Quantum Gravity: A Dogma of Unification?

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1 Introduction

To 'combine general relativity and quantum mechanics'—as the issue of quantum gravity (QG) is frequently summarized—is typically understood to be the central challenge for fundamental physics. The common conviction is that this quest for QG is not only fuelled, but generated by external principles (*cf.* Mattingly (2005) and Wüthrich (2006, 2012)). Accordingly, the research program of QG is believed to be driven, first and foremost, by reasoning involving philosophical assumptions. It is suspected that specifically approaches in the context of particle physics are essentially based on, for example, metaphysical premises rather than experimental data or physical arguments. I disagree. In fact, it is exactly Weinberg's and others' particle physics stance that reveals the issue of QG as a genuine physical problem arising *within* the framework of quantum field theory (QFT).

In this paper, I argue that the quest for QG sets an important and often misconceived example of physics' *internal* unificatory practice. Physics' internal strategies, e.g. exploiting the explanatory capacities of an established theory, suffice to explain the search for a theory of quantum gravity. To set the stage, I will first recap what the research program of QG is about and what remarks suspecting a 'dogma of unification' amount to. To support my claim, I will then investigate the spin-2 approach to the matter focussing on Weinberg's quantum field theoretic reconstruction of Einsteins principle of equivalence. Subsequently, two important consequences for our understanding of general relativity (GR) and the issue of QG are briefly discussed: First, it is suggested that we should not take GR as a fundamental theory because it can be reduced

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to QFT. Second, the investigation serves as a clarification of what the problem with QG actually is. Afterwards, some objections against the advocated picture are mentioned and very briefly replied to. Finally, I will revisit the opening question concerning the alleged 'dogma of unification'.

2 Some Remarks on Quantum Gravity

Fundamental physics is based on two theories, the standard model of particle physics (SM)[2] and the general theory of relativity (GR). While the first describes the electromagnetic, the weak and the strong interaction of subatomic matter particles as well as the Higgs mechanism in a quantum field theoretic framework, the latter addresses the fourth fundamental interaction, *i.e.* gravity, in terms of a classical field theory. To reconcile these basic pillars within one framework uncovering their common ground or, more specifically, finding a quantum theory of gravitation or an even richer all-encompassing theory comprising it (e.g. string theory), is frequently understood to be the central challenge for contemporary physics.

Such reconciliations do not necessarily result in a particularly substantial type of unification. One might simply be concerned with issues of consistency or some law-like connection. For instance, as a first attempt, one could merely try to merge or couple classical GR and QFT without further modifications to form so-called semi-classical theories (e.g. Carlip (2008)). While such theories acknowledge that according to quantum theory the matter fields are fundamentally quantum theoretic structures, they insist that gravitation, *i.e.* spacetime, is fundamentally classical ('non-quantum'). Accordingly, a simple semi-classical theory rewrites Einstein's equations as:

$$G_{ab} = 8\pi\langle T_{ab}\rangle \ . \tag{2.1}$$

Here, the matter fields are introduced by the expectation value of the stress energy tensor, $\langle T_{ab}\rangle$. However, despite some convenient properties according to the Ehrenfest theorem that links the quantum mechanical expectation value to Newton's classical equations of motion, the expectation value is not a fully classical object. Therefore, it gives rise to problematic discontinuities as many have pointed out (e.g. (Eppley and Hannah , 1977); see also Wald (1984) and Kiefer (2007)). As a result, most physicists typically do not seriously consider semi-classical theories. It should be noted though that some have criticized these objections against semi-classical theories as not compelling (*cf.* Huggett and Callender (2001a,b), Mattingly (2005, 2006), Wüthrich (2005)). So, technically semi-classical theories may not be ruled out yet.

[2] I do not distinguish between 'theory' and 'model (of a theory)' here. More accurately, one would refer to the SM as a 'model (of QFT)'.

Still, what is typically understood by 'quantum gravity' is a more substantial reconciliation in terms of some sort of *quantization* of gravity (e.g. Huggett and Callender (2001a,b), and Wüthrich (2005)). To 'quantize' a classical theory means to construct a quantum theory whose classical limit agrees with the classical theory. Note that quantization does not necessarily imply discreteness. For instance, in the case of quantum mechanics (QM) some observables did become discrete after quantization, but others like position and momentum operators did not. Accordingly, to quantize GR does not imply discreteness of spacetime. Making spacetime discrete is merely one possibility—and it is a possibility that comes with a cost as it actually compromises an important symmetry of physics: Lorentz-invariance.

Now, there are many different approaches to QG of this more substantial kind. According to Kiefer (2007) they may be grouped into primary and secondary theories of quantum gravity. The former employ standard procedures of quantization (canonical or covariant quantization) as it has been done in the case of quantum electrodynamics, for example. The latter comprise QG as a limit of some fundamental quantum theoretic framework, e.g. string theory. Note that this classification is based on how the approaches *proceed*. Systematically the respective approaches may nonetheless be related. For instance, Weinberg (1999) emphasizes a relation between quantum field theoretic, *i.e.* covariant, approaches and string theory.

