Quantum Gravity: A Primer for Philosophers*

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'Quantum Gravity' does not denote any existing theory: the field of quantum gravity is very much a 'work in progress'. As you will see in this chapter, there are multiple lines of attack each with the same core goal: to find a theory that unifies, in some sense, general relativity (Einstein's classical field theory of gravitation) and quantum field theory (the theoretical framework through which we understand the behaviour of particles in *non-gravitational* fields). Quantum field theory and general relativity seem to be like oil and water, they don't like to mix—it is fair to say that combining them to produce a theory of quantum gravity constitutes the greatest unresolved puzzle in physics. Our goal in this chapter is to give the reader an impression of what the problem of quantum gravity is; why it is an important problem; the ways that have been suggested to resolve it; and what philosophical issues these approaches, and the problem itself, generate. This review is extremely selective, as it has to be to remain a manageable size: generally, rather than going into great detail in some area, we highlight the key features and the options, in the hope that readers may take up the problem for themselves—however, some of the basic formalism will be introduced so that the reader is able to enter the physics and (what little there is of) the philosophy of physics literature prepared.[1] I have also supplied references for those cases where I have omitted some important facts. Hence, this chapter is intended primarily as a catalyst for future research projects by philosophers of physics, both budding and well-matured.

1 The Strange Case of Quantum Gravity

Quantum gravity involves the unification of the principles of quantum theory and general relativity. Constructing such a theory constitutes one of the greatest challenges in theoretical physics. It is a particularly hard challenge for many reasons, both formal and conceptual, some of which I aim to elucidate in what follows. Even up until the 1970s, quantum gravity was, as Michael Duff remarks, "a subject ... pursued only by mad dogs and Englishmen" ([Duff, 1999], p. 185). That is something of an exaggeration, of course: for starters, when Duff speaks of quantum gravity, he has in mind the particle physicist's approach to the problem, according to which the gravitational

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[1] Unlike the chapters on quantum theory and statistical mechanics—less so quantum information theory—this chapter is, therefore, mainly devoted to spelling the various research programmes out, without quite so much emphasis on the nitty gritty philosophical problems.

interaction involves an exchange of gravitons (the quanta of the gravitational field). However, quantum gravity, understood as the general unificatory problem sketched above, has been pursed for around eighty years in some form or another, by many of the greatest physicists, many of whom were not English! The remark has more than a grain truth to it though; even now quantum gravity research is looked upon with some trepidation and, often, bemusement. This attitude stems primarily from the extreme detachment of quantum gravity research from experimental physics—a feature that leads Nambu [1985] to refer to quantum gravity research as "postmodern physics"! As a result, much of the research conducted in quantum gravity looks like an exercise in pure mathematics or, sometimes, metaphysics. This aspect makes quantum gravity especially interesting from a philosophical point of view, as I shall attempt to demonstrate throughout this chapter.

Quantum gravity is, in fact, rather curious from the point of view of the philosopher of physics because it is one of the few areas of contemporary physics where (some of) the physicists who are central figures in the field actively engage with philosophers, collaborating with them, participating in philosophy conferences, and contributing chapters to philosophical books and journals (a pair of recent examples are: [Callender and Huggett, 2001], and [Rickles et al., 2006]). Carlo Rovelli, co-founder of one of the main lines of attack known as 'loop quantum gravity', explicitly invites philosophers' cooperation, writing (in an essay from another philosophy collection: [Earman and Norton, 1997]):

> As a physicist involved in this effort [quantum gravity—DR], I wish the philosophers who are interested in the scientific description of the world would not confine themselves to commenting and polishing the present fragmentary physical theories, but would take the risk of trying to look *ahead*. ([Rovelli, 1997], p. 182)

Similarly, John Baez—a mathematical physicist who has done important work in making loop gravity rigorous—(again writing in a philosophical collection: [Callender and Huggett, 2001]) writes:

> Can philosophers really contribute to the project of reconciling general relativity and quantum field theory? Or is this a technical business best left to the experts? [...] General relativity and quantum field theory are based on some profound insights about the nature of reality. These insights are crystallized in the form of mathematics, but there is a limit to how much progress we can make by just playing around with this mathematics. We need to go back to the insights behind general relativity and quantum field theory, learn to hold them together in our minds, and dare to imagine a world more strange, more beautiful, but ultimately more *reasonable* than our current theories of it. For this daunting task, philosophical reflection is bound to be of help. ([Baez, 2001], p. 177)

This 'intellectually open' attitude, coupled with what we might call the 'fluid' state of play in quantum gravity, makes it possible that philosophers of physics might get involved with the *constructive* business of physics, as the philosopher Tian Yu Cao points out, "with a good chance to make some positive contributions, rather than just analysing philosophically what physicists have already established" ([Cao, 2001], p. 183).[2] However, the exact nature of these 'positive contributions' is still unclear at the present stage, though this primer will point out some possible directions.

However, perhaps the most important reason for the introduction of philosophical reflection in the area of quantum gravity research is, as suggested above, the fact that it does not (thus far) have the character of an *empirical* problem: current physics, as exemplified by the standard model of particle physics plus general relativity, does not contradict any piece of experimental evidence.[3] What matters most, in quantum gravity, is *internal consistency*, in the sense of some particular approach to the problem being logically coherent, and *external compatibility*, in the sense of the particular approach being compatible with our most well-established background knowledge (i.e. with what we know from both theory and experiment)—cf. [t'Hooft, 2001]. These constraints do not appear to be sufficiently stringent to uniquely determine the desired theory of quantum gravity; instead there are multiple research avenues that each seem to satisfy the constraints (or at least approximate them). The extent to which the various approaches are *really* quantum theories of gravity is somewhat controversial: string theory is only known at a perturbative level (as is quantum electrodynamics), which is not sufficient to provide the full theory of quantum gravity we are seeking; loop quantum gravity faces (amongst other problems) a 'reconstruction problem' according to which classical general relativity is not demonstrably proven to be its classical limit. This problem aside, satisfying these demands can often direct the specific research programmes into conceptual problems that philosophers are well acquainted with—problems to do with the nature of space, time, matter, causality, change, identity, substance, and so on (i.e. the warhorses of traditional philosophy). We discuss this aspect in the next section, and also consider what the possible motivations of quantum gravity research might be if not empirical ones.

Let us now turn to the general characterization of quantum gravity—this primarily involves explaining the nature of the problem that such a theory is intended to resolve. We will then give a brief history of quantum gravity. After this, we shall present the central ideas required from the ingredient theories of quantum gravity, namely quantum theory and general relativity. Then we can turn our attention to the various approaches aimed at reconciling these two theories. We then consider several issues of 'special interest': the nature and rôle of background independence, the experimental status of

[2]We should not get too carried away though, and ought to heed Dirac's warning—self-professed enemy of philosophy though he was—that "[u]nless such [philosophical] ideas have a mathematical basis they will be ineffective" ([Dirac, 1978], p. 1). What the above quotations are intended to convey is the fact that 'mathematical' and 'philosophical' are woven together more tightly than usual in a great deal of quantum gravity research, not that we can make scientific progress by idle philosophical speculation.

[3]Very roughly, the standard model of particle physics is our best description of the strong nuclear, weak nuclear, and electromagnetic forces (or interactions)—of course, the standard model unifies the weak and electromagnetic into a single 'electroweak' force. It tells us that matter is composed of particles called 'fermions' bound together by the exchange of (strong, weak, and electromagnetic) force-carrying particles called 'bosons'. Gravity is not included in the interactions treated in the standard model. Some quantum gravity researchers—especially those from the particle physics community—view the search for a quantum theory of gravity as tantamount to the search for a unified description of *all* interactions. That is, they suppose that the problem of quantum gravity can only be satisfactorily resolved by unifying the gravitational force with the other forces of nature and matter. This would supply the fabled 'theory of everything' or 'TOE'.

quantum gravity, the relevance of quantum gravity research to the interpretation of quantum theory, and 'cross-fertilization' amongst the various approaches. We finish off by speculating about the future of the field and the future for philosophical research within this area. A brief annotated resource list is appended to aid readers new to quantum gravity.

2 What is the Problem of Quantum Gravity?

This is perhaps the most speculative of the chapters in this textbook for the simple reason that, as mentioned above, an established theory of Quantum Gravity does not yet exist. However, the problem that a theory of quantum gravity is supposed to resolve *does* exist, and it is this problem and its possible solutions (of which there are many) that we wish to focus upon.[4] We can isolate three strictly separate research programmes, in the literature, that can be found to go by the name 'quantum gravity'.

2.1 Quantum Gravity as a Theory of Everything

On the one hand, as briefly described in footnote 3, there is a problem concerning two theories—general relativity and the standard model of particle physics (formulated in the framework of quantum field theory)—that aim to describe the way particles interact in fields, and these must be *unified* in some way. The latter theory deals with non-gravitational interactions (the strong, weak, and electromagnetic forces), that involve physics of order of magnitude of atoms and smaller, and the former deals with the gravitational interactions, at orders of magnitude much greater than that of atoms.[5] General relativity is a fully classical field theory, meaning it considers only the interaction of classical matter and fields with the (classical) gravitational field: so, no particles or fields with indefinite properties and trajectories—i.e. no uncertainty principle operating.[6] This should impose, as a minimal constraint on quantum gravity,

[4]Contrary to what some other philosophers might say (e.g. [Weinstein, 2005], p. 2), there *is* a sense in which these proposed solutions (i.e. particular approaches to resolving the problem of quantum gravity) are amenable to the sort of ontological and epistemological analysis that philosophers of physics typically engage with (i.e. for well-established theories such as special relativity and quantum mechanics). One can ask what the ontological consequences of a particular approach are, what it says about space, time, matter, causality, and so on. This will tell us what kind of a universe the approach describes. And one can ask epistemological questions, such as whether it is possible to distinguish between certain approaches or certain interpretations of a particular approach and whether and what we could come to know about the universe as given by some approach. Quantum gravity is a perfectly suitable subject for interpretive questions of this kind—cf.. [Callender and Huggett, 2001], p. 3, for a similar viewpoint.

