent information-theoretical phenomenon is that some of the problematic implications of the hydrodynamic and condensed matter models, e.g. their possible inability to achieve background-independence, can be avoided. The information-theoretical emergent gravity / emergent spacetime scenarios are almost automatically background-independent. – But many alternative scenarios with different substrate constructions exist. Most presuppose quantum principles, but some start from a non-quantum substrate and try not only to elucidate the emergence of gravity and spacetime, but also to reconstruct Quantum Mechanics as an emergent phenomenon.

The idea that spacetime emerges from a purely information-theoretical pregeometric substrate goes back to Wheeler's It from bit concept. Lloyd modifies this in his Computational Universe approach to an It from qubit: Spacetime is here to be reconstructed as an emergent result of a completely background-independent quantum computation – a background-independent quantum computer.

And because of the background-independence of the substrate, emergent spacetime fulfills – as Lloyd suggests – necessarily the Einstein field equations in their discrete form as Einstein-Regge equations. But, as in almost all emergent gravity / emergent spacetime scenarios, the concrete substrate dynamics, finally, remains obscure. For the Computational Universe approach this means: It is unknown, on which concrete computation our universe with its specific spacetime chronogeometry is based.

3.3 Quantum Gravity without the need for Quantization of General Relativity

It cannot be emphasized enough that the most essential requirement for any approach to a theory of Quantum Gravity consists – besides conceptual consistency and coherence – in its ability to reproduce General Relativity (or at least its phenomenology) as a classical limit or a low-energy approximation (up to the exactitude of the already existing empirical data). If no theory that can be constructed by means of a (direct) quantization of General Relativity should be able to fulfill this requirement, two alternative options remain: One could either try to find a quantum theory with the appropriate classical limit by means of the quantization of another classical theory instead of General Relativity. Or one could try to construct or to find such a theory 'directly' – without any quantization of a classical theory at all.

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. The probably best-known of these emergent quantum approaches goes back to 't Hooft. He proposes a deterministic, pregeometric, non-quantum substrate, which should possibly be modeled by something like cellular automata. None of these proposals has achieved a concrete theoretical framework so far.

4.2 No Fundamental Theory – The Possibility of an Anomological Substrate

There are also approaches that do not call into question especially the universal validity of Quantum Mechanics, but instead that of a fundamental nomologicity of nature in general. The idea is that the laws of nature themselves – and all of them – are emergent, resulting from a lawless substrate, possibly by means of something like a statistical coarse-graining. (Or they are even a consequence of our scientific methodology and its search for regularities and nomological structures.) Then, the laws of nature would be only approximately valid, 'macroscopic', low-energy phenomena. Nature would ultimately, on its most fundamental level, be anomological and chaotic. Best known is Wheeler's idea of a Law-without-law physics. In the context of Nielsen's Random Dynamics – a concretization of Wheeler's idea – it was even possible to derive some of the physically most important symmetries and regularities as approximately valid lawful structures from a lawless, chaotic substrate.

4.3 No Fundamental Theory – Patchwork Physics

The divergence theorem in its usual form applies only to suitably smooth vector fields. For vector fields which are merely piecewise smooth, as is natural at a boundary between regions with different physical properties, one must patch together the divergence theorem applied separately in each region. We give an elegant derivation of the
resulting patchwork divergence theorem which is independent of the metric signature in either region, or which is thus valid if the signature changes.

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. Maybe we are living in a Dappled World, consisting of disparate realms of phenomena, each of which makes necessary a different, more or less completely autonomous scientific approach. Maybe there are even sectors of reality that completely block out all scientific endeavors. – Under these conditions, a (successful, empirically adequate) theory of Quantum Gravity would not be achievable. But, before being satisfied with this option, one should have taken into account and tried out all alternatives: known or still unknown, orthodox or as radical as they might be. And under which conditions one could say that this has already been done!

“Physics is the only real science, the rest are just stamp collecting.” – Ernest Rutherford

5.0 Thankyou

Thank you to everyone who has read my paper whether that be you have a common knowledge of Quantum or you are just passionate about the unveiled phenomena’s in Physics just like us! It has been a dream of mine to have a published paper since I was 16 and thanks to the continuous work from physicists all around the world now my dream is a reality!