But why should we seek a quantum theory of gravity at all? Usually, theoretical considerations are understood to indicate an incompleteness of present-day physics related to the issue of QG (e.g. Kiefer (2006)). Frequently listed key reasons for 'quantizing gravitation' include, amongst others, cosmological considerations, black hole evolution, theoretical problems in QFT, and aiming at unification (*cf.* Kiefer (2006), Huggett and Callender (2001b), Wüthrich (2005)). Many suspect that unification ideals are particularly crucial (e.g. Mattingly (2005)), especially with respect to approaches in the context of particle physics.

This is mainly based on the following: First of all, it seems that there is no empirical need whatsoever to construct the theory. In fact, both theories (SM and GR) are in perfect agreement with all available, and—concerning quantum gravitational effects—presumably even all expectable data. The typical energy (or length) scale where quantum gravitational effects are understood to become relevant is roughly 16 orders of magnitude higher (smaller) than presently available (e.g. Arkani-Hamed (2012)). So, one might argue that, pragmatically, we cannot really hope for direct experimental data—it is by no means excluded though and we particularly might hope for indirect indications.[3] Still, up to now, experiment does not suggest any need for modifications.

[3]Furthermore, actually suggestions are put forward for how theory assessment without experimental data could work (Dawid, 2013)—a very interesting, but also highly controversial project (*cf.* Rovelli (2016)).

Second, skeptics add that also invoked theoretical arguments are in fact—or in principle—not compelling (e.g. Mattingly (2005)). Finally, and probably most importantly, many share the conviction that GR and QFT are *fundamentally incompatible* for quite a simple reason: "according to GTR [general relativity], gravity simply is not a force" like the electromagnetic, the weak, and the strong interaction (Maudlin, 1996). This is not to say that GR and quantum theory are incompatible in a logical sense, but to argue that they are "incommensurable (families of) theories" (Wüthrich, 2005, 778).

In summary, there seems to be neither empirical ground, nor any genuine physical reason to pursue the quest for QG. That is why some suspect that internal strategies of physics alone (e.g. inductive generalization, expanding the realm of an established theory or exploiting the explanatory capacities of an established theory) cannot account for such programs. Instead, physicists are said to employ *external* arguments, for example a 'dogma of unification' (Mattingly (2005); see also Maudlin (1996) and Wüthrich (2005, 2012)). In this perspective, physicists would employ metaphysical principles (e.g. 'unity of nature'), metatheoretical principles (e.g. 'economy of thought') or epistemological principles (e.g. physicists pursue unification for its own sake—*i.e.* the mere fact of the theory dualism itself is considered a defect of theoretical physics), that is *philosophical* reasons (Mattingly, 2005; Wüthrich, 2006, 2012). Against this I insist that a quantum theoretic account of gravity is already part of the well-known framework of QFT and that it prompts the quest for QG.

Let me rephrase it as follows: Positions arguing that physics generally aims at unification (or a minimal theoretical system or representing an assumed 'unity of nature') can neatly explain attempts at QG. But what about positions arguing that physics aims at empirical adequacy, for example? Are such positions able to explain the quest for QG? Do physicists employ philosophical reasons, or can we understand the search for a theory of QG internally? To answer this, let us first be clear where the objections against QG typically arise: in the geometrization picture of gravity as the canonical interpretation of GR.

3 The Canonical Picture of General Relativity

In the canonical formulation of GR already basic notions like 'metric' and 'curvature' seem to strongly suggest a reductionist view on gravitation. In fact, the interpretation of GR as a reduction of gravitation to spacetime curvature is often attributed to Einstein himself (Weinberg, 1972, vii, 147)—a common misreading as Lehmkuhl (2014) insists. As a matter of fact, GR is usually presented as a geometrization of gravity in textbooks:

> General relativity (GR) is Einstein's theory of space, time,

> and gravitation. At heart it is a very simple subject (compared, for example, to anything involving quantum mechanics). The essential idea is perfectly straightforward: while most forces of nature are represented by fields defined on spacetime (such as the electromagnetic field, or the short-range fields characteristic of subnuclear forces), gravity is inherent in spacetime itself. In particular, what we experience as "gravity" is a manifestation of the curvature of spacetime. Our task, then, is clear. We need to understand spacetime, we need to understand curvature, and we need to understand how curvature becomes gravity. (Carroll, 2004, 1)

In this interpretation, gravity reveals as a geometrized pseudo force: Gravitation is reduced to spacetime geometry and becomes a mere effect of the curvature of spacetime. As we have seen, for example Maudlin (1996) advocates this view. Undoubtedly, the textbook interpretation is very appealing. First, it remains close to the mathematical formalism that successfully unifies two apparently very different concepts: gravitation and spacetime geometry. Second, the textbook version yields quite transparent ontological commitments, most importantly that spacetime is a Riemannian manifold, M, with a metric, g, [4] and that gravitation is not an interaction (or 'force'), but simply curvature of spacetime. Altogether, this is a perfectly fine interpretation of GR.