[5]Hence, one often sees the claim that quantum theory is our 'theory of the very small', and general relativity is our 'theory of the very large'—see [Penrose, 2000] for an example. This demarcation of the domains of fundamental physical theory has allowed for the 'schizophrenic' worldview to persist for so long: general relativity and particle physics can safely ignore each other at currently accessible scales.

[6]It is also non-linear, which causes many a formal headache, especially when attempting quantization by standard methods. The structure of quantum theory is, of course, linear. One of the drastic approximation methods used to aid quantization of the gravitational field is precisely to 'linearize' the theory. However, this is *too* approximate to deliver much insight about full quantum gravity: the interesting features of gravity are, to a large extent, determined by the non-linearity. Note, however, that Roger Penrose, and some others, view the non-linearity as being implicated in the (nonlinear) collapse of the wavefunctions of quantum systems—

the (correspondence) principle that when quantum effects can be neglected (i.e. when $\hbar \to 0$) we recover classical general relativity (with no fluctuations as a result of the uncertainty relations), and when general relativistic effects can be neglected (i.e. when $G \to 0$) we recover standard quantum field theory (with no deviations from flat, or at least *fixed* spacetime geometry)—of course, when $c \to 0$ (i.e. when velocities are much lower than c) we can neglect special relativistic effects.[7]

According to this view of the problem of quantum gravity, the issue is one of *unification* of a rather grand sort. In order to achieve a unification of quantum theory with general relativity one must devise a single framework for treating *all* interactions, and so describe gravitational and non-gravitational interactions in the same scheme—hence, this goes beyond the 'mere' quantization of gravity. This is the approach of string theory. Problems with straightforward quantizations of gravity lead most string theorists to believe that quantum gravity and grand unification in a theory of everything are one and the same problem. Needless to say, this view is not shared by many outside of string theory.

2.2 Quantum Gravity as Quantum Cosmology

Quantum gravity is sometimes erroneously used to refer to quantum cosmology, the programme aimed at understanding 'the universe as a whole' quantum mechanically (and, therefore, in the absence of 'external' observers)—a prime example of this conflation is [Robson, 1996] (see especially §1.1); see [DeWitt, 1967c; Wheeler, 1968; Misner, 1969] for the first real steps in the field of quantum cosmology. Hence, one speaks in this context of the 'wavefunction of the universe', governed by the famous 'Wheeler-DeWitt' equation $\hat{H}\Psi = 0$ (in the canonical formalism). Here the quantum state Ψ is a functional of the metric and matter fields. This is a constraint equation, the vanishing of which informs us that the states have to be diffeomorphism invariant. That this equation is the central dynamical equation of the theory and is time independent forms one of the thorniest conceptual problems of quantum gravity: the problem of time—we return to this in §6.4.6.

Certainly, quantum cosmology is philosophically very interesting, and intimately connected to the problem of quantum gravity, but it is strictly distinct. Quantum cosmology is presumably something a quantum theory of gravity would have to tell us about,[8] but one can also discuss quantum cosmology independently of specific quantum theories of gravity, and *vice versa*. The obvious difference is that the fact that our

see §3.7 below for more on this. Note, however, that non-linearity is by no means a special feature of general relativity: any interacting theory is non-linear, and they face the same kinds of technical problems.

[7] One would, of course, like this constraint to uniquely specify a theory. Unfortunately, however, this minimal constraint appears to be satisfiable by multiple approaches. Indeed, there are 'folk theorems' that point to the fact that it will be met by any Lorentz invariant quantum theory of a spin-2 particle (coupled to a suitable energy-momentum tensor)—see [Wald, 1986] for a thorough examination.

[8] Indeed, there are thriving research sub-programmes being pursued in the different approaches to quantum gravity: string cosmology [Gasperini, 2007], loop quantum cosmology [Bojowald, 2005], causal-set cosmology [Sorkin, 2000] and more. These applications of the approaches to quantum gravity are yielding predictions that have the potential to be tested with current, or near-future technologies. Hence, ultimately, it may prove to be the case that quantum cosmology is the testing-ground of quantum gravity: i.e. the very large is used to test claims about the very small. We shall have more to say about this in §7.3.

universe contains gravity is a contingent matter: there are possible universes in which gravity does not exist. Structurally, of course, it will be a very different kind of universe, with different interactions, but given that it is a *single* object, one can talk about quantum cosmology in that universe too, despite the fact that gravity does not exist within it at all. Hence, the two topics are logically quite distinct despite being, in fact, physically related.

Even given this physical relatedness, in our own universe, differences emerge in the kinds of problems quantum cosmology and quantum gravity each deal with. Most obviously, quantum gravity will ultimately be concerned with systems that are miniscule, whereas quantum cosmology will be concerned with systems that are enormous—although, as I mentioned in the previous footnote, the two have things to say to each other. In particular, since gravity is the dominating force at large scales, a theory of quantum cosmology will involve a quantum theory of gravity. Moreover, since we have evidence that there are epochs in the universe's history—including likely future epochs—in which the universe is incredibly dense (and small), it seems evident that quantum mechanical effects will be in operation, and so quantum gravity is required.

2.3 Quantum Gravity as Synthesis of 'Quantum' and 'Gravitation'

More generally, when we speak of 'the problem of quantum gravity' we will not mean either of these two things. Instead, we will mean the integration of general relativity with quantum theory *simpliciter*, rather than with the standard model (our most empirically successful quantum theory). The latter is essential only for grand unification models or theories of everything (such as string theory and many particle physics-inspired approaches), and not strictly part of quantum gravity *per se*. Most approaches to the quantum gravity problem do not consider the standard model (string theory is an exception), or attempt at best aim to demonstrate compatibility with it. Quantum gravity in the sense of this chapter is a more minimal notion; one can consider a 'pure' quantum theory of gravity, independent of any other fields whatsoever.

Thus, Ashtekar and Geroch, in their superb early review of quantum gravity, characterize quantum gravity as "some physical theory which encompasses the principles of both quantum mechanics and general relativity" ([9], p. 1213).[9] This way of understanding the problem is at the same time more specific and more general than the other ways. It is more general in that, inasmuch as the two approaches mentioned above will qualify as a possible solution of the problem so conceived, they are included in this characterization. On the other hand, it is more specific in that it focuses attention on one particular kind of interaction, gravitation, in much the same way that quantum electrodynamics [QED] focuses on electromagnetism, ignoring the rest—although, strictly speaking, the validity of QED is hedged on the imposition of a cutoff, which depends on the presence of other fields. That is, this viewpoint allows for the possibility of quantum gravity theories that are not at the same time theories of everything.

[9]However, exactly what is meant by 'integration' or 'encompasses' here is not completely clear, and the various approaches differ in how they understand these notions (and their close cousins: 'synthesize', 'unify', and so on). We return to this point below in §3.5.

3 Why Bother? Arguments for Quantum Gravity

Both of these theoretical frameworks, general relativity and quantum (field) theory, are experimentally very well confirmed: no experimental test has conflicted with either—many of these tests have been highly novel and *incredibly* accurate. If there is no empirical anomaly, then why bother with quantum gravity: why do we need such a theory? There are two main lines of response to this question: one is formal the other conceptual—there are also some experimental considerations, but these are far from decisive.[10] There are other reasons that fall somewhere between formal and conceptual. We outline some of these below.[11] Firstly, let us spell out the peculiar nature of the quantum gravity problem some more.

It was commonly believed that the quantum nature of gravity would never make itself felt in any physically realizable experiment. This is still a common notion, and it isn't entirely clear whether the voices to the contrary are right or not. No definitive experiment has been performed to reveal these quantum properties yet. As Unruh ([1984], p. 238) explains, there is an enormous difference between the coupling of an electron's charge to the electromagnetic field and the coupling of its mass to the gravitational field: a coupling of 10^{-2} as compared with 10^{-22}![12] Unruh's response to the question of whether we can ignore quantum gravity is nonetheless a resounding No: the coupling to the gravitational field of small masses is indeed miniscule, but large *aggregates* of matter, consisting of enormous numbers of particles, can have huge coupling constants (i.e. huge masses). That is, mass is itself an aggregative property of objects; an object composed of two objects with masses m_1 and m_2 will simply have the mass $M = m_1 + m_2$: if you want to increase the coupling constant just add more masses. On this basis Unruh advances an experiment based on neutron stars, acting as a source of gravitational waves, rather than electrons. The idea is to set up an analogue of the slit experiments so as to exhibit macroscopic quantum interference effects, using another (cold) neutron star as the 'detector' and a black hole as the 'slit'. One then 'counts quanta' (gravitons) hitting the detector star and watches for discontinuous variations in the number. From this (nomologically possible) setup and these transitions one can read off the required interference effects. Hence, we have an 'in principle' experiment that would exhibit, at a macroscopic level, the quantum nature of the gravitational field. As Unruh points out, however, this does not tell us much about how to actually formulate a theory to explain these results and advance predictions about new phenomena. Attempts to apply standard quantization methods have thus far failed to yield a consistent, complete, and/or empirically satisfactory theory. The question remains, then, given the lack of an experimental basis, why bother pursuing quantum gravity?

