The Philosophy behind Quantum Gravity

Henrik Zinkernagel
Department of Philosophy, Campus de Cartuja,
18071, University of Granada, Spain.
zink@ugr.es

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Abstract

This paper investigates some of the philosophical and conceptual issues raised by the search for a quantum theory of gravity. It is critically discussed whether such a theory is necessary in the first place, and how much would be accomplished if it is eventually constructed. I argue that the motivations behind, and expectations to, a theory of quantum gravity are entangled with central themes in the philosophy of science, in particular unification, reductionism, and the interpretation of quantum mechanics. I further argue that there are – contrary to claims made on behalf of string theory – no good reasons to think that a quantum theory of gravity, if constructed, will provide a theory of everything, that is, a fundamental theory from which all physics in principle can be derived.

1. Introduction

One of the outstanding tasks in fundamental physics, according to many theoretical physicists, is the construction of a quantum theory of gravity. The so far unsuccessful attempt to construct such a theory is an attempt to unify Einstein's general theory of relativity with quantum theory (or quantum field theory). While quantum gravity aims to describe everything *in* the universe in terms of quantum theory, the purpose of the closely related project of quantum cosmology is to describe even the universe as a whole as a quantum system. At present, a quantum theory of gravity is mainly sought along two avenues (both of which are associated with a number of technical and conceptual problems). The first of these is canonical quantum gravity in which the classical Einstein equations are somehow quantized.[1] The second, and most popular, program for quantum gravity is that of string theory. Contrary to canonical quantum gravity, string theory aims to unite the description of gravity with those of the other forces in nature (electromagnetic, weak, and strong forces), and is in this sense the most ambitious attempt of a quantized theory of gravity. Thus, string theory not only postulates (like canonical quantum gravity) unification in the sense that all forces are quantum in nature but also that all the quantum forces can be derived from one single theory. String theory is therefore often referred to as a candidate for a theory of everything.

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[1] Such a quantization might be carried out e.g. by making the space-time metric a quantum operator. In a sense this amounts to a 'discretization' of space and time insofar as one can at all speak of space and time in quantum gravity (see below). For a good popular introduction to the different approaches to quantum gravity, see Smolin (2001).

The quantum gravity project raises a number of philosophical issues, some of which I shall deal with below (in this paper the hard technical problems associated with quantum gravity will be ignored). In particular, I will critically examine the motivations behind quantum gravity and the question of whether such a theory is, if not strictly necessary, then at least desirable. Furthermore I will address the question of whether a quantum theory of gravity, if constructed, can fit the bill of being a kind of ultimate theory which could in principle account for all physical phenomena.

The outline of the paper is as follows. I first (section 2) discuss how the motivations behind a quantum theory of gravity are related to the ideas of unity and reductionism in physics. In this connection, I review Bohr's idea of unity without reductionism, and discuss how the enterprise of quantum gravity is related to the interpretation of quantum mechanics. I then (section 3) briefly review an argument for the necessity of a quantized theory of gravity, and argue that such a theory is necessary neither for consistency reasons nor (at least so far) on experimental grounds. In a broad sense quantum gravity may be conceived of as any theory which couples general relativity (and thus a classical description of gravity) with quantum theory. I argue that the expectation – which serves as a motivation for quantum gravity in the broad sense – that general relativity and quantum theory must be connected in the high energy regime might be questioned (in particular due to the so-called cosmological constant problem). In section 4, I put forward an argument which suggests that the eventual construction of a quantum theory of gravity is not likely to be a fundamental theory in the sense often advocated (i.e. a theory from which all other theories of, and phenomena in, physics could be derived). I point out that whatever formal relations can be established between quantum gravity and the supposedly less fundamental (classical) theories, the latter are in any case needed to specify the field of application of the former. This raises doubts concerning the sense in which quantum gravity could be *the* fundamental theory.

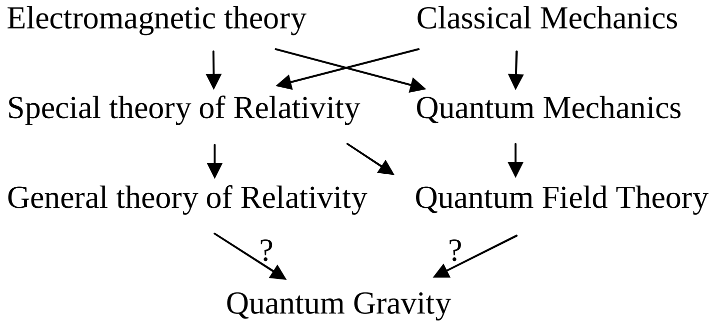
2. Reductionism and the Unity of Physics

The quest for unification is a major drive behind the search for quantum gravity. For instance, Kiefer (2004, p. 2) writes in the introduction to his recent book on quantum gravity concerning the main motivations for this theory:

> The first motivation is unification. The history of science shows that a reductionist viewpoint has been very fruitful in physics (Weinberg 1993). The standard model of particle physics is a quantum field theory that has united in a certain sense all non-gravitational interactions. [...] The universal coupling of gravity to all forms of energy would make it plausible that gravity has to be implemented in a quantum framework too.