But why adopt this interpretation? What underpins the geometrization picture except the fact that the canonical formalism of GR contains the mathematical objects mentioned above? To answer this, one needs to look at what GR is based on conceptually: At the core of GR, and at the core of the geometrization picture as well, we find Einstein's principle of equivalence. Note that the equivalence principle comes in different varieties. Essentially, there is a weak and a strong version (e.g. Carroll (2004, 48–54)). The weak equivalence principle (WEP) states that the inertial mass, m_i, and the gravitational mass, m_g, of any object are equal in value. Remember the case of Newtonian mechanics: Here, the inertial mass is the constant of proportionality between some force and the acceleration of the object the force acts on. Since the value of the inertial mass of the object is the same for any force, the inertial mass is universal in character (Carroll, 2004, 48). On the other hand, the gravitational mass is a specific quantity only related to the gravitational force—it is the constant of proportionality between the gradient of the gravitational potential and the gravitational force (Carroll, 2004, 48). *Prima facie*, both masses are conceptually independent. Hence, m_g/m_i may differ for different objects and may therefore be thought of as a 'gravitational charge' (Carroll, 2004, 48). Accordingly, the behavior of different objects in a gravitational field would generally depend on the (different) gravitational charges, just as the behavior

[4] Note that in light of the hole argument, the focus has shifted to the metric alone.

of electromagnetically charged particles in an electromagnetic field depends on the particles' charges. However, since Galilei we *empirically* know that inertial and gravitational mass are always equal in value, $m_i = m_g$. Every object in a gravitational field falls at the same rate regardless of its properties including mass. Thus, in Newtonian mechanics inertial and gravitational mass are conceptually different (or different in type), but empirically equal in value. In this sense, gravitation is *universal* in Newtonian mechanics and obeys the WEP (Carroll, 2004, 48f)—without explanation. The geometrization picture of GR, on the other hand, is able to provide an explanation for the WEP by eliminating m_g from the theory altogether as we will see in a moment.

First, to better understand the geometrization rationale and to prepare for the formulation of the *strong* equivalence principle (SEP) let us rephrase the essence of the weak version in a famous thought experiment:

> Imagine [...] a physicist in a tightly sealed box, unable to observe the outside world, who is doing experiments involving the motion of test particles, for example to measure the local gravitational field. Of course she would obtain different answers if the box were sitting on the moon or on Jupiter than she would on Earth. But the answers would also be different if the box were accelerating at a constant velocity [...] (Carroll, 2004, 49)

According to the WEP, it is impossible to decide whether the observed effects on freely-falling test particles stem from a gravitational field or from being situated in a uniformly accelerated frame. This is a result of the universality of gravitation. As mentioned, for the electromagnetic field such an empirical distinction is possible: we would simply have to compare the behavior of particles with different charge. Since for gravity the particle's 'gravitational charge' is universal, this does not work (Carroll, 2004, 49). Note that because of possible inhomogeneities in the gravitational field this is only true for sufficiently small frames, technically speaking: it is only true *locally*. We can then formulate the WEP as follows:

> The motion of freely-falling particles are the same in a gravitational field and a uniformly accelerated frame, in small enough regions of spacetime. (Carroll, 2004, 49)

Since special relativity (SR) tells us that 'mass' is a manifestation of energy and momentum, the SEP generalizes the above statement:

> In small enough regions of spacetime, the laws of physics reduce to those of special relativity; it is impossible to detect the existence of a gravitational field by means of local experiments. (Carroll, 2004, 50)

This means that locally we can always 'transform away' a gravitational field and the laws reduce to the laws of SR.[5] In this sense, gravity becomes a 'pseudo force': There is no such thing as a gravitational potential in GR.

Now, this is not to say that gravity is fictitious. Quite the contrary, it means that gravity turns out to be *inescapable*: a 'gravitationally neutral object' with respect to which we could measure the acceleration due to gravity *does not exist* (Carroll, 2004, 50). Hence, every object in the universe carrying energy and momentum is subject to gravity. In fact, every object is subject to gravity *in the same way*. Gravity does not distinguish between different types of objects. All objects, regardless of their properties including mass, are attracted *universally* (Carroll, 2004, 48).

It is exactly gravity's universality that seems to strongly suggest a geometrization picture of gravity. For gravitation essentially *being* curvature of spacetime, *being* a feature of the Riemannian manifold (or the metric, respectively), *being* a geometrical background structure perfectly explains why the SEP should hold. If gravitation is curvature of spacetime, then it is obvious why we can always perform local transformations so that gravitation vanishes, why the laws of physics locally look like the laws of SR. It is then also obvious why this should affect every single object in the universe in the same way. The simple fact that gravitational effects are apparently independent of the objects' properties supports the claim that gravitation arises from spacetime itself and that the notion of gravitational mass needs to be eliminated.[6] As a result, the SEP does not only play an important role for GR, but also for the theory dualism in physics: A geometrization picture of gravity seems fairly disconnected from how we understand the other fundamental interactions (*cf.* Weinberg (1972, viii)). While gravitation *is* spacetime, the other fundamental interactions are fields *in* spacetime.

However, this perspective on GR is not exclusive. Lehmkuhl (2008) argues that interpretations within the canonical formalism are not committed to the geometrization thesis that gravitation is reduced to spacetime geometry. Clearly, GR associates gravitation with spacetime, but the type of association is not fixed (Lehmkuhl, 2008, 84). Besides the geometrical interpretation, one may as well put forward the *field interpretation* or the *egalitarian interpretation*. The former claims that—contrary to the geometrization picture—spacetime geometry is reduced to a gravitational field, *i.e.* the metric, which is taken as 'just another field'. Instead, in its strongest version, the latter argues for a conceptual identification of gravity and spacetime in GR (Lehmkuhl,

[5]Note that Carroll's definition of the SEP is not very precise. Read et al. (2017) carefully distinguish and discuss four versions of the SEP.