[10] For example, the Higgs boson—supposedly responsible for the spontaneous violation of gauge symmetry, giving masses to gauge bosons and fermions—has yet to be experimentally detected. The Large Hadron Collider [LHC] should be able to generate sufficient beam energy to produce the Higgs. Similarly, Hawking radiation has yet to be discovered.

[11] One of these—the 'formal necessity' response—will occupy us when we reach the 'semi-classical gravity' section in the context of the various 'Methods'—see §6.1.

[12] Feynman ([1963], p. 697) gives an example that perhaps highlights this difference more dramatically by showing how the gravitational coupling between a proton and an electron in a hydrogen atom would shift the wave-function by just 43 arcseconds over a time period of 100 times the age of the Universe!

3.1 Dimensional Analysis

There are three fundamental constants that are expected to play a rôle in quantum gravity: c, G, and $\hbar$.[13] The values of these constants inform us about the scale at which relativistic, gravitational, and quantum effects become important:

- $\hbar$ (Planck's constant, with dimension L^2MT^{-1}) sets the size at which quantum effects become important.
- G (Newton's universal constant of gravitation, with dimension $L^3M^{-1}T^{-2}$) sets the size at which gravitational effects become important.
- c (the speed of light, with dimension LT^{-1}) sets the scale at which relativistic effects become important.

As Planck noticed [Planck, 1899], these constants can be combined in a unique way so as to determine a fundamental length: $l_P = \sqrt{\hbar G/c^3} \approx 1.62 \times 10^{33} cm$ (known as the *Planck length*). The Planck energy, running inversely to the Planck length, is 1.22×10^{19}GeV. At lengths bigger than this we can safely adopt a schizophrenic attitude with respect to gravity and the quantum (i.e. we can ignore possible interactions between them). However, close to this length there will be a non-negligible interplay between them: this is the scale at which quantum gravity is expected to play a rôle.[14] Since it is a length composed of the fundamental constants of our well-established theories, we should expect there to be physics operating at this scale in such a way as to combine the physics associated with the various constants. Many believe that this combination will result in fluctuations of the metric of spacetime at such scales.

In more detail, general relativity cannot be ignored when the mass of an object is of the order of its Schwarzschild radius. If one has a particle of mass m and a Compton wavelength near to its Schwarzschild radius, then one would require both general relativity and quantum field theory (and so, presumably, quantum gravity). The Compton wavelength l_C of a particle tells us that if we wish to localize a particle of mass m to within length l_C then we must input sufficient energy to create another particle of mass m. This length is associated with quantum field theory; it is formed from a combination of $\hbar$ and c: $l_C = \hbar/mc$. The Schwarzschild radius l_S is similar: it tells us that if we condense an object of mass m to a size $s < l_S$ a black hole will

[13] We should expect to see Boltzmann's constant at some level too; however, we shall ignore thermal considerations here. We mention some 'semi-classical' phenomena in §6.1.2 (and more briefly in the next subsection), where we discuss the results from the physics of quantum black holes, in which black holes radiate (approximately) thermal radiation.

[14] Hence, as Schweber points out, "it is constants of nature ... that demarcate domains" ([Schweber, 1992], pp. 138–9). By this is meant that the scales at which the physics circumscribed by some theory become important is set by the fundamental constants that the theory depends on—Heisenberg unpacked this idea in a systematic way in [Heisenberg, 1934]. However, Diego Meschini has recently argued that we should express the relevance of Planck units to quantum gravity research as "a humble belief, and not as an established fact" ([Meschini, 2007], p. 15). The main argument is that the final theory of quantum gravity might either contain additional constants, or else be missing c, G, or $\hbar$: only empirical research can tell us which alternative is the case. This is perfectly true and Meschini is right to draw attention to the laxness in the dimensional argument. However, while the dimensional argument cannot demonstrate the necessity of the Planck scale for quantum gravity, it does appear to point to its sufficiency.

form as a result. This length is associated with general relativity, being formed from a combination of G and c: $l_S = Gm/c^2$. Now, when $m = M_P = \sqrt{\hbar c/G}$ (the 'Planck mass') the two lengths become identical. (Note that short distance measurements δx demand very high energy waves compressed into a very small volume (length and energy being inversely related via $\hbar$)—this process forces the creation of microscopic black holes, as mentioned. However, these will Hawking evaporate in a decay time $\delta t \sim l_P^2/\delta x$. This simple fact crops up in a variety of contexts in quantum gravity research.)

Now, the more pragmatic reader may still be wondering why we should bother with quantum gravity, since the length is so miniscule as to be utterly out of reach empirically speaking. However, this would ignore crucial physical implications of our well-established theories: namely that they predict singularities of various kinds. It ignores certain phenomena that should exist in universes with both quantum fields and gravity (such as black hole evaporation). It also ignores fundamental conflicts between these background theories, such as the cosmological constant problem, and also recent advances made on the experimental side of quantum gravity—on which, see §7.3. We deal with these implications, and others, in the remainder of this section.

3.2 Black Holes and Spacetime Singularities

A great deal of the motivational underpinning of quantum gravity, especially in more recent times, has had to do with various aspects of black hole physics and cosmology. Of paramount importance in this regard was Stephen Hawking's discovery that black holes radiate [Hawking, 1975].[15]

Hawking's Black Hole Information Paradox is one important way in which the conflict between quantum mechanics and gravity—and the need for a quantum theory of gravity—becomes readily apparent.[16] Suppose we have some matter in a pure quantum state $|\psi\rangle$, with density matrix $\rho = |\psi\rangle\langle\psi|$. The entropy of a system in such a state is given by $S = -\mathrm{Tr}\rho\ln\rho = 0$.[17] Hawking radiation causes the black hole to radiate, thus decaying.[18] The emitted radiation is (approximately) thermal, so that the

[15]Erik Curiel bemoans the ubiquitous practice of referring to these black hole results as "physical fact". On the equally widespread practice of using the results to defend approaches to quantum gravity he writes that "[t]he derivation of the Bekenstein-Hawking entropy formula by the counting of microstates, intriguing and impressive as it may be in many ways, cannot serve as a demonstration of the scientific merit of a theory of quantum gravity, for the Bekenstein-Hawking entropy formula itself has no empirical standing" ([Curiel, 2001], p. S435). However, this does not mean that it has no standing at all, and that it does not have sufficient standing to provide reasons for upping the credence one is willing to give to some approach to quantum gravity. The fact remains, if we believe (to some degree) in general relativity and quantum field theory, given the direct empirical support of those theories, then we can reasonably believe in those results that are a necessary consequence of their merger. However, we can perhaps agree with Curiel that the practice of treating the black hole results as *data* is simply false.

[16]The quantum and statistical mechanical background required by this example can be found in the chapters by Wallace, Frigg, and Timpson.

[17]Note that it was Jacob Bekenstein [1973] who made the connection between black holes (or, rather, their horizon areas) and entropy on the basis of Hawking's theorem [1971] that a black hole's surface area can never decrease.

[18]Not surprisingly, given the equivalence principle, an analogous effect occurs for accelerated observers in the Minkowski vacuum: the observer will detect thermal radiations known as 'Rindler quanta' (this effect is known as the 'Unruh effect' or, sometimes, the 'Davies-Unruh effect').

state is represented by a (mixed) density matrix $\rho = \Sigma_n p_n |\psi\rangle\langle\psi| \neq 0$ (the entropy is of the order M_p: the Planck mass = $\sqrt{\hbar c/G} = 2.17665 \times 10^{-5} g$). Hence, the process of black hole evaporation results in an apparent loss of information: as entropy goes up, information goes down according to $\Delta\mathrm{Information} = -\Delta\mathrm{Entropy}$. What has happened? To get this result Hawking used a semi-classical analysis involving a quantum field on a classical, fixed black hole background geometry. We seem to have a conflict: black hole evaporation leads to an evolution of a pure state into a mixed state, in violation of basic quantum mechanical principles. Bryce DeWitt endorses the view that the quantum aspects of black holes motivate quantum gravity research in the very strongest of terms, writing that "Hawking's discovery ... shows in a most striking way that general relativity *must* be wedded to the quantum theory if consistency with statistical mechanics is to be assured" ([DeWitt, 1980], p. 697).

There are several proposals for accounting for the missing information:

- **Information Loss**: the black hole together with the information stored in it disappear entirely in blatant violation of unitarity (since pure states can evolve into mixed states). This is a bullet-biting strategy and, as such, is the least popular.[19]

- **Information Recovery**: the information is 'contained' in the outgoing Hawking radiation and is recoverable *in principle* (if not in practice), thus preserving unitarity. This is the standard response to the problem.