As discussed below, it is not always the case that unification coincides with reductionism. In any case, it is true that the idea of unification between the different natural phenomena, and the theories that describe them, has been a guiding principle in physics at least since the days of Galileo. Indeed, the 'success' history of physics can, at least partly, be portrayed as the history of unification. Think for example of Newton's unification of heavenly and terrestrial phenomena by the universality of gravitation; or Ørsted, Faraday, and Maxwell's unification of electric and magnetic forces embedded in Maxwell's equations. A more modern example is provided by Glashow, Salam and Weinberg's electroweak theory of elementary particles which couples electromagnetic and weak forces (the latter being responsible for certain types of radioactivity). In order to see where quantum gravity fits into the unification picture, it is helpful to briefly review the relations between some of the central theories of physics.

Quantum field theory and general relativity stand as two of the greatest achievements in 20th century physics.[2] Both theories are already unified in the sense that they combine various former theories in a common framework. Thus, the special theory of relativity is a combination of electromagnetism and the non-gravitational part of classical mechanics; and general relativity is a generalization of the special theory in which gravitation is also included. In a similar manner, quantum field theory is a combination of special relativity and quantum mechanics. The situation can be schematically represented as follows (note that only the physical theories relevant for this paper are included):



The arrows in this scheme represent the direction towards deeper or more general layers in our description of nature (see below). The question marks represent that a theory of quantum gravity and – more generally – the connection between the quantum (right-hand) side and general relativity, is still a speculation only.

In various ways the scheme is an expression of reductionism. On the one hand, the arrows indicate the direction towards something smaller (right hand side). On the other hand, the arrows indicate the direction towards something more general (both left and right hand side). A theory of quantum gravity (in particular string theory which aims to unify all forces known in nature) combines these trends by describing something both smaller and more general than what is found on the higher levels.[3]

In accordance with these reductionist trends the higher levels are often seen as merely useful special cases of the deeper levels. Quantitatively, this thought is backed by the fact that at least some of the mathematical expressions of the deeper levels are identical with those of the higher levels in certain limiting cases.[4] When such

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[2] Quantum field theory is here and in the following understood as the common framework for the theory of light and electrons as fields (quantum electrodynamics), the theory of weak nuclear forces, and the theory of quarks and gluons. The combination of these theories – known as the standard model of particle physics – describes the inner structure of atoms via quantum fields.

[3] A referee points out that one ought to distinguish between theoretical and ontological reductionism since the former is much more difficult and limited than the latter. However, this distinction is not without problems in the quantum context. For instance, while modern physics asserts that matter is made up of atoms, any adequate description of these objects (and the precise sense in which they constitute matter) requires quantum theory. Moreover, recent studies (of decoherence) have revealed that atoms and molecules can behave as quantum objects in one context, and as classical objects in another (see e.g. Arndt *et al* 1999).

[4] As noted e.g. in Weinstein (2005, p. 5), none of the programs for quantum gravity has as yet succeeded in showing that the less fundamental theories (general relativity in the case of canonical quantum gravity or general relativity + the standard model of particle physics in the case of string theory) can be obtained in some limiting case.

mathematical identity can be established, reductionism contains the possibility of reconstructing the higher levels from the deeper ones. Indeed, an important motivation behind the most ambitious quantum gravity program, string theory, is precisely to reverse the arrows of the above scheme and derive all known physics from a few basic principles of this theory. This idea is in accordance with Einstein's declaration from 1918:

> The supreme task of the physicist is to arrive at those universal laws from which the cosmos can be built up by pure deduction.[5]

The Einsteinian ambition is thus not just a reduction to more fundamental theories – that is, either to dissect objects into smaller and smaller parts or show that theories on a higher level are special cases of those of a deeper level (or both in the case of string theory). Also, and more explicitly in the quote, the idea is *reconstructing* the universe from scratch. That is, if we have the universal laws described by a fundamental theory, and we have identified the fundamental constituents of matter, then we can derive – at least in principle – all phenomena in the universe (modulo the indeterminism stemming from quantum theory), as well as the theories describing these phenomena.[6] A contemporary expression of such an ambitious reductionism/reconstructivism can be found in Tegmark and Wheeler (2001). These authors include a much more general scheme than the one above, in which subjects such as chemistry, biology, psychology and sociology are all seen as derived from fundamental physics.

Unity without reductionism?

Various doubts can be raised against reductionism. Often the debate is focused on the notion of emergence – the question of whether new and irreducible phenomena exist at the higher levels of description (irreducible in the sense that the emergent phenomena cannot be explained by the deeper level).[7] For the subsequent discussion on how much can be expected from a theory of quantum gravity, however, it will be more useful to briefly review a different anti-reductionistic argument which can be associated with Bohr's insistence on the necessity of classical physics in the description of quantum phenomena. If correct, this argument demonstrates not only that phenomena of (some of) the higher levels cannot be reduced to (or reconstructed from) the deeper ones, but also that the phenomena of the deeper levels cannot be defined, and are therefore dependent on, (some of) the higher levels.

Bohr contended that we cannot account for (or understand) the quantum phenomena – for instance the motion of an atom, or the interference pattern in the famous double-slit experiment – unless reference is made to a specific experimental

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[5] The quote is from a conference entitled 'Principles of research' delivered in Berlin in connection with the 60th birthday of Max Planck.

[6] It should be noted that Einstein was unsatisfied with quantum theory as a final theory and would therefore, presumably, not have agreed with quantum gravity being a candidate for such a unified theory. Indeed, Einstein did not engage in quantum gravity debates and instead worked, until his death in 1955, on a classical unified theory of physics (attempting to combine electromagnetism and gravity), see Stachel (1999).