[6]While Newtonian physics was unable to provide an explanation for why the equivalence principle should hold, the geometrical picture of GR provides an explanation in terms of an elimination (of gravitational potential and gravitational mass). As we will see in a moment, it is also possible to give a reductive account.

2008, 84). Such alternative interpretations seem to reduce the conceptual differences between GR and the other field theories and may be further supported by gauge theoretic formulations of classical GR in the so-called tetrad or vielbein formalism (e.g. Carroll (2004, 483–494). Also, Brown famously argues for a *dynamical* perspective (*cf.* Brown (2005); Brown and Pooley (2001, 2006); Brown and Read (2016)) that may be viewed as a variant of the field interpretation.

But these responses do not close the (technical) gaps between both frameworks, GR and QFT. Vague formal similarities between theories cannot be considered a substantial and physical reason for unification. Just think of the case of Newton's law of gravitation and Coulomb's law of electricity: The fact that both laws exhibit the exact same mathematical form does by no means imply that the phenomena of gravitation and electricity are linked in any substantial sense. Accordingly, one might still suspect that for explaining unificatory approaches like QG we need to impose additional external principles guiding physics.

However, concerning an argumentation against the geometrization picture in favor of a unified perspective another approach appears to be much more relevant: Weinberg (1964a, 1965b, 1995) and others—for example Feynman (1995), and more recently Donoghue (1994, 2014)—advocated a "nongeometrical" (Weinberg, 1972, viii) understanding of GR based on QFT. But let us not get ahead of ourselves and slowly approach the matter by help of Weinberg himself.

4 Weinberg's Conception of General Relativity

Weinberg is very clear in expressing his opposition to the geometrical understanding of GR:

> In learning general relativity, and then in teaching it to classes at Berkeley and M.I.T., I became dissatisfied with what seemed to be the usual approach to the subject. I found that in most textbooks geometric ideas were given a starring role, so that a student who asked why the gravitational field is represented by a metric tensor, or why freely falling particles move on geodesics, or why the field equations are generally covariant would come away with an impression that this had something to do with the fact that space-time is a Riemannian manifold. (Weinberg, 1972, vii)

Furthermore, Weinberg considers the geometrization picture as historically contingent:

> It is certainly a historical fact that when Albert Einstein was working out general relativity, there was at hand a preexisting mathematical formalism, that of Riemannian geometry, that he could and did take over whole. However, this historical fact does not mean that the essence of general relativity necessarily consists in the application of Riemannian geometry to physical space and time. (Weinberg, 1972, 3)

Weinberg argues that the geometrization picture ultimately confuses 'representation' and 'represented'. He suggests to conceive Riemannian geometry merely as a mathematical tool to account for "the peculiar empirical properties of gravitation, properties summarized by Einstein's Principle of Equivalence of Gravitation and Inertia" (Weinberg, 1972, vii–viii, 3). The tool of Riemannian geometry should not be confused with the physical content of the principle of equivalence:

> In place of Riemannian geometry, I have based the discussion of general relativity on a principle derived from experiment: the Principle of the Equivalence of Gravitation and Inertia. [...] so that Riemannian geometry appears only as a mathematical tool for the exploitation of the Principle of Equivalence, and not as a fundamental basis for the theory of gravitation. (Weinberg, 1972, viii)

According to Weinberg, Riemannian geometry is *one* possibility to represent the physical essence of GR, *i.e.* the SEP. But there are others as well. Weinberg puts forward an attitude that may be summarized as: "Don't look at the formalism, look at the physics!" However, after withdrawing the natural incorporation of the SEP via the usual foundation of GR in spacetime geometry, Weinberg then needs to come up with a proposal why gravitation should obey the SEP:

> This approach naturally leads us to ask why gravitation should obey the Principle of Equivalence. (Weinberg, 1972, viii)

Interestingly, Weinberg does not expect to find an answer within the general framework of classical physics or within GR. Instead, Weinberg argues that one has to consider "the constraints imposed by the quantum theory of gravitation" (Weinberg, 1972, viii). In the course of the following section, we will see what this means and how this reasoning can be spelled out.

5 Deriving the Principle of Equivalence

As we have seen, in the canonical interpretation of GR the SEP proves to be essential for describing the phenomenon of gravitation and for interpreting it as curvature of spacetime. Hence, it is for the SEP that gravity appears to be completely separated from the rest of fundamental physics. Accordingly, especially attempts at QG in the framework of particle physics seem to rest purely on philosophical considerations pursuing unification based on external principles. However, in the following, we will find that the SEP can be recovered in a quantum field theoretic framework. As a result, the SEP turns out to be the *link* between our theory of gravitation and particle physics. The unificatory practice of physics proves to proceed *internally*, based on genuine strategies of physics alone.