- **Remnants**: the information release is a quantum gravitational effect that kicks in once the black hole is of the order M_p. Computations on the time needed to release all of the stored information given the small amount of available energy mean that a *persisting* slowly decaying 'remnant' must remain.[20]

It is widely believed that in order to resolve the problem satisfactorily one needs a quantum theory of gravity to tell us about the nature of 'the final state' of evaporation. Indeed, the thermal spectrum of a black hole is now considered to be a 'target' that any respectable theory of quantum gravity must hit: both of the main contenders (string theory and loop gravity) do so, in very different ways and at different levels of generality. In more detail, what one requires is a *microscopic* description of black holes, or a way of counting the quantum states of black holes. With the quantum geometry of string theory and loop quantum gravity this is possible, albeit given certain provisos: the former uses D-brane technology (where D-branes are the microstates of black holes) and the latter uses the intersections of spin-networks (the quantum states of the gravitational field) with the surface of the black hole (i.e. the horizon). The computation of the entropy of a black hole is then just a combinatorial procedure.

An interesting aspect of the black hole information problem in relation to quantum gravity is the fact that, in many approaches to quantum gravity, time is no longer

[19]Note that this was in fact Hawking's own response to the information problem. In controversial circumstances, at the GR17 conference in Dublin in 2004, he recently rejected his earlier view in favour of the more orthodox 'correlation' response, mentioned below—see http://math.ucr.edu/home/baez/week207.html for a transcript of his talk, with commentary by John Baez.

[20]A philosophical 'mini-debate' on the cogency of the remnant resolution can be found in [Belot et al., 1999; Bokulic, 2001; 2005]. I refer the reader to these papers for more details.

fundamental. Given that the information problem has to do with whether black hole evaporation does or does not violate unitarity, one has to say something about time (unitarity being conservation of probabilities *over time*). If time is simply absent at the quantum gravitational level then it seems that the problem evaporates too, thus offering more (admittedly somewhat ad hoc) support for the idea that we need a quantum gravity—cf. [Kiefer, 2006] for more on this issue.

3.3 Cosmological Considerations

Given the observed expansion of the universe, if we were to trace it back we would find that it leads to an initial ('Big Bang') singularity.[21] Naturally, given the magnitude of the curvature and tidal forces at such a singularity, the equations of classical general relativity will not be applicable. At this scale, as we have seen, we will have quantum effects and gravity operating together, and so will need a quantum theory of gravity to describe what is going on.[22]

As mentioned above, the independence of quantum gravity from quantum cosmology can be seen clearly by comparing the class of questions that each deals with. Quantum cosmology is focused on the problem of constructing a quantum theory of a single object with no environment: no external, classical observers. However, in quantum gravity a perfectly reasonable problem is to consider measurements of the gravitational field in a region of space made by just such an external, classical observer—see [Rovelli, 1991], §7 for more on this. Hence, cosmology and quantum gravity are strictly independent domains of inquiry. However, given the contingent facts as revealed by the cosmic background radiation, it is clear that there is at least one epoch in our own universe's history in which quantum gravitational effects (as delineated by the Planck units) will become important. Hence, cosmological considerations point to the demand for a quantum theory of gravity—note also, that much of the work carried out in quantum cosmology (especially in the early days) is conducted in the framework of quantum geometrodynamics.

3.3.1 The Cosmological Constant Problem

A more pressing problem is known as the 'cosmological constant problem'. This is too big a problem to cover in this primer, however, it is an important part of quantum gravity research. The cosmological constant Λ corresponds to vacuum energy present throughout space. As is well known, it was originally introduced by Einstein as a way

[21] Our best evidence for the existence of a Big Bang in the universe's past is, of course, encoded in the quasi-uniformity of the cosmic background (blackbody, $T_0 = 2.728K$) radiation predicted by Gamov and found by Penzias and Wilson—we can safely set aside the various problems with this view (e.g. the horizon problem and the 'clumpiness' problem since they lie outside our domain of interest in this chapter). For more details, see the excellent book [Maoz, 2007] for an elementary guide or the equally excellent book [Dodelson, 2003] for a more in depth guide—[Mukhanov, 2005; Liddle and Lyth, 2000] offer more advanced presentations, both well worth a read.

[22] Recall from §2.2 that this situation might be viewed as signalling the need for a quantum cosmological theory instead, so that a wave-function of the universe replaces a classical spacetime geometry. Again, this does not thereby imply that we will have a quantum theory of gravity on the table since the two can proceed independently of one another.

(the only way in four dimensions) to extend his field equations for gravity to achieve a (quasi-) static Universe.[23] The problem relevant to quantum gravity research has to do with fact that quantum field theory and general relativity have very different ways of computing the value of the cosmological constant (yielding *very* different values).

The energy spectrum of an harmonic oscillator, $E_N = (N + 1/2)\omega$, has a nonzero ground state in quantum mechanics. This is the zero-point energy, standardly explained by reference to the uncertainty principle (i.e. there's no way to freeze a particle). In the context of (free) quantum field theory the field is understood to be an infinite family of such harmonic oscillators, therefore the energy density of the quantum vacuum is going to be infinite on account of the nonzero contribution from each vibrational mode of the fields being considered. One can bring this value down in various ways: by imposing a cutoff at the Planck length, ignoring those modes that have wavelengths smaller than this, or by turning on the interactions between the vibrational modes. This still leaves an extremely large value.

Very loosely speaking, in quantum field theory this infinite (or very large) value can be swept under the rug (the energy can be rescaled to zero): only energy *differences* between the vacuum and energy states make sense. That is to say: the absolute value of the energy density of the vacuum in quantum field theory is unobservable. The value one gives is largely a matter of convention. This is not true in cosmology. Here the cosmological constant, or the curvature of spacetime, is taken to measure the energy density of empty space. This provides a way to perform experiments to empirically determine the correct value. The energy density, as actually observed in curvature measurements, comes out as $\rho \simeq 10^{-30} gcm^{-3}$. Very close to zero.

The problem is, then: why is the measured value of the cosmological constant so much smaller than that predicted by quantum field theory? Here is a theoretical conflict between our two great fundamental theories. It is partly empirical too since we have a constraint impose by the measured value for the curvature of the Universe. Resolving this problem is one of the challenges for a quantum theory of gravity.

3.4 Non-Renormalizability of General Relativity

Quantum field theory amounts to a synthesis of quantum mechanics and special relativity: fields are pretty much *forced* by this unification, since one must account for situations with variable particle number (i.e. the creation and annihilation of particles) as indicated in high-speed collision experiments. The framework it provides has found a home for quantum theories of the electromagnetic, strong, and weak interactions. In this approach—specifically, focusing on perturbation theory—the excitations of the various fields (photons, gluons, etc.) mediate the various interactions—for example, photons mediate the electromagnetic interactions between charged particles in the context of quantum electrodynamics [QED]. An old and venerable approach tried to accommodate gravity in the same formal framework: here the gravitational interaction would be mediated by the graviton (the massless, spin-2 quanta of the gravitational

[23] The history of the cosmological constant is an extremely interesting episode in physics. I refer the reader to Norbert Straumann's [2008] excellent account. See also [Straumann, 2008] for a more advanced account, including the connection to the problem of Dark Energy. Sean Carroll has some excellent free online material on the cosmological constant problem at his website: http://preposterousuniverse.com.

field). As in the other examples of quantum fields theories, quantum gravity along these lines runs into formal difficulties: when one tries to compute probability amplitudes for processes involving graviton exchange (and, indeed, involving the exchange of other particles in quantum field theory) we get infinities out. Since we cannot readily make sense of measuring infinite quantities, something has clearly gone awry. In standard quantum field theories, QED for example, these infinities can be 'absorbed' in a procedure called renormalization—note that many of the founding fathers of quantum field theory were not fond of the renormalization methods (see [Brown, 1992] for historical perspectives on renormalization). The problems occur when the region of integration involves very short distances (or, equivalently, very high momenta on the virtual particles). In quantum gravity, as the momenta increase (or the distances decrease) the strength of the interactions grow without limit, so that the divergences get progressively worse.[24]

Renormalization then refers to singularities of another kind, but essentially to do with spacetime issues. Quantum gravity, given the dimensional argument above, should provide us with a description of the behaviour of fields—the gravitational field—at very short distances (so called 'ultraviolet' distances). There is no doubt that general relativity performs remarkably well at the scales it has been tested at thus far. However, if we view it through the lens of quantum field theory then, in four-dimensions at least, it is perturbatively non-renormalizable.[25] In other words, when one attempts to predict the values of observables, following the method of Feynman diagrams, one finds that there are infinite amplitudes that cannot be absorbed through the machinery of renormalization theory.[26]

This is usually taken to mean the scales at which these divergences make their entrance mark the cut-off point at which general relativity breaks down, and a new theory with new physics must take over. Or, in other words, that general relativity is not a fundamental theory, only an *effective* theory. One might legitimately wonder whether there is such a thing as a Fundamental Theory, at the root of all other phenomena. We might be able to do no better than finding a tower of effective theories for the simple reason that there is no true *basis* theory. Certainly, recent work in condensed matter physics and complexity science makes such a view more appealing—see [Morrison, 2006] for example; [Laughlin, 2006] gives an interesting (popular) account of the non-reductionist alternative. It can't be denied that the search for fundamental theories has proven itself to be heuristically very useful in the development of physics. It is in-

[24]For a pedagogically outstanding introduction to renormalization (restricted to QED), see [Mills, 1993]. The other contributions to the book featuring this article (namely [Brown, 1992]), dealing with historical and philosophical issues of renormalization, are also well worth reading.