[7] Note that some proponents of emergent phenomena still agree with reductionism but reject reconstructionism. For instance, Anderson (1972) holds that "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe". Precisely how the relation between different levels should then be understood, however, is unclear; see e.g. Cat (1998) for a critical discussion of Anderson's view and for a detailed discussion of the relationship between unity, emergence, and (different notions of) reductionism in modern physics.

context in which the measurement apparatus must be described by the concepts of classical physics, see e.g. Bohr (1958, p. 4). The idea of being described by classical physics concepts implies that the measurement apparatus – in contrast to quantum systems – has well-defined values of both position and momentum, and thus it is not subject to any quantum uncertainties or superpositions. According to Bohr a main reason for the necessity of this distinction between the quantum objects and the measuring instrument is that the interaction between the object and the apparatus is a defining feature of the quantum phenomena (Bohr 1958, p. 4).

Of course, Bohr's view is just one of a number of proposed alternative interpretations of quantum theory. Most of these alternatives follow the line of von Neumann and attempt (in a reductionist spirit) to treat the measurement apparatus itself as a quantum system. As is well known, however, such approaches run into the notorious measurement problem. Stated briefly, the problem is that *if* everything, including measurement apparatuses, is quantum (and thus correctly described by Schrödinger's equation), then we ought to see superpositions in the measurement outcomes, e.g. apparatus pointers being in various positions at the same time – and that clearly contradicts what we in fact do see. Responding to this problem involves invoking assumptions – such as many worlds, hidden variables, or modified dynamics – which go beyond the quantum formalism itself to somehow 'explain away' why no quantum strangeness is seen in the measurement results (for an overview of proposed responses to the measurement problem, and their problems, see e.g. Albert 1992).[8]

Bohr actually agreed that the measurement apparatus can also be described by quantum theory. However, he writes (1939, p. 104):

> ...in each case some ultimate measuring instruments, like the scales and clocks which determine the frame of space-time coordination – on which, in the last resort, even the definitions of momentum and energy quantities rest – must always be described entirely on classical lines, and consequently kept outside the system subject to quantum mechanical treatment.

The point is that we can treat a measuring apparatus (or part of this) as a quantum system, but only when some other system is then treated classically. This requirement guarantees, in consistency with what we observe, that measurements do indeed have definite outcomes.[9] Thus Bohr can effectively be taken to argue that *any* system, at least in principle, can be treated quantum mechanically, but that not all systems can be treated that way at the same time. This means that to those who hold that all objects *are* quantum in some ontological sense, Bohr might well have responded that although the existence of both measurement apparatuses and, say, atoms are beyond doubt – we cannot say exactly what these objects are like. All which can be inferred is that in some

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[8] Note that even if some of these 'quantum reductionist' approaches (in which all systems are treated as being quantum) are taken as adequate responses to the measurement problem, the general reductionist program in physics is not automatically vindicated. For instance, hidden variable theories like Bohm's and the spontaneous collapse models of Ghiradi, Rimini and Weber have been charged of being incompatible with special relativity (see e.g. Barrett 2000 and 2003).

[9] See Howard (1994) for an interesting suggestion of how Bohr's ideas on this point might be reconstructed and understood in terms of entanglement between the measurement apparatus and the quantum object under investigation. Howard hints (1994, p. 204) that Bohr's insistence on classical descriptions can be understood without assuming any "...fundamental ontological or epistemological distinction [between the classical and the quantum]". I do not agree with this claim but I cannot argue the point here.

circumstances objects can be described *as if* they were quantum and in other circumstances *as if* they were classical.[10]

These brief remarks cannot, of course, constitute a comprehensive analysis of Bohr's view – and much less a satisfactory defence of it. But they indicate one way to have unity without reductionism. For if quantum physics (and quantum phenomena) cannot be understood without classical physics (and classical phenomena, e.g. objects with well-defined values of both position and momentum), it is altogether unclear what it would mean to reduce the latter to the former.[11] And unity is not denied if this is taken to mean that entities and phenomena of two theories are interconnected but not reducible to each other. Indeed, Bohr emphasized both that, on the one hand, classical physics is necessary to define quantum phenomena, and, on the other hand, quantal laws are needed to explain the stability of classical objects (see e.g. Bohr 1958, p. 2).

This brief discussion illustrates that a motivation for quantum gravity based on an appeal to reductionism in physics can be resisted – even while the quest for unity is maintained. More importantly, as we shall see in section 4, there is a sense in which Bohr's insistence on the necessity of classical physics for understanding quantum physics might be vindicated in connection with specifying the field of application for a quantum theory of gravity.

3. Is a theory of quantum gravity necessary?

Considerations of whether or not reductionism has been a successful doctrine in physics would, of course, be largely irrelevant for motivating the project of quantum gravity if such a theory were in any case needed on experimental or logical grounds. With respect to the latter, Bryce DeWitt argued in the early 1960s that just as the electromagnetic field must be quantized to be consistent with quantum mechanics, the gravitational field should be quantized for the same consistency reason. DeWitt's argument (1962), which has since been repeated by other physicists, rests on two premises; 1) the existence of logical arguments for the quantization of the electromagnetic field; and 2) that the electromagnetic case is sufficiently analogous to the gravitational case. According to DeWitt and others, the first premise is supposed to follow from a famous analysis from 1933 in which Bohr and Rosenfeld discussed the measurability of the quantized electromagnetic field. In particular, the Bohr-Rosenfeld analysis is claimed to show that the uncertainty relations for a charged particle interacting with an electromagnetic field necessitates that the electromagnetic field is also quantized.