Essentially, the reconstruction of the equivalence principle according to Weinberg (1964a,b, 1965a,b, 1995, 1999) is done in three steps: First, it is argued that starting from SR and QM as 'first principles' we arrive at QFT (e.g. Weinberg (1999) and Arkani-Hamed (2013)). Second, while particles may in general have any spin in QFT, it turns out that in the low-energy limit (or 'long-range limit')[7] QFT provides a restrictive framework that only allows for fundamental particles with very specific spins—in the long-range limit we can only have particles with spin 0, $1/2$, 1, $3/2$, or 2. Third, analyzing this menu it can be shown that Lorentz invariant interactions with massless spin-2 particles *require* the equivalence principle to hold. So it turns out that the equivalence principle is not a fundamental principle itself, but can be *derived* from SR and QM. Actually, one can even prove that GR can be fully reconstructed in this approach as the only possible theory of gravitation at low energies (e.g. Arkani-Hamed (2010b)).

Now, we will not be able to demonstrate and appreciate all steps of the argumentation here. Instead, I will focus on a (as far as possible) non-technical presentation of step three. To set the stage, I will very briefly review some basics. To get accustomed to Weinberg's rationale, we will then—as a warm-up—consider what constraint Lorentz-invariance imposes on interactions with spin-1 particles, *i.e.* photons, in the low-energy regime: low-energetic photons may only participate in interactions that conserve charge. Afterwards, we will discuss the spin-2 case and show how Weinberg is able to recover the WEP and implicitly also the SEP within QFT.

In principle, there are several ways to do so. Weinberg first formulated the argument in the context of S-matrix-theory (Weinberg, 1964a,b, 1965a,b). The following presentation rests on Weinberg's original work, on his textbook on QFT (Weinberg, 1995, 534–539), an illuminating lecture by Arkani-Hamed (Arkani-Hamed, 2010b), and lecture notes by Nicolis (Nicolis, 2011).

To motivate what follows, recall that QFT can be understood as a theory of particles.[8] In general, quantum particles have the following essential pro-

[7]Here, 'low energy' means low energy with respect to the so-called Planck energy. Even the highest presently available energy scales in physics can safely be considered 'low' in that sense.

[8]Of course, quantum *field* theory can be thought to be, first and foremost, a theory of

perties: mass, charge, and spin. Still, particles may have zero mass, carry no charge, or have spin-0. In QFT, particles divide into fermions or matter particles with half-integer spin, and bosons with integer spin. Furthermore, particles can interact with each other. The interactions of the Standard Model are represented by the exchange of certain mediator particles, so-called gauge bosons with spin-1. For example, the electromagnetic interaction between two electrons is understood as an exchange of a massless spin-1 particle, the photon. The fact that it does not carry electromagnetic charge itself tells us that there is no self-interaction, its zero mass accounts for electromagnetism being a long-range interaction, and its odd spin incorporates that like charges repel. Accordingly, a hypothetical mediator particle for gravity, usually referred to as the graviton, is required to be massless as well, but to have *even* spin to account for the fact that gravity is attractive.

For the interaction processes of such particles, we can calculate so-called transition amplitudes to determine the ‘cross section’ or probability of the process. To calculate such amplitudes, we need to specify certain parameters. That is, most importantly, the strength of the specific interaction, the so-called coupling strength, and the masses, charges and spins of the participating particles. If two particles do not ‘couple’, the respective interaction is not allowed to take place.

Now, Weinberg’s argument takes its departure from calculating such amplitudes of scattering processes in QFT. As Fig. 5.1a shows, in a scattering process a bunch of particles come in, interact in some way, and then a bunch of particles (the same particles or others) go out again. For any such process we can write down an amplitude, for example using the so-called Feynman rules which can be read off the corresponding Lagrangian. However, for our purpose it is not even necessary to write down the full scattering amplitude. We are not interested in the details of the scattering process or any specification of its interactions. Therefore, we represent the full scattering process, *i.e.* the sum of all possible Feynman diagrams for the process $\alpha \to \beta$, by the sphere in Fig. 5.1a. What we are actually interested in, is, without loss of generality, the analysis of a slight modification of such a generic scattering process (see Fig. 5.1b) to see if and how the corresponding interaction is constrained.

So, assume we know the amplitude, $\mathcal{M}_{\alpha\beta}(p_1, \ldots, p_\mathrm{n})$, for some arbitrary scattering process as in Fig. 5.1a. We would like to know the amplitude for the exact same process where additionally a soft massless particle with momentum q is emitted from one of the in- or outgoing particles (*cf.* Fig. 5.1b). Here, ‘soft’ means that the particle has very low energy—that is vanishing

fields. The corresponding particles are then derivative of the fields in the sense that they are *excitations* of the fields. Nevertheless, as the term *particle* physics stresses, we can also perceive it as a theory of particles. However, by talking about particles instead of fields I do not mean to have claimed anything substantial about the nature of QFT.