[25]Power counting arguments are sufficient to show that, like the abandoned Fermi theory of the weak interaction, the gravitational coupling constant has a negative mass dimension. This is a necessary symptom of a non-renormalizable theory.

[26]The standard definition of renormalization is an 'absorption of the infinities via a redefinition of a finite number of physical parameters'. What does that mean? The physical parameters are such things as mass m and charge e. They have perfectly finite values when observed in real experiments. The way out of this is to deny that the 'bare' mass and charge in the Lagrangian are the 'true' representational devices, but instead one uses the more realistic case of the mass and charge of an electron swarming with virtual particles. In the case of gravity we find that the perturbative theory is not renormalizable in this manner. To renormalize the theory one would have to insert infinitely many 'absorption parameters', that would each (infinitely many of them) have to be determined through experiment, as above.

teresting to speculate about what physics would be like without this belief in a 'base' that underlies and (reductively) explains all other phenomena. If the work in, say, condensed matter physics is anything to go by then we could expect a more 'practical' physics. This distancing of science from practical matters might be what underlies Nancy Cartwright's distaste (as expressed in, e.g., [Cartwright, 1999]) with what she labels 'fundamentalism' (namely, a belief in the 'unity of Nature'—a matter we turn to in the next subsection). One can certainly appreciate the sentiment, but robbed of the excitement that the belief in fundamentalism offers, the development of physics would surely be a much slower, more tedious affair! However, this is no argument for fundamentalism. The effective field theory approach seems to be a legitimate alternative.[27]

There are several directions this state of affairs (*viz.* non-renormalizability) might point: string theorists believe that because their theory is finite and reproduces general relativity at the appropriate scales, it is the best game in town (some erroneously say the *only* game in town). Alternatively, one might try to modify the action by adding terms that would serve to cancel out the divergences—much effort was put into such approaches in the seventies, leading to so-called 'higher-derivative theories' and 'supergravity'. Another option that has led to a serious competitor to string theory is to put the non-renormalizability of general relativity down to the questionable assumptions that the perturbative methods rely on, such as a fixed, classical, continuum spacetime background. Sidestepping this methodology, and proceeding with a non-perturbative quantization of general relativity can be shown to lead to finite results, as in the case of loop quantum gravity. As Abhay Ashtekar, a leading light of this approach, writes:

> Why should a smooth continuum be then a good approximation to represent the space-time geometry? We should not presuppose what the microstructure should be. Rather, we should let the theory itself tell us what this structure is. This, in turn, means that when one comes to gravity, the basic assumptions of perturbation theory are flawed. ([Ashtekar, 1995], p. 193)

Without these presumptions of perturbation theory, the divergence problems evaporate. The eradication of infinities by quantum gravity has been a common aspiration for a long time. The idea is that it might 'cure' the ultraviolet divergences of field theories by providing some kind of physically realistic cutoff:

> It is possible that this new situation so different from quantized theories invariant with respect to the LORENTZ group only, may help to overcome the divergence difficulties which are so intimately connected with a c-number for the light-cone in the latter theories. (Pauli in [Klein, 1956], p. 69[28])

There are two things to say here. Firstly, just because a theory is nonrenormalizable does not mean that we should discard it: it can still be predictive and, hence, useful (see

[27]For philosophical investigations of this approach, see: [Hartmann, 2001] and [Castellani, 2002]. This work can be directly applied to the problem of quantum gravity by arguing that the relativity principle is an emergent phenomenon. Detailed initial work has been carried out in [Laughlin, 2003]. Jon Bain [2008] provides a philosophical analysis of this condensed matter physics-based modelling of spacetime.

[28]See also [Pauli, 1967] for more on this idea.

[Kubo and Nunami, 2003] for a well-argued defense of this point). Secondly, perturbative nonrenormalizability does not mean that there is no consistent *nonperturbative* quantization available. As canonical quantum gravity researchers (such as Ashtekar above) argue, the machinery of perturbative quantization methods, with their presuppositions of smooth, fixed, spacetime backgrounds, are bound to be inadequate when it comes to quantizing gravity, since gravity is inextricably entangled with spacetime geometry.

3.5 Dreams of Unification

The idea of unification has the status of a regulative principle, or an ideal which should be striven towards. Maxwell's theory beautifully unified electricity and magnetism into a single structure (the electromagnetic field), and got a constant of nature into the bargain! Einstein—in an equally beautiful way—unified Maxwell's theory with the principle of Galilean relativity, thereby resolving a serious empirical anomaly (namely, the null effect of the æther wind experiments): here, thanks to Minkowski, space and time were unified into a single four dimensional structure, spacetime. The theory of gravitation was unified with special relativity in Einstein's general theory of relativity: here gravity is unified with spacetime. Quantum theory was unified with special relativity in quantum field theory (the fields being necessitated by the Lorentz-invariant, spacetime description). Unification has seemingly gone into overdrive in the latter part of the last century, with unifications of the weak and electromagnetic interactions (in the Weinberg-Salam electroweak theory):

> Just as Einstein comprehended the nature of gravitational charge in terms of spacetime curvature, can we comprehend the nature of other charges, of the entire unified set, as a set, in terms of something equally profound? This briefly is the dream, much reinforced by the verification of gauge theory predictions. ([Salam, 1980], p. 723)

Carlip calls the "appeal to unification" motivation of quantum gravity "[t]he stock reply" ([Carlip, 2001], p. 888). One can certainly find this belief in many writings on quantum gravity. For example, Ashtekar writes:

> Everything in our past experience tells us that the two descriptions of Nature we currently use [quantum mechanics and general relativity—DR] must be approximations, special cases which arise as suitable limits of a single, universal theory. That theory must be based on a synthesis of the basic principles of general relativity and quantum mechanics. This would be the quantum theory of gravity that we are seeking. ([Ashtekar, 1995], p. 186)

Einstein too, of course, hoped for and sought a theory that would (geometrically) treat both gravitation and electromagnetism (ignoring the other less well-known interactions then in evidence) as "one unified conformation" (Einstein's Leyden Lecture, quoted in [DeWitt, 1980], p. 681).

The 'standard model' is often portrayed as the example of unification *par excellence*. It is a Yang-Mills theory with gauge group $SU(3) \times SU(2) \times U(1)$. However, many are unhappy with the way the standard model is *stitched* together (specifically, the way $SU(3)$ is tacked on): what would be preferable is a framework that encompasses all interactions within a single gauge group, a single interaction. This naturally involves gravity.

The appeal to unification is, however, based on a questionable assumption: there is no *a priori* reason why nature should be unified, and many approaches to quantum gravity only seek to unify (if that is the right word for it) general relativity and quantum theory, rather than unifying all interactions. There is no reason why the world shouldn't be a Frankenstein's monster, with one force serving one purpose, and another distinct (irreducible) force serving some other purpose—a "dappled world" to borrow Cartwright's phraseology. The belief that there is just one underlying force or law responsible for everything else borders on religious belief, a belief that the world *has* to be a certain way.

One might make an inductive case based on past unifications that unification has led to progress, and is *converging* to a single interaction or law of nature, but the present situation, the experimental situation at least, paints a non-unified picture of the world—the formal situation too is problematic: QCD is not unified with the electroweak theory, as mentioned above. Simply bunching together some gauge groups does not give us unification. Moreover, 'unification' is a rather vague notion, and there are many distinct ways in which one might be said to have unified something or some group of things.[29]

This vagueness filters through into quantum gravity, for although there is a sense in which quantum gravity is about unification—i.e. the sense in which quantum mechanics and general relativity have to be accounted for in some common framework—the different methods go about this in different ways. Loop quantum gravity is rather 'minimalist' in that it seeks *only* to produce a quantum theory of the gravitational field, such that the possibility of unifying this theory with the theories of the other interactions is secondary. String theory, by contrast, amounts to a 'theory of everything', namely a theory in which one kind of interaction determines every other fact and facet of reality.[30] While this latter view—that Nature is unified—may have held sway, certainly amongst physicists, in the past, it is no longer believed to be enforced by the physics (if that ever were the case). It seems very possible, and I think plausible, that loop quantum gravity is on the right track, and if this is the case, then we could wind up having a disunified picture of the world in which we have quantum gauge field theories of all interactions, but only two of the four (the electromagnetic and the weak interactions, giving the elecroweak interaction) are *truly* unified (in the sense of having been merged into a single interaction).

That said, it is a fairly incontestable claim that unification has proven to be a major player in contemporary physics and its development. But in each of these cases there has been some empirical anomaly that drove the unification, and some observational data to guide the development of theory. In the case of quantum gravity the anomalies

[29] See [Maudlin, 1996] for a careful philosophical analysis of unification in physics. See also [Rüger, 1989] for a philosophical discussion dealing explicitly with quantum gravity.

[30] Note too that even the 'hybrid' view of semi-classical gravity, where gravity is kept classical and interacts with quantized matter (or the expectation value of quantized matter) can be said to be unified in this very weak sense.

are purely formal and there is no data to guide the construction.[31]

Note, however, that quantum gravity should not be confused with so-called 'unified field theories'. Unified field theories—as developed by Einstein, Eddington, Kaluza, Weyl, Schrödinger, and company—aimed to modify spacetime in various ways to accommodate non-gravitational fields (mainly, it has to be said, the electromagnetic field). However, elements of these unsuccessful attempts at unification still play a crucial rôle in many quantum gravity approaches. Most notable here is the introduction, by Kaluza, of extra dimensions of spacetime and, by Klein, their compactification into a tightly curled circle (whose winding number properties are automatically responsible for quantizing the electric charge). Also central, of course, is Weyl's notion of gauge invariance.