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[10] Of course, many scholars have been dissatisfied with Bohr's 'dissolution' of the measurement problem (by always having part of the system being described classically). Among the problems with Bohr's account are that there is no clear prescription of how the borderline between the classical and the quantum should be made (rather it is context dependent from case to case), see e.g. Bell (2004, p.171); and that is does not give an account of (but rather black-boxes) exactly what happens in a measurement situation, that is, how precisely the classical apparatus interacts with the quantum object, see e.g. Howard (1994, p. 211).

[11] Note that this is not in conflict with the formalistic fact that quantum expressions may correspond to classical expressions in certain limiting cases. One way in which classical mechanics may be said to be a limiting case of quantum mechanics is via the so-called Ehrenfest's theorem which is the quantum mechanical equivalent of Newton's second law. However, since this theorem involves mean (or expectation) values of quantum operators, and since such expectation values are bound up with the quantum mechanical measurement process, there is – in spite of formal identity of Ehrenfest's theorem and Newton's second law in certain limits – no question of deriving classical behaviour from the quantum formalism, see e.g. Joos et al (2003, p. 87). For examples of how, on a Bohrian understanding, quantum mechanics coincide with (but do not reduce) classical physics in certain limits, e.g. via the correspondence principle, see Falkenburg (1998).

Rosenfeld himself, however, saw matters differently. Although he had been the first to try to construct a theory of quantum gravity (in 1930), he later expressed hesitations towards the project – in particular because there was no experimental evidence for any quantum effects of gravity (this is still true, see below). With respect to DeWitt's argument, Rosenfeld (1963) pointed out that the Bohr-Rosenfeld analysis showed the consistency of the electromagnetic field quantization (i.e. that it is possible to treat the electromagnetic field with quantum principles), *not* its necessity. Furthermore, Rosenfeld argued that the analogy between the gravitational and the electromagnetic field (DeWitt's second premise) is problematic due to the appearance of a definite scale for space and time intervals in the quantum theory of gravity. Such length and time scales, referred to as Planck scales, result from the combination of Newton's gravitational constant G, Planck's constant $\hbar$, and the speed of light c – the Planck length is $\sqrt{G\hbar}/c^{1,5} \approx 10^{-33}$cm, and the Planck time is $\sqrt{G\hbar/c^{5}} \approx 10^{-43}$seconds. Rosenfeld notes that such small length and time scales may not be well-defined since considerations of an analogous case from quantum electrodynamics in which scales are involved (when the charge and current distributions are quantized) suggest an absolute limit to space-time localization given by the proton radius, 10^{-13}cm, which is 20 orders of magnitude larger than the Planck length scale (see also Rosenfeld 1966, p. 605). Finally, Rosenfeld stressed that the eventual construction of a quantum theory of gravity could not essentially change the fundamental role of classical theory for the understanding of quantum theory. Commenting on the early Bohr-Rosenfeld analysis, he wrote (Rosenfeld 1963, p. 443):

> The ultimate necessity of quantizing the electromagnetic field (or any other field) can only be founded on experience, and all that considerations of measurability of field components can do is to illustrate the consistency of the way in which the mathematical formalism of a theory embodying such quantization is linked with the classical concepts on which its use in analysing the phenomena rests.

Thus, Rosenfeld most likely agreed with Bohr's vision of the unity of physics implying that quantum gravity could not possibly be a final theory from which classical physics (and classical phenomena) can be derived.

Recent studies have shown that the situation concerning the necessity of quantizing the gravitational field has remained essentially unchanged since Rosenfeld's remarks. Thus, Callender and Huggett (2001) and Wüthrich (2004), reviewing and evaluating arguments concerning the necessity of quantization, both argue that there are no convincing reasons to affirm that gravity must be quantized. However, all of these authors agree that a theory of quantum gravity – understood in the broad sense as any theory which couples general relativity and quantum theory – is nevertheless desirable, and that there are situations in which such a theory is needed. We turn to their arguments below after a quick look at the empirical situation.

Quantum gravity vs. observations and experiments

No observations or experiments have so far observed any quantum effects of gravity. This is, however, not surprising since quantum effects of gravity are expected to show up primarily at the above mentioned Planck scales. The most likely *observational* signatures of quantum gravity are to be found in the very early (small time scale) universe, or the extreme conditions (high energy scale) associated with black holes (see below) – and none of these regions are easy to access observationally.[12] Another option for probing quantum gravity effects is to try to access the Planck scales via *experimental* studies of phenomena at very small length scales. Such experimental studies, however, seem remote. For instance, Baez (2001) notes:

> To study a situation where both general relativity and quantum field theory are important, we could try to compress a cell to a size 10^{-20} times that of a proton. We know no reason why this is impossible in principle, but we have no idea how to actually accomplish such a feat.