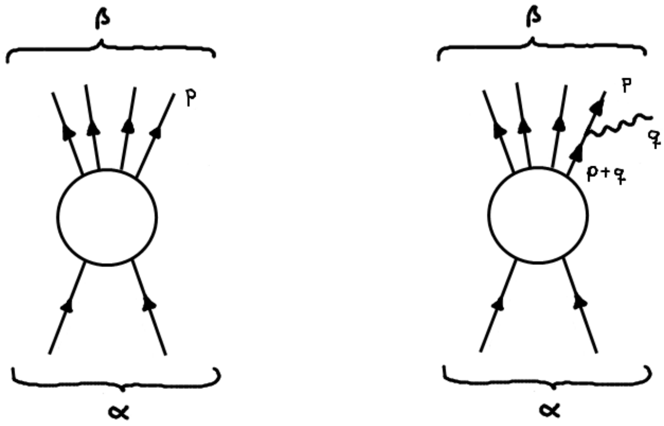

Figure 5.1: **a**. Arbitrary scattering process $\alpha \to \beta$ (modification of Weinberg (1995, 536)). **b**. Dominant diagram for additional emission of soft photons or gravitons from an outgoing particle in an arbitrary scattering process (Weinberg, 1995, 536).

momentum, $q \to 0$. For example, the additionally emitted particle could be a photon. Note that in general the emitted particle may have any spin. We will now analyze the emission process for the photon case and learn about properties and constraints in the long-range limit. Specifically, we will explore the consequences of Lorentz-invariance for massless particles of spin-1. To mathematically account for the additional emission process, we have to multiply the original amplitude by a non-trivial factor. Because we want to model long-range phenomena, we shall only consider the most leading possible contribution that will survive 'at infinity', that is in the long-range limit. Generally, this factor will depend on the polarization vector of the photon, $\epsilon_\mu(q)$, the momentum of the photon, q, all the momenta of the other particles, p_i, and their charges, e_i.[9] Accordingly, we obtain the following amplitude for the slightly modified process of Fig. 5.1b (Arkani-Hamed, 2010b):

$$\mathcal{M}_{\alpha\beta}(p_1, \ldots, p_{\mathrm{n}}, q)|_{q\to 0} = \mathcal{M}_{\alpha\beta}(p_1, \ldots, p_{\mathrm{n}}) \times \sum_i e_i \frac{p_i^\mu}{2p_i \cdot q}\, \epsilon_\mu(q) \ . \quad (5.1)$$

However, the emission factor in the amplitude is not completely arbitrary. The additional emission of a soft photon should not spoil Lorentz-invariance. Thus, we demand that Lorentz-invariance is preserved.[10] As a result, Eq. (5.1) is required to become zero for $\epsilon_\mu(q) \to q_\mu$. Since the original amplitude, $\mathcal{M}_{\alpha\beta}(p_1, \ldots, p_{\mathrm{n}})$, is assumed to be non-zero (the original process is not

[9]Here, the charge of a particle is defined as its coupling constant for emission of soft photons (Weinberg, 1965b, B989)

[10]That means that we demand the polarization vector to transform as $\epsilon_\mu(p) \to (\Lambda\epsilon)_\mu(p) + \alpha(\Lambda p)_\mu$.

forbidden), the emission factor itself has to vanish:

$$\sum_i e_i \frac{q^\mu p_{i,\mu}}{2p_i \cdot q} = 0 \,. \tag{5.2}$$

Accordingly, we arrive at the fact that the sum over all charges needs to be zero, $\sum_i e_i = 0$, which means that the process is forced to obey charge conservation. So, interactions with soft massless spin-1 particles always conserve the respective charges. One could go on and derive Maxwell's equations by using perturbation theory (Weinberg, 1965b), but we will stop here and turn to the next and more interesting case instead: a massless spin-2 particle, commonly referred to as the graviton.

As mentioned, such a spin-2 particle is among the quantum field theoretically allowed particles in the long-range limit. We can now essentially follow the same argumentation. Again, we want to investigate the long-range behavior, so we write down the leading contribution for our emission factor in the case of a soft graviton (Arkani-Hamed, 2010b):

$$\mathcal{M}_{\alpha\beta}(p_1, \ldots, p_\mathrm{n}, q)|_{q\to 0} = \mathcal{M}_{\alpha\beta}(p_1, \ldots, p_\mathrm{n}) \times \sum_i \kappa_i \frac{p_i^\mu p_i^\nu}{2p_i \cdot q}\, \epsilon_{\mu\nu}(q) \,. \tag{5.3}$$

Here, $\epsilon_{\mu\nu}(q)$ is the polarization tensor of the graviton, and κ_i are the coupling constants for the particles with momenta p_i emitting a soft graviton (Weinberg, 1965b, B989). Now, if we demand Lorentz-invariance (and again assume that the original process is allowed, *i.e.* $\mathcal{M}_{\alpha\beta}(p_1, \ldots, p_\mathrm{n}) \neq 0$), we arrive at:

$$\sum_i \kappa_i p_i^\nu = 0 \,. \tag{5.4}$$

So, what does this mean? According to Eq. (5.4) the sum over all momenta, p_i, weighted by the coupling constants, κ_i, is required to be conserved in all possible scattering processes. However, we know that already (unweighted) momentum conservation, $\sum_i p_i = 0$, should hold in all scattering processes. If both, momentum conservation and Eq. (5.4), are supposed to hold, there are only two options: Either the scattering between the particles of momentum p_i is trivial, that means the particles do *not* interact at all, or all coupling constants, κ_i, have to be *identical* for all particle species regardless of their properties, that is $\kappa_i = \kappa$.