3.6 Incompatibilities

An intuitive argument for the need for a quantum theory of gravity is as follows. Our best theory of gravity is at the same time a theory of spacetime, and since our theories of the other interactions and matter (all of which are quantum gauge field theories) are local in spacetime, we can naturally expect some kind of linkage between the two, gravity and quantum.[32] In particular, one might expect that the coupling between spacetime geometry (gravitation) and quantized matter sources will lead to a quantum geometry, quantum spacetime. We might call this 'the infection argument'. We find this basic idea appearing in other arguments too; some examples of a 'formal' and 'conceptual' nature are given below—we consider the validity of the infection argument in §6.1.

3.6.1 Conceptual Compatibility Issues

As we will see in §5, there exist basic incompatibilities between general relativity and quantum theory—at least insofar as the examples of quantum theories we currently have at our disposal go. The great advance of general relativity is its background independence, related to (but not equivalent to) its lack of a preferred reference frame or preferred family of frames. More accurately, general relativity does not involve *fixed* spacetime geometry with values given *a priori*. The spacetime geometry is what one gets out of the theory by solving the field equations. By contrast, quantum theory appears to *demand* that there be a fixed spacetime geometry (i.e. it appears to be be necessarily background dependence), related to (but not equivalent to) the existence of a preferred reference frame, or a family of such—see [Weinstein, 2001] for a clear

[31] We might make a case for the cosmological constant problem constituting genuine data to guide the construction of the theory. In this case, the different approaches to the energy density of the vacuum by general relativity and quantum field theory lead to very different numbers. Quantum field theory gives either infinity (on the assumption of continuous spacetime) or an extremely large but finite number (if we count only the larger than Planck length contributions). Experiment puts the energy density near to zero, so we have a serious clash here. Unification of quantum field theory with general relativity might be one way to get a sensible number from quantum field theory. For philosophical discussions of this problem see [Rugh and Zinkernagel, 2002] and [Saunders, 2002].

[32] However, there is a large amount of disagreement over how best to conceptualize and formulate this linkage in a theory of quantum gravity leading to a proliferation of competing approaches.

discussion of this apparent dependence of quantum theory on absolute spacetime structure.

The basic dynamical variable in general relativity is the metric. The metric serves a dual purpose in this theory: it both determines the geometry of spacetime (and so the kinematic structure against which physical processes are defined) and acts as a (pre-) potential for the gravitational field. Since it is a dynamical variable that also is responsible for spacetime geometry, it follows that geometry itself is dynamical: one has to solve the dynamics in order to get to the kinematics. This feature is a central part of 'background independence', the notion that there are no absolute objects (or 'unmoved movers') in the theory (or, at least, that the *metric* is not such a fixed structure). This feature has tended to separate out the various approaches into two camps: those who feel that background independence is a necessary component of quantum gravity, to be preserved at all cost, and those that don't mind using background dependence to get an approach off the ground (generally, but not always in the hope of one day demonstrating that their approach is, at bottom, background independent too). Those who adopt the former position tend to have academic histories in general relativity, while those who adopt the latter position tend to be part of the particle physics community.

General relativity is in conflict with quantum theory as standardly understood, then, because the former is a theory in which the geometry of spacetime is a dynamical variable, a physical degree of freedom. We are solving for the structure of spacetime when we solve general relativity's field equations. However, it is very much a classical dynamics: spacetime geometry does not fluctuate in general relativity, and its evolution and properties are quite definite (up to diffeomorphism symmetry). Quantum theory apparently demands a classical spacetime geometry too, but it also *prima facie* demands a *fixed* geometry, one that does not vary from solution to solution depending on how the matter-energy content of the universe looks. Hence, we appear to have very divergent treatments of spacetime in these two frameworks: in the former case we have to solve equations of motion to get the geometry of spacetime out; in the latter case we do not. How one deals with this problem determines the path one follows in resolving the problem of quantum gravity. One can reject the background dependence of quantum theory or modify quantum theory in some way and try to quantize the geometry—the idea here is that the metric representing geometry and gravity is a dynamical variable and since one would like a quantum dynamics of gravity one also gets a quantum dynamics of geometry. Alternatively, one can overrule the dynamical nature of geometry, and follow the path of standard quantum theory in retaining a fixed geometrical structure. There are various 'intermediate' paths and paths leading 'off the beaten track' too, as we will see in §6.

3.6.2 The Problem of Time.

A particularly troublesome incompatibility, certainly one that has received most attention from philosophers, is 'the problem of time'. This is a consequence of background independence and will be an issue for any theory of quantum gravity (or, indeed, any classical theory) that seeks to retain background independence. Time is a fixed 'external' parameter in standard quantum theory, a structure against which dynamics unfolds but that is not itself determined dynamically. In quantum mechanics time appears in the fundamental dynamical equation (the Schrödinger equation) as Newtonian absolute time:

$$H|\psi, t\rangle = i\hbar\frac{\partial}{\partial t}|\psi, t\rangle \tag{1}$$

This t is insensitive to the nature of ψ and is not converted into an operator in the quantum theory: it remains a classical parameter and is not the eigenvalue of some operator.[33] This property of time in quantum theory is considered to be vital in setting up the fundamental formal sectors of the theory: inner-product, basic variables, conservation of probabilities (in time!), and so on. Similar remarks can be made about the special relativistic quantum theory, in which there exist preferred foliations of successive events in the form of Lorentz frames. Not so in general relativity where the spacetime geometry will be determined by the state of matter.[34]

3.6.3 Formal Compatibility Issues

There are a number of apparent formal incompatibilities between general relativity and quantum mechanics. Here I simply present several of these without going into details: many will be developed further in subsequent sections.

- It seems we would lose unitarity in quantum gravity: in quantum mechanics probabilities have to add up to unity *at a fixed time* (or a fixed time in a preferred slicing). This is meaningless in general relativity since there are no preferred foliations.

- Time evolution is determined by a hamiltonian operator in quantum theories. In general relativity (for compact universes) the hamiltonian is a sum of constraints. In the quantized version of this theory the hamiltonian operator is identically zero on physical states (i.e. it annihilates them).

- Causality (or rather, microcausality) is axiomatic in quantum field theory: spacelike separated bosonic fields must commute, and spacelike separated fermionic fields must anti-commute. However, in general relativity causality is determined by the matter distribution. In quantum gravity it is reasonable to expect that the light cones will fluctuate, but then so will the causal structure!

- QFT is a local theory: the observables are spacetime local (with support in spacetime *regions*). General relativity is diffeomorphism invariant, so the observables of a general relativistic theory will have to be non-local.

[33] An argument due to Pauli [1926] (known as "Pauli's theorem") demonstrates that time cannot be an operator because it's conjugate, energy (the Hamiltonian operator), is bounded below, whereas time is not. What we would need to have a time operator is for the Hamiltonian operator to have a continuous spectrum spanning the whole of the real number line.

[34] Rather oddly, Curiel maintains that "there is no manifest contradiction between the two theories themselves" ([Curiel, 2001], p. S431). I submit that this is as clear an example of a contradiction as one could ever wish for!

- General relativity requires nonlinear equations, whereas quantum theory is a linear theory. This nonlinearity is at the root of the divergences that are faced when perturbative quantization methods are applied to general relativity. This clearly is not unique to general relativity, however; any theory with interactions will be a nonlinear theory.

There is a further intuitive formal compatibility issue concerning the 'quantumness' of quantum theory and the 'classicalness' of general relativity. There are arguments suggesting that a classical field coupled to a quantized source will violate the uncertainty principle, since one will be able to use the classical field to determine with a precision greater than that allowed by the uncertainty relations the simultaneous position and momentum of a particle. Furthermore, if we adopt a collapse interpretation of quantum theory, so that the classical field's measurement sends the particle's state from a superposition into a definite state, then the principle of conservation of momentum is violated. If we adopt a no-collapse interpretation, then it becomes possible to exploit the coupling to transmit superluminal signals. Empirical inadequacies result if we adopt the Everett-DeWitt Many Worlds interpretation. Given a superposition of position states of some massive object, the coupling ought (formally) to lead, after a measurement, to a state in which the field is sensitive to the average of the uncollapsed superposition of position states of the matter; but we really would observe that the field is sensitive to the apparently collapsed state (i.e. one of the other 'branch'). We return to these issues in §6.1.

3.7 Gravity and the Measurement Problem

Roger Penrose believes that the measurement problem of quantum mechanics provides the deepest and clearest reason to seek a quantum theory of gravity. In his most recent book this problem trumps the compatibility issues and, indeed, all of the issues just mentioned (see [Penrose, 1999], p. 581). To see Penrose's perspective, we simply note that linear, unitary evolution does not provide a good description of the macroworld: we do not, it seems, observe macroscopic superpositions—although one might legitimately question the coherence of this statement. What about 'no-collapse' interpretations, such as the Many-Worlds interpretation? Even in this case, as Penrose points out, 'rules of experience' are needed to make sense of the relationship between unitary reality and the (illusory) definiteness of our observations. If we adopt a collapse interpretation, so that unitarity is supplemented ('in the large'), then we need to know what this supplementary factor is.