Nevertheless, as another motivation for quantum gravity it is sometimes mentioned (e.g. Callender and Huggett 2001, p. 5) that although no effects of *quantum* gravity has been seen, experiments have established that classical gravity is indeed related to (non-relativistic) quantum theory. One such experiment used a so-called neutron interferometer to demonstrate that the gravitational field affects the behaviour of quantum systems such as a beam of neutrons (see e.g. Greenberger and Overhauser 1980). The fact remains, however, that there is a big step from the relation between classical gravity and quantum mechanics to quantum effects of gravity itself. For instance, there are no experimental signatures of a relation between quantum *field* theory (like quantum electrodynamics) and gravity.[13] On the one hand, the absence of such experimental signatures is not surprising since quantum field theory deals almost exclusively with microscopic systems (in contrast to e.g. the neutron interferometer which allows for a test of quantum mechanics at the macroscopic level) and since the gravitational force is very small in the microphysical domain. On the other hand, this situation emphasizes how difficult it is to establish whether there are any quantum effects of gravity (as a quantized field) or even any observational effects of a coupling between general relativity (gravity as a classical field) and quantum field theory.

Alternative relationships between general relativity and quantum theory?

Given that quantization of the gravitational field is not required on consistency or empirical grounds, it is natural to ask how the relationship between general relativity and quantum theory could be conceived in case the gravitational field is not quantized. For instance, Butterfield and Isham have remarked (Butterfield and Isham 2001, p. 57):

> If it is indeed wrong to quantise the gravitational field […] it becomes an urgent question how matter – which presumably *is* subject to the laws of quantum theory – should be incorporated in the overall scheme.

As we shall see, the urgency of this question depends on how relevant (experimentally and observationally) such an 'overall scheme' is – and, of course, whether there is one!

In his 1963 paper Rosenfeld argued that since there is no experimental need for quantizing gravity, it is better to stick with the so-called semi-classical gravity, which combines a classical description of the gravitational field with a quantum treatment of

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[12] Other effects are being contemplated within the field known as quantum gravity phenomenology. For instance, it has been suggested that quantum gravity effects could be responsible for certain puzzling observations of cosmic rays. The situation, however, is still far from settled; see e.g. Amelino-Camelia (2003).

[13] The so-called Unruh-Davies effect and the Hawking radiation from black holes are theoretical phenomena which are predicted from a relation between quantum field theory and gravity, but so far they have not received empirical support.

all other force fields and matter. Technically, the left hand side of the classical Einstein equation, describing the curvature of space-time, is equated with the quantum expectation value of the so-called energy-momentum tensor which is a measure of the energy associated with (quantum) matter and radiation:

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

where $R_{\mu\nu}$ and R refer to the curvature of space-time, $g_{\mu\nu}$ is the metric, and $T_{\mu\nu}$ the energy-momentum tensor. However, this equation is problematic – not least because the quantum expectation value on the right hand side is calculated in a *fixed* space-time background, whereas the left hand side describes a *dynamical* space-time (this leads to difficult non-linearity and back-reaction problems; see e.g. Callender and Huggett (2001) and Rugh and Zinkernagel (2002)). Such problems are sometimes used to argue that the semi-classical approach, at least in its simplest form given by equation (1), is not likely to be the fundamental theory describing the interaction between general relativity and quantum field theory; see e.g. Kiefer (2004, p. 14 ff.).

But if there is no strict need to quantize gravity, and if semi-classical gravity is a problematic answer to the question of the relationship between general relativity and quantum theory, could one then not choose to forget about the whole business of quantum gravity? Callender and Huggett (2001, p. 4) comments on this possibility:

> Another philosophical position, which we might dub the ‘disunified physics’ view might in this context claim that general relativity describes certain aspects of the world, quantum mechanics other distinct aspects, and that would be that. According to this view, physics (and indeed, science) need not offer a single universal theory encompassing all physical phenomena. We shall not debate the correctness of this view here but we would like to point out that if physics aspires to provide a complete account of the world, as it traditionally has, then there must be a quantum theory of gravity [in the general sense of a connection between general relativity and quantum theory]. The simple reason is that general relativity and quantum mechanics cannot both be correct even in their domains of applicability.

As a first argument for this conclusion Callender and Huggett mention that the two theories “...cannot both be universal in scope, for the latter strictly predicts that all matter is quantum, and the former only describes the gravitational effects of classical matter...”. Now, for all the impressive empirical successes of quantum theory, it does not predict that all matter *is* quantum. This conclusion only follows by adopting an ontological interpretation of quantum theory according to which, indeed, everything ultimately is quantum. I have already mentioned that, on Bohr’s view, this move can be resisted insofar as objects are not either quantum or classical (even if, say, macroscopic systems are more prone to a classical description than are microscopic systems).

Whatever the plausibility of Bohr’s position, however, Callender and Huggett offer a further argument for their conclusion that general relativity and quantum theory must somehow interact (this is a common argument, contained also in the quote by Kiefer in section 2): The Einstein field equation couples the gravitational field, and thus the space-time structure, to all matter and energy. And,

> [q]uantum fields carry energy and mass; therefore, if general relativity is true, quantum fields distort the curvature of spacetime and the curvature of spacetime affects the motion of the quantum fields. If these theories are to yield a complete account of physical phenomena, there will be no way to avoid those situations – involving very high energies – in which there are non-negligible interactions between the quantum and gravitational fields...