So, by demanding Lorentz-invariance the coupling of a massless spin-2 particle to any other particle (including other spin-2 particles) is forced to be *universal*. This is precisely the quantum field theoretic version of the weak equivalence principle that gravitation is supposed to obey.[11] Hence,

[11]Here we used a slight simplification, but for example Nicolis (2011) carefully proves that the gravitational coupling constants, κ_i, are indeed forced to be universal.

the WEP is established within QFT. Note that for obtaining the *strong* equivalence principle the coupling is usually also required to be *minimal* (*cf.* Read et al. (2017)). This is fulfilled here because all terms violating the SEP essentially behave as high-energy corrections and are therefore absent in the low-energy limit. In this sense, the WEP effectively implies the SEP.[12]

To further appreciate this result, one can also prove that the massless spin-2 particle is *unique*. There can only be exactly *one* massless spin-2 field (Arkani-Hamed, 2010b). Also, we can show that for higher spins all respective coupling constants must vanish in the long-range limit, so there are *no* Lorentz invariant theories of massless particles with spins higher than spin-2 (Weinberg, 1965b, B989). In conclusion, we find that the massless spin-2 particle uniquely represents an attractive long-range interaction that universally couples to all forms of energy and momenta. Also self-interaction, another important property of gravitation, is automatically established (Weinberg, 1964a). The massless spin-2 particle is therefore correctly called 'graviton'.

Before I comment on what follows regarding unification, let me first briefly summarize what follows regarding the relation between GR and QFT.

6 What Do We Learn from This?

In the light of Weinberg's argument, the equivalence principle, usually perceived in close connection with the geometrization thesis, turns out to be the *link* between a theory of gravitation and particle physics. The low-energy limit of our empirically best tested and theoretically most advanced framework, namely QFT, proves to be highly constraining (Arkani-Hamed, 2010a,b, 2013). In the low-energy limit it is impossible to construct a Lorentz invariant quantum theory for massless spin-2 particles that does not obey the SEP:

> In other words, by asking for a theory of a spin-2 field coupling to the energy-momentum tensor, we end up with the fully nonlinear glory of general relativity. (Carroll, 2004, 299)

The equivalence principle is not merely postulated, but explained. In QFT the SEP is "not a principle, but a theorem" (Nicolis, 2011, 28). The fundamental principles of locality (SR) and unitarity (QM) that ground QFT enforce the SEP to hold, they enforce a theory of gravitation (Weinberg, 1999; Arkani-Hamed, 2013). Hence, a reductive account of GR is obtained: GR can be *deduced* from QFT. In terms of principles, GR can be deduced from bringing together SR and QM:

[12] Still, given that Read et al. (2017) argue that minimal coupling may violate certain versions of the SEP, there definitely remains more to be said. Ultimately, all claims involving the SEP here are in need of further clarification.

> All of these things that Einstein did—Einstein thought about these falling elevators and he discovered the Principle of Equivalence and all these deep facts about classical physics that led him to think about General Relativity—all of those things could have been discovered by much more mediocre theoretical physicists who knew about Quantum Mechanics. (Arkani-Hamed, 2013)

Typically, the conviction is that GR is more fundamental than SR. But according to the analysis above, it is in fact the other way around.

However, there is a well-known caveat that we have to mention. Weinberg's approach is only able to consistently account for a theory of gravitation at *low* energies. At high energies the theory is rendered non-predictive. That is the infamous problem of gravity's nonrenormalizability (Weinberg, 1972, 289). Due to this QFT is not able to provide a full-fledged theory of quantum gravity. But—and this should be appreciated—the spin-2 approach is an existing quantum theory of gravitation encompassing all presently known experimental data:

> A lot of portentous drivel has been written about the quantum theory of gravity, so I'd like to begin by making a fundamental observation about it that tends to be obfuscated. There is a perfectly well-defined quantum theory of gravity that agrees accurately with all available experimental data. (Wilczek, 2002)

So, we learn how to adequately understand and formulate the actual problem with QG. Usually, it is presented somehow like this: 'Combining GR and QM leads to a meaningless theory.', or 'We don't know how to combine QM as a theory of the very small and GR as a theory of the very big.', or as Wüthrich (2005, 782) states it: "In a sense, then, quantum mechanics and general relativity when combined already contain the seeds of their own destruction." In the light of Weinberg's argument, these statements prove false or at least misleading. First of all, the problem with QG is not that we have no grounds whatsoever to talk about such a theory—we actually already have one. Instead, the problem is that this theory is not valid at high energies. Accordingly, solving the problem amounts to finding the correct high energy theory (*cf.* Donoghue (2014)). Thus, the problem with finding a (full-fledged) theory of QG is more subtle than often described.

Moreover, as discussed above, the problem is not constituted by bringing together GR and QM, but by bringing together SR and QM, since QFT is solely based on these two theories and the assumption of the cluster decomposition principle (*cf.* Weinberg (1999)). As a consequence, we can infer that it is *SR* and QM that exhibit a very subtle conflict at high energies.[13]

[13] According to Maudlin (2011), there is another, very general conflict between SR and QM

7 Critical Remarks

There are some objections against this presentation. I will not be able to address them in detail, but they should at least be mentioned. Since I will only sketch responses, there certainly remains more to be said as the topics are fairly complex. First of all, one may be skeptical if the recovered result in Weinberg's argumentation really needs to be identified with Einstein's principle of equivalence because many general relativists would typically not state it in terms of 'universal coupling' (plus minimal coupling). This is an issue that needs to be addressed and investigated further—a task that I have to postpone.