Penrose's answer is that the unitarity of quantum theory has to be modified precisely when gravitational effects become important (see [Penrose, 1996])—that is, quantum theory turns into a non-linear theory at the Planck length.[35] Gravity is the supplementary factor. As Penrose puts it himself: "the phenomenon of quantum state reduction is a *gravitational* phenomenon ([Penrose and Marcer, 1998], p. 1932). Specifically, when a body is in a quantum superposition of locations the state becomes very

[35]Penrose is not alone in thinking that quantum theory is modified by gravitational effects. For similar proposals, see: [Károlyházy, 1966; Károlyházy et al., 1986; Diósi, 1989; Ghirardi et al., 1990]. A good review of the general idea is [7].

unstable, becoming more unstable as the mass increases. The system then collapses into some one or the other state in the superposition with a time proportional to the gravitational self-energy of the difference between the superposed field configurations (i.e. the different mass distributions). Hence, there is an objective reduction that is at odds with unitary quantum evolution—Penrose has proposed an experiment to verify the predictions of his approach (see [Penrose and Marcer, 1998], §6). We have yet to see the results of this experiment. If it confirms Penrose's prediction then this would constitute another feature that any worthy approach to quantum gravity ought to be able to account for. Note that since decoherence effects will be present in the kind of experimental situation Penrose describes, these will have to be separated out from the collapse process.

3.8 For Knowledge's Sake

Ashtekar and Geroch write that "a quantum theory of gravitation would represent an extension of our conceptual framework for the description of nature" and that "any such extension would be of interest in itself" ([9], p. 1213). Natural curiosity certainly plays a large rôle in the quest for quantum gravity. The problem of quantum gravity certainly has something of the character of a jigsaw puzzle (of extreme complexity). Such a puzzle taxes the imagination, keying in to those aspects of physics that are absolutely fundamental to our worldview. We strongly suspect that quantum gravity will profoundly alter the way we think about the world, about space, time, matter, and causality. This is taken as a given amongst virtually all approaches to the problem. It is a worthwhile quest precisely because of the dramatic advance in understanding that it will precipitate.

Conclusion

There are, then, several reasons (not entirely watertight) that together conspire to suggest that a quantum theory of gravity is a theoretical compulsion, if not an experimentally provoked necessity. What is curious about them is that they cropped up at different periods of research. As we see in the next section, what drove the search *initially* was an intuition that quantum matter would 'no doubt' *have* to modify the gravitational field in some way, just as the gravitational field would *have* to modify the behaviour of quantum matter in some way. Heisenberg's dimensional considerations quickly tell one that this modification will not be observable at any energies within our capabilities; hence, matters were largely shelved for many decades. When quantum gravity was finally studied in a systematic way, it was undertaken to a considerable degree on the basis of analogies with other fields. Inferences were made (not always soundly) on the basis of these analogies to physics of the Planck scale. Later work revealed the inadequacies in this analogical reasoning. We trace this development, albeit very briefly, in the next section.[36]

[36]I should point out, before closing this section, that James Mattingly has recently argued—convincingly I think—that the case for *quantizing* the gravitational "has yet to be articulated" ([Mattingly, 2006b], p. 328). This is a distinct question from that posed here; namely, why bother with quantum gravity (whether that involves an actual quantizing of the gravitational field or not—that is, there might be some alternative

4 A Potted History of Quantum Gravity

In order to get a grip on quantum gravity as a research field as a whole it is important to appreciate its historical trajectory, from its genesis to the present day. There is still very little that has been written on the historical aspects of quantum gravity;[37] this is somewhat surprising given that it has been with us in some form or another just as long as quantum field theory: such a study would make a fine research project—I would urge historians of physics to take up this challenge sooner rather than later, since many of the physicists who were involved in the early episodes are unfortunately fast departing! To further this end we present a potted history of the highlights of quantum gravity. This brief excursus, interesting in itself, will give us a better handle on the methods to be discussed in §6, for we can see how these methods fit into the overall scheme and how they are interrelated. (I should remark that many of the early papers on quantum gravity, especially the early reviews, are the easiest way to get to grips with the field: as a field progresses, certain results come to be taken for granted and the steps leading to them are leaped over. Unfortunately, such steps are often those that give one *physical* insight into the nature of the problem.[38])

4.1 The Early History of Quantum Gravity

The foundations for general relativity were finally in place by 1915; those of quantum mechanics by 1926; and those of quantum field theory by 1927 (naturally, these dates are fairly arbitrary and refer to the publication of key ideas rather than their creation—see [Cao, 2004; Mehra, 2000; Schweber, 1994; Janssen et al., 2006] for good historical studies of this work). The earliest attempts to bring these theoretical frameworks together involved the same methods as had and would be used for the other fundamental interactions.[39] As Abhay Ashtekar puts it, the methodology was "to do unto gravity as one would do unto any other physical field" ([Ashtekar, 1991], p. 2). As is becoming clear after decades of intense effort, gravity is *not* like any other force, at least not in terms of its formal representation, nor, many believe, in terms of how it is (or ought to be) conceptualized.

method that does not get to the quantum theory by quantizing a classical theory). Again, we discuss these matters in §6.1.

[37]Notable exceptions are: [Stachel, 1999; Gorelik, 1992; Rovelli, 2002]. I lean heavily on the latter in what follows. [DeWitt, 1967c] also offers an excellent historical insight into the early days of quantum gravity.

[38]Unfortunately for English-only readers like me, many of the early papers are written in German, French, and Russian: it would make another excellent project to translate these papers and provide a commentary and contextual framework for them (to enable the poor 'mono-linguists' like myself access too!).

[39]Almost as soon as general relativity was completed, Einstein was aware of a possible conflict between it and the principles of quantum theory, and the need for a quantum theory of gravity. He writes: "because of the intra-atomic movement of electrons, the atom must radiate not only electromagnetic but also gravitational energy, if only in minute amounts. Since, in reality, this cannot be the case in nature, then it appears that the quantum theory must modify not only Maxwell's electrodynamics but also the new theory of gravitation" ([Einstein, 1916a], p. 696). Gorelik ([1992], p. 365) argues that an "analogy with electrodynamics" lay behind Einstein's comment, since a calculation of the collapse time under the (miniscule amount of) gravitational radiation gives 10^{37}, which is too long to be inconsistent with the empirical evidence. This analogy was a persistent feature of early research on quantum gravity—see below).

Einstein's early remarks seem to have inspired no further research efforts at all, neither by himself nor others. However, similar claims were made intermittently over the next decade or so, but nothing amounting to a serious attempt to construct a full-blown quantum theory of gravity was undertaken. It was generally assumed that there would be no *special* difficulty in quantizing the gravitational field as opposed to the electromagnetic field. Interest was, curiously, restricted to the latter field, general relativity being largely ignored by theoretical physicists at the time—perhaps because of electromagnetism's greater simplicity or because the subatomic structure of matter was deemed more interesting and fruitful (and, presumably, more accessible). For example, we find Heisenberg and Pauli explicitly voicing this position[40]:

> One should mention that the quantization of the gravitational field which appears necessary for physical reasons [presumably Einstein's—DR], may be carried out without any new difficulties by using a formalism wholly analogous to that applied here. ([Heisenberg and Pauli, 1929], p. 3)

This attitude—which involves using weak gravitational fields, so that geometrical aspects can be ignored—persisted for many decades, and was responsible for the first serious 'split' between the approaches in the fifties: dividing particle physicists and general relativists. The approach suggested involves the downplaying of the geometrical features of gravity and the fact that the metric, rather than a field with respect to the flat metric, is dynamical. When general relativity became more widespread and the general relativists began to turn their attentions to the quantum problem, they were horrified at this degradation of Einstein's theory. This same pair of attitudes persists to the present day in the battle between string theory and loop quantum gravity. This split underwrites a substantial difference in the importance the researchers from the two camps place on conceptual issues: general relativists often have a preoccupation with issues of the nature of space, time, matter, causality, and so on, whereas the particle physicists tend to give such issues very little credence (if any)—see [Rickles, 2005a; 2006; 2007; 2005b; Rickles and French, 2006] for a discussion of these matters.[41]

The challenge finally began to be taken up seriously in the 1930s, though the 'electromagnetism-gravity' analogy persisted for some time longer.[42] Here we find the

[40]In this paper, we also find for the first time the idea that gravity corresponds to a massless, spin-2 field, so that the particle carrying the force would be massless and spin-2 (note that the presence of spin-2 particles implies that a theory containing them would, *ceteris paribus*, be generally covariant)—see also [Fierz, 1939; Fierz and Pauli, 1939] (especially §6 from the latter). This particle was coined 'graviton' by Blokhintsev and Gal'perin [Blokhintsev and Gal'perin, 1934]. This fact underlies string theory's claim to be a quantum theory of gravity: the spectrum of the (closed) string contains an oscillatory mode that when quantized corresponds to just such a particle.

[41]Those working on so-called 'canonical quantization' methods have contributed to many philosophers' workshops and conferences, and can be found contributing chapters to books (for example, essays by two prominent figures from the canonical camp can be found in [Rickles et al., 2006]).