As I will discuss further below, the situations where such interactions become relevant are mostly associated with the very early universe or with speculative features of black holes. Now, it could be objected that these situations are not relevant (at least yet), since there are still no experimental or observational evidence which make them so. This could for instance be argued within the framework of Cartwright's 'Dappled World' – which might well be the implicit target for Callender and Huggett's reluctance towards 'disunified physics'. Cartwright argues (1999, p. 24 ff.) that we have no reasons to believe our theories outside the domain where the successes of these theories have been established or, at least, not outside the domain where an adequate model of the phenomena in question can be formulated – and in this sense physical theories should not be expected to give a complete account of physical phenomena. For instance, Cartwright holds that a 1000 dollar bill swept away by the wind cannot be taken to follow Newton's second law since no good-fitting molecular (or otherwise) model of the wind is available. In the absence of such a model, on Cartwright's view, the belief that the wind operates on the bank note via forces is "...another expression of fundamentalist faith" (1999, p. 28). However, as Hoefer (2003, p. 1408) reasonably complains, Cartwright's rejection to make inductive inferences from our successful theories to not easily modelled cases comes dangerously close to reject making any inductions at all!

Nevertheless, without committing myself to Cartwright's general thesis, I do think a bit of scepticism about the scope of our inductions is in order in the present case. For there are reasons to suspect that our intuitions about the relationship between general relativity and quantum (field) theory are insufficient to allow extrapolations (inductions) into the very high energy regime. I am here thinking in particular of the so-called cosmological constant problem which *might* threaten the very idea of a formal connection (like equation 1, or any other type of coupling) between quantum field theory and general relativity. In essence the problem is that whereas quantum field theory predicts an astronomically high value for $\langle T_{\mu\nu} \rangle$ – implying an extreme curvature of space-time – it is observationally known that space-time is flat or almost flat.[14] The cosmological constant problem, which is so far unsolved, is conceived to be a 'veritable crisis' for fundamental physics, see Weinberg (1989). As discussed in Rugh and Zinkernagel (2002), the problem rests fundamentally on two assumptions – both of which can be questioned: (i) The quantum field theoretic vacuum energy is physically real (as in the standard interpretation of quantum field theory); and (ii) the validity of some semi-classical approach in which quantum (vacuum) energy acts as a source in Einstein's field equation. This last assumption implies a formal coupling between general relativity and quantum field theory, and the cosmological constant problem

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[14] More precisely, when the expectation value of $T_{\mu\nu}$ is evaluated in the vacuum state, it takes the same form as the cosmological constant in general relativity (this constant has, for simplicity, not been included in equation 1).

could therefore be argued to constitute a threat to the idea of a connection between these two theories.[15]

Thus, the apparently straightforward assumption made by Callender and Huggett that general relativity couples to all forms of (quantum) energy might be questioned. In any case, the cosmological constant problem suggests that our understanding of the connection between general relativity and quantum field theory is (still) too premature to trust extrapolations into the high energy regime. I emphasize that this does not constitute an argument to the effect that general relativity and quantum field theory are *not* connected. It is rather that, given the present unclear situation surrounding the cosmological constant problem, all cards should be left on the table.

So much by way of sketching how some of the motivations behind the search for a quantum theory of gravity – either as a theory of quantized gravity or in the broad sense of a theory which couples general relativity and quantum theory – could perhaps be resisted. In the following section, I will disregard possible scepticism as concerns the motivations for quantum gravity, and instead ask how much would be accomplished if such a theory is eventually constructed.

4. Could quantum gravity be *the* fundamental theory?

Although a quantum theory of gravity in which gravity is quantized has still not been found, the eventual construction of such a theory is often associated with at least two conjectures:

1. Quantum gravity will imply that our usual classical notions of space and time are only approximate valid concepts (valid at our length and time scales), which somehow emerge from the 'real' quantum nature of space and time; see e.g. Butterfield and Isham (1999).

2. More generally, quantum gravity will provide the ultimate explanation of classical physics from a deeper quantum physics level (for instance from string theory); see e.g. Weinberg (1993) and Tegmark and Wheeler (2001).

I have already indicated that the second of these (reductionist) conjectures is in conflict with Bohr's thesis that classical physics is necessary to account for the quantum phenomena, and, as I shall briefly hint below, the first conjecture is also problematic from a Bohrian perspective. Not surprisingly, therefore, many physicists working on quantum gravity (and quantum cosmology) often appeal to some version of the Everettian many-worlds interpretation of quantum mechanics; see e.g. Butterfield and Isham (1999, p. 144). Disregarding the other alternative interpretations of quantum mechanics, it may therefore seem as if one is faced with a choice between Bohr's 'one world-two theories', or Everett's 'one theory-many worlds'. While I cannot, of course, attempt to seriously adjudicate between these interpretations here, I will suggest that Bohr's idea of the necessity of classical physics cannot be as easily dismissed in

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[15] It should be mentioned that the cosmological constant problem has also been read as an argument for the necessity of quantum gravity – and solutions to the problem have been proposed within this framework (and the related idea of quantum cosmology), see also Zinkernagel (2002). Apart from the fact that no general framework for quantum gravity exists as yet, however, these solutions seem to be problematic, see Weinberg (1989, p. 20ff.) for discussion and references.

discussions of quantum gravity as is sometimes suggested.[16] This suggestion can be developed by asking how the theory of quantum gravity is supposed to work without classical physics.