However, it would seem dubious if we should not be allowed to translate a physical concept from one theoretical framework to another as a matter of principle. Such translations will in general involve non-trivial reinterpretations of the respective structures—business as usual in physics during theoretical progress. And, certainly, this may result in considerable deviations, but that does not necessarily undermine the new perspectives significance. In fact, I would rather suggest to read it as follows: By means of this practice, we learn something about how modern physics addresses the notion of fundamentality. In recovering and reinterpreting an established fundamental structure like the SEP within another framework, we obtain another perspective and learn more about the essential aspects of the structure. For example, the structure may reveal as nonfundamental. In this sense, physics continuously challenges alleged fundamentality of structures—again this needs to be investigated further.

Second, the issue of nonrenormalizability is certainly very important and constitutes the main objection against quantum field theoretic approaches. Still, as we have seen, this approach turns out to be quite illuminating. Also, the fact that such approaches are nonrenormalizable is not straightforwardly problematic in the light of effective theories (Donoghue, 1994). Still, one has to clarify whether being an effective field theory is a serious defect in general as some do suspect (Redhead, 1999). Keep in mind, however, that also classical GR is effective in that it does not contain higher powers of the curvature tensor.

Finally, another frequent complaint against quantum field theoretic approaches to QG concerns the issue of background independence (e.g. Huggett and Callender (2001b); Rickles and French (2006)). Especially general relativists (and many philosophers) assume that background independence constitutes the other key feature of GR besides Einstein's equivalence principle.

due to Bell's theorem. Note, however, that this is an entirely different issue closely connected to the debate on the interpretation of QM—a debate which physicists might be safe to ignore as long as the theory is empirically adequate. The high energy conflict mentioned here is not of that kind: While QFT is empirically adequate, consistent and highly predictive at low energies, it becomes non-predictive at high energies.

It is typically understood to render GR fully dynamical. On the contrary, approaches in the context of QFT simply employ the Minkowski metric. Thus, QFT is argued to be background dependent.

However, first of all, background independence is a very loose concept. It already proves highly difficult to define what background independence precisely means (Belot, 2011; Read, 2016). Second, background independence may already be destroyed in classical GR (Belot, 2011). For instance, a non-empty universe that contains matter and electromagnetic fields is not fully background independent (Belot, 2011). To appreciate this result, remember that Weinberg's approach already includes matter and all interactions. On the contrary, approaches that start from GR and value background independence are typically concerned with spacetime alone. I suspect that praising background independence is closely tied to contestable philosophical premises.

8 Unification Revisited

Finally, what about the suspected 'dogma of unification'? I suggest to take the presented argumentation as an example for physics' *internal* capacity to promote theoretical progress by fully exploiting an existing theoretical framework and thereby uncovering substantial links to allegedly disconnected phenomena and theoretical structures.

Weinberg's quantum field theoretic derivation of the equivalence principle bridges the gulf between seemingly isolated theories. It should be emphasized that this perspective evolves *internally*. On its own, QFT provides a quantum theory of gravitation and—though this is not the final answer—resources to investigate and evaluate its flaws. As a result, we do not need to refer to any external principle to account for Weinberg's approach or to explain the quest for QG. The research program does not rely on external principles and does not commit to or execute a 'dogma of unification'. Hence, the situation is not special at all compared to previous endeavours in theoretical physics. To obtain a quantum theory of gravitation, Weinberg and others only had to take the best theoretical framework, namely QFT, seriously and analyze it thoroughly.

However, applying the same methods further and expanding the theory's realm to higher energies unfolds that QFT itself has its problems: As mentioned, Weinberg's spin-2 approach is nonrenormalizable. It does not provide meaningful, *i.e.* finite, results at high energies. According to particle physics, *this* is the issue of QG.

To solve this problem, one could generally proceed by either dismissing the theory as a whole (or at least one of its basic principles) and start from scratch, or try to dissolve the anomalies while keeping the basic principles (*cf.* Arkani-Hamed (2013)). As argued in Section 6, the problem with constructing a full-fledged theory of QG arises from bringing together QM and SR at high energies. The core principles by which we were able to construct our most accurate theoretical framework prove in tension in an even more fundamental way. In this view, a full-fledged theory of QG may result as a *by-product* of better understanding QFT (which again is a completely internal endeavour of physics).

Furthermore, if approaches to QG do not rely on external principles, but turn out to be a mere by-product of physical research applying its internal methods, it seems that the objections, doubts, and worries raised against these approaches become less persuasive. The theory itself tells us that there is more to come.

The presented argumentation was concerned with Weinberg's approach only. What about other takes on QG? Do they also solely rely on internal principles or are external principles involved? One would have to investigate their practice, too. But let me add the following: By help of Weinberg's approach we saw that QFT is already able to incorporate gravity. In fact, we saw that GR can be reduced to QFT. That does not seem to be the case the other way around. The classical framework of GR does not provide links to particle physics. It seems to be a perfectly consistent and self-contained theory. Also arguments concerning singularities do neither prove GR inconsistent, nor do they hint at a quantum theory of gravity (Wüthrich, 2012, 2). In the light of the presented argumentation, this should come as no surprise, since GR is a classical theory deduced from QFT. As a result, one may argue that it somehow seems odd to start approaches to QG from GR (*cf.* Weinberg (1999)).

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