As we have seen above, it is usually assumed that the effects of quantum gravity should become relevant at very small (Planck) time- and length-scales, respectively $\sim 10^{-43}$ sec and $\sim 10^{-33}$ cm. There are two types of situations, both involving very high energies, where these effects should manifest themselves. The first is the very early universe where the extreme conditions near the Big Bang are expected to make Planck scale physics necessary (the high energies near the Big Bang results because the time parameter in this cosmological model is inversely proportional to the square of the temperature – and hence to energy). The second situation is connected to black holes. These exotic objects, which are supposedly common in the universe, are expected to gradually lose energy (Hawking radiation). Due to curious effects of so-called black hole thermodynamics, the final stages of a black hole is supposed to be characterized by energy loss in the form of radiation in which each photon has an energy close to the Planck energy. Consequently, it is expected that this final stage can only be understood by a full quantum theory of gravity (in which gravity is quantized); see e.g. Smolin (2001, p. 92). Moreover, quantum gravity is also expected to describe the black hole singularity at – or very near – the center of a black hole.

It is sometimes said that since general relativity predicts space-time singularities (the Big Bang and the center of black holes), this theory predicts its own demise as it is unable to describe the vicinity of these singularities (due to quantum gravity effects). As discussed below, however, theoretical (and observational) access to either the very early universe or black holes relies firmly on classical theory – namely classical general relativity. This seems to imply that one must *presuppose* classical theories in order to *define* the field of application for quantum gravity. If this is correct then it at least limits the sense in which general relativity can be reduced to quantum gravity. On the other hand, the formalism of general relativity is expected to be derivable from an eventual theory of quantum gravity in some limiting case. This situation is somewhat analogous to Bohr's view on the role of classical mechanics in quantum mechanics. For instance, Landau and Lifshitz – quoting Bohr approvingly – wrote in the introduction to their book on quantum mechanics (1981, p. 3):

> Thus quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case, yet at the same time it requires this limiting case for its own formulation.

A way to understand this claim is, as we have seen, that formal identities between quantum and classical expressions notwithstanding, the measurement problem implies that quantum theory by itself cannot account for any classical phenomena – such as definite measurement outcomes with well-defined space-time and energy-momentum properties. I should note that the above mentioned necessity of general relativity for quantum gravity is only somewhat analogous to the necessity of classical mechanics for quantum mechanics – for the role of the classical theory in the former case is not to account for observed phenomena but rather to specify the field of application of the quantum theory. Nevertheless, in the case of quantum gravity, it is much less obvious that one can circumvent the need for a classical theory by opting for a different interpretation of quantum mechanics.

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[16] An example of a dismissive evaluation of Bohr's position in connection with quantum gravity can be found in Butterfield and Isham (1999, p. 143).

The problems of time

In order to spell out more clearly the way in which classical physics is presupposed in defining the field of application of quantum gravity, I shall briefly consider the role of the concept of time in the very early universe. Although quantum gravity is supposed to fundamentally change our usual notion of time, it is notoriously difficult to see how the notion of time employed in the less fundamental theories could somehow emerge from quantum gravity. For instance, the central equation in canonical quantum gravity, the Wheeler-DeWitt equation, does not depend on time at all, and this obviously makes it hard to see how the equation can be relevant for theoretical descriptions of the very early (but evolving) universe. This much discussed 'problem of time' in quantum gravity is a consequence of the very different role that time plays in quantum theory (where it is a fixed background parameter) and general relativity (where time is dynamical and depends on the matter-energy distribution).[17] But apart from the problem of how time could emerge from timeless quantum gravity (which is closely related to the 'problem of time', see e.g. Butterfield and Isham 1999), it is also hard to make sense of the "reverse" transition from time in the early universe to timeless quantum gravity.

This problem, which could be called the reverse problem of time, arises as follows: As mentioned above, it is conjectured that quantum gravity (and quantum cosmology) will be particularly relevant for discussing the conditions in the very early universe where quantum effects of gravity are expected to be important. But any discussion of the 'early' universe obviously requires that we have a cosmic time concept which indicates that we are close (temporally) to the Big Bang singularity. Indeed, a cosmic time concept is one of the fundamental ingredients in the Big Bang model of the universe.[18] The cosmic time parameter is the proper time of a standard clock (for instance, an imagined perfect wrist watch) at rest in the so-called co-moving frame, and it is this time concept physicists and cosmologists have in mind when discussing conditions in the *early* universe. Indeed, the Planck scale is reached in cosmology by extrapolating backwards the Big Bang model in this cosmic time. Thus, the assumption that quantum gravity (or quantum cosmology) is relevant for the study of the very early universe rests on a solid classical (i.e. not described by a quantum operator) notion of time. But if it is conjectured that timeless quantum gravity is *the* fundamental theory – from which classical physics and concepts can be derived – it appears paradoxical that its central field of application (the early universe) is only defined by a concept (classical cosmic time) which is completely alien to the theory.

The above argument may be seen as a particular instance of Bohr's (and Rosenfeld's) point that classical physics and classical concepts are necessary in order to define and analyze the quantum phenomena. Thus, whether or not one agrees with Bohr that we need classical physics to relate the quantum formalism with measurements, the very definition of the central field of application for quantum gravity rests on classical concepts.[19] As already hinted, it is difficult to circumvent this argument by referring to

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[17] Kiefer (2004, p. 4) mentions the problem of time as the third main motivation behind the search of a quantum theory of gravity. However, this motivation only makes sense when it is already assumed that general relativity and quantum theory must be brought together in a unified framework (Kiefer's first motivation) or, at least, that there are situations where both of these theories are relevant (Kiefer's second motivation).

[18] In general, there is no global time parameter in classical general relativity, but such a parameter is part of the particular Big Bang solution to Einstein's field equations which is assumed to be a reasonable approximate description of our universe.

[19] A similar point may be argued for the case of quantum gravity effects related to black holes. I leave it out here however, since such effects in a sense are even more remote than those related to the very early

other interpretations of quantum theory, as also such other interpretations will have to rely on a classical notion of time in order to discuss the early universe. In turn, if we cannot even discuss the central application of quantum gravity without assuming a classical time concept, it is not clear what we should understand by an assumption like 'the ultimate nature of space-time is non-classical' and, more generally, what we should understand by the assumption that 'classical physics can ultimately be explained from the deeper level of quantum gravity'.

It should finally be noted that not all researchers in quantum gravity subscribe to the reductionist conjectures associated with the theory (related to an 'all is quantum' interpretation of quantum mechanics). Thus, Rovelli mentions in the conclusion of his recent book on quantum gravity (2004, p. 370):

> I see no reason why a quantum theory of gravity should not be sought within a standard interpretation of quantum mechanics (whatever one prefers). [...] We can consistently use the Copenhagen interpretation to describe the interaction between a macroscopic classical apparatus and a quantum gravitational phenomenon happening, say, in a small region of (macroscopic) spacetime. The fact that the notion of spacetime breaks down at short scale within this region does not prevent us from having the region interacting with an external Copenhagen observer.

Now, on Bohr's version of the Copenhagen interpretation, the important point is not the observer but rather that the measurement apparatus is to be described on classical lines. In any case, and in the light of the above discussion, I think the quote expresses a highly recommendable attitude – namely that the search for quantum gravity should not *a priori* exclude specific interpretations of quantum mechanics. In fact, Rovelli's idea that space-time breaks down *within* a small macroscopic space-time region might support the idea that classical space-time concepts (e.g. the macroscopic region surrounding the 'breakdown region') are needed to formulate the 'domain of application' of quantum gravity – and can in this way hardly be seen to be derivable from this theory.[20]

I do not claim, however, that Rovelli would endorse this conclusion. For one thing, the close connection between quantum gravity and quantum cosmology (in which even the universe as a whole is described in quantum terms), and in particular the fact that quantum gravity (also on Rovelli's view) is held to be relevant for the very early universe, would seem to make it difficult to accommodate either classical apparatus or classical concepts (such as a macroscopic region of space-time) at the very early stages of the universe. In any case, I think Rovelli would have to accept that these early stages

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universe: There is good empirical evidence of a universal expansion and thus of a smaller and denser state of the universe in the past. To reach the very early universe we therefore 'only' need to extrapolate backwards an empirical successful model (see however hesitations to this extrapolations in Rugh and Zinkernagel 2006). By contrast, since Hawking radiation from black holes has not yet been observed, and since nothing is known about the interior of black holes, it would seem that more than extrapolations of successful models are involved in contemplating quantum gravity effects in connection with black holes.

[20] Perhaps this could be taken to mean that on a Bohrian understanding of quantum theory, the quantization of the gravitational field, and therefore of space-time, can be done only 'locally' (within a classically described space-time volume). This would be in accordance with the quote by Bohr in section 2 according to which an ultimate measurement apparatus which determine a spatio-temporal framework for the quantum phenomena must be described by classical physics concepts (in particular, this would fit with a relationist account of space-time which links classical space-time to classically described rods and clocks, see e.g. Teller (1999) and Rugh and Zinkernagel (2006b)).

can only be addressed (and observationally accessed) via the classical time concept of standard cosmology.

Summary and Conclusions

A quantum theory of gravity is presently considered the holy grail of theoretical physics. In this manuscript I have tried to argue that the motivations behind the quest for this theory may be resisted, and that – in any case – there are good reasons to doubt that it can be the ‘theory of everything’. More specifically:

By reviewing Bohr’s conception of quantum mechanics, I have first illustrated one way to question reductionism in physics. Since reductionism serves as a motivation for quantum gravity, this shows a sense in which quantum gravity depends on interpretative issues in quantum theory. Secondly, I pointed out that there is no compelling argument to the effect that quantum gravity is necessary – neither logically nor (at least, as yet) empirically. Furthermore, as discussed in section 3, even the more modest ‘unified physics’ expectation that general relativity and quantum theory must somehow come together at high energy could be resisted. Both because of the lack of empirical evidence of any interplay between general relativity and quantum theory and – in particular – due to our limited understanding of the form of such interplay (even at low energy) evidenced by the cosmological constant problem. Finally, I have argued that even if a theory of quantum gravity – in a form in which gravity is quantized – could be constructed, there are good reasons to believe that this would not remove the in principle necessity of classical physics, at least for specifying the field of application of quantum gravity. Obviously, it is hard to make predictions concerning what a quantum theory of gravity will eventually look like. But at least there are reasons to believe that quantum gravity will not supersede present physics in the sense that all other physical theories and phenomena can (even in principle) be derived from, for instance, some future form of string theory.

None of this, of course, should be taken to imply a recommendation that the quest for a quantum theory of gravity ought not to be pursued. All I suggest is that the motivations behind this quest can be resisted, and that a bit of scepticism concerning what could actually be achieved with such a theory seems appropriate.

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