[42]Formal analogies between general relativity and Maxwell's theory misled researchers for many years. Bryce DeWitt notes that at the time of the earliest attempts to quantize gravity quantum field theory's "umbilical cord to electrodynamics had not yet been cut" ([DeWitt, 1970], p. 182). However, the formulation of Maxwell's theory, championed by Mandelstam, using path-dependent variables (holonomies) was very productive, leading the way to loop gravity—see [Mandelstam, 1962], p. 353 and also [Gambini and Pullin, 1996].

term 'gravitational quanta' being used for the first time, by Léon Rosenfeld [Rosenfeld, 1930]. We find a large-scale, trail-blazing approach by a relatively unknown Russian, Matvey Petrovich Bronstein—see [Gorelik, 1992; 2005]. From then on, there is a progressive expansion of work on the problem of quantum gravity. The major lines of attack are developed, and an enormous amount of work is devoted to pushing the approaches to completion. This continues until the beginning of the 70s, where it becomes clear that there are severe consistency problems in all the main approaches. In particular, the main dynamical equation for the 'canonical' approach is eventually viewed to be ill-defined and, almost fatally for the 'covariant' approach, results begin to accumulate concerning the perturbative non-renormalizability of general relativity. In the late 80s these issues are finally resolved. A dramatic shift involving the use of spatially extended fundamental objects ('strings') cures the regularization issue in the covariant approach, and a shift to new variables cures the ill-definedness (and absence of solutions) in the canonical approach—there are, of course, still various formal problems facing both approaches, but not nearly so severe.

4.2 Developing the Research Avenues

From the early efforts of Rosenfeld, Dirac, Bergmann, Wheeler, Schwinger, DeWitt, Gupta, Mandelstam, Feynman, Misner, and others, came three distinct methodologies that are, more or less, still in operation in the varied approaches around today—there are points of intersection between these methodologies, as we will see.[43] These are (with a historical breakdown of key events—here I borrow heavily from [Rovelli, 2002]):[44]

- **Covariant**: construct quantum gravity as a theory of the fluctuations of the metric field over a flat (non-dynamical) spacetime. In other words, split the metric into a background part and small perturbations and quantize only the latter, leaving the former classical and non-dynamical—this, roughly, is known as the *method of the background field*. In this way, one splits apart the dual rôle the metric plays in general relativity.
  - **Initiated:** first attempt to bring gravitation into the realm of particle physics and quantum field theory using linearized gravitational field equations (with non-linear terms 'patched in' at a later stage)—[Rosenfeld, 1930; Fierz, 1939; Fierz and Pauli, 1939; Gupta, 1952b; 1952a; Kraichnan, 1955; Thirring, 1961; Mandelstam, 1962]
  - **Feynman rules:** covariant quantum gravity formulated using Feynman diagrams giving the contributions of each diagram to the overall amplitude (which is simply the sum of amplitudes contributed by the topologically

[43]Naturally, one can find other ways to divide the approaches (particle physics versus general relativity; background dependent versus background independent, etc.), but the taxonomy given here fits the standard practice of physicists. One finds it repeated in most general review papers on the subject.

[44]Naturally, this is heavily truncated, and many important players and events have been omitted in the interests of brevity. Important omissions are Misner's instigation of 'Quantum Cosmology' [Misner, 1969] (using mini-superspace models) and Hawking's discovery that black holes radiate at a thermal spectrum [Hawking, 1975]. We have treated these topics, albeit briefly, elsewhere in this primer.

distinct diagrams); given this one can then go about computing the probability for the process concerned by squaring the absolute value of the total amplitude—[Feynman, 1963; DeWitt, 1965; 1967a; 1967b; Faddeev and Popov, 1967; Mandelstam, 1968]

  – **Non-renormalizability:** on the basis of work on the Feynman rules, covariant perturbative quantum gravity was found to have ineradicable UV divergences—[Deser, 1957; t'Hooft, 1971; t'Hooft and Veltman, 1972; Deser and van Nieuwenhuizen, 1974]

  – **Higher-derivative/supergravity/strings[45]:** these approaches all emerged in a bid to evade the divergence problems while remaining firmly wedded to the covariant quantization methodology—[van Nieuwenhuizen, 1981; Green and Schwartz, 1984; Witten, 1995]

- **Canonical ('Hamiltonian')**: construct quantum gravity as a theory of the fluctuations of the metric as a whole, so no fixed metric is involved—however, spacetime is split into space and time, with a fixed topological structure. The metric information is represented, in full, by operators on a Hilbert space. One aims to find the eigenvalues of the operators along with their transition probabilities.

  – **Initiated:** The basic ideas of a canonical approach to general relativity are formulated and potential problems vis-á-vis quantization discussed (leading to incredibly detailed investigation of the phase space structure of general relativity)—[Bergmann, 1949a; 1949b; Dirac, 1950; 1951; 1958b; Peres, 1962; 1968; Bergmann and Komar, 1972][46]

  – **New variables I:** Arnowitt, Deser, and Misner put general relativity into a form fit for running through the basic quantization steps[47]—[8]

  – **Dynamical equations:** explicit formulations of the constraints (the basic dynamical equations of Hamiltonian general relativity) of general relativity are found—[DeWitt, 1967c; Wheeler, 1968]

  – **New variables II ('spin-connection'):** geometrical information is now contained in connections (or more accurately, fluxes)—[Sen, 1982; 10]

  – **Loop representation:** Jacobson and Smolin find a class of exact solutions to the Wheeler-DeWitt equation based on Wilson loops. Rovelli joins the

[45]The shift to string theory has a curious history. The crucial first step is generally agreed to have been taken by Gabriele Veneziano [1968]. His contribution concerned the connection of the data coming from experimental investigations into hadrons with Euler's Beta function. This was purely descriptive or 'phenomenological'; no mechanism was postulated for why the function might be applicable in this context. The explanation came from three independent sources: Nambu [1970], Nielson [1970], and Susskind [1970], who each realized that the function could be seen to make sense if the strong forces were understood as oscillating strings. We return to this history, and some finer details of the other approaches, in §6.

[46]Donald Salisbury [2007] argues that Rosenfeld was really the creator of the constrained Hamiltonian formalism (the formal core of canonical quantization approaches), and missed out on writing down the Hamiltonian for general relativity by dint of not choosing one of his tetrad fields to be normal to the foliation of spacetime he gave.

[47]Note that this approach makes use of asymptotically flat spacetime, and hence introduces background structure at infinity.

partnership, eventually producing, along with the help of many others, a viable contender to string theory using the Wilson loops as the fundamental variables[48]—[Jacobson and Smolin, 1988; Rovelli and Smolin, 1988]

- **Feynman Quantization**: a close cousin of the covariant approach involving the construction of quantum gravity as a theory involving Feynman's functional-integral (path-integral; sum over histories) quantization techniques applied to the metrics of general relativity—hence, the focus is on entire spacetime histories. In this case, the amplitude to go from one metric state h at t_0 to another h' at t_1 is given by the integral over all possible field configurations that coincide with the specified metric states at t_0 and t_1 (the boundaries): $\langle h', t_1 | h, t_0 \rangle = \int \mathcal{D}[g] \exp(iS[g])$ (where $\mathcal{D}[g]$ is a measure on the space of all 4-geometries and $S[g]$ is the action for general relativity).
  - **Initiated:** Misner formulates the basic structure of the approach, involving a specification of the weights of the paths (= spacetime geometries) in the Feynman integral, an operator form of the field equations, and a "partial evaluation of the Feynman propagator", recovering from this the canonical result that the Hamiltonian operator is zero—[Misner, 1957]
  - **Euclidean 'Sum-Over-Histories' approach:** Misner's early approach was picked up by Hawking, who 'Wick rotated' to imaginary time it (thus summing over Riemannian/Euclidean metrics only) to simplify the path integral and overcome some consistency problems in the original approach, such as the lack of a rigorous measure on the space of geometries. By dealing with single boundary and triple boundary situations Hawking (and Hartle) were able to describe universe creation *ex nihilo* and the birth of 'baby universes'—[Hawking, 1978; 1979]
  - **Discretization:** represent quantum gravity as a theory of dynamical triangulations so that the path integral can be computed in a combinatorial fashion, by counting the geometries; continuum aspects emerge in an appropriate limit—[3; 4][49]
  - **Spin-Foam Models:** covariant, discrete, path-integral representation of the constraints of loop quantum gravity (in many ways this approach can be viewed as a synthesis of the three methodologies—[Barrett and Crane, 1998; Baez, 1998; Oriti, 2005]

In addition to these main lines of attack, there are several 'external' approaches that do not readily fit into the categories laid out (this is just a very small sample):

[48] Following this work, there was a considerable amount of technical work still to be done to make the theory rigorous: e.g. regularization, defining the inner-product structure, and so on. Many of the formal troubles with the loop representation were resolved by shifting to a basis of spin-networks—[Rovelli and Smolin, 1995]. See Rovelli's entry on "Loop Quantum Gravity" in the *Library of Living Reviews* for a more detailed breakdown of key events: http://relativity.livingreviews.org/Articles/lrr-1998-1.

[49] A very good general review of discrete approaches to quantum gravity, including many not mentioned here, is [Loll, 1998].

- **External**: Twistors [Penrose, 1967], Non-Commutative Geometry [Snyder, 1947; Connes, 1994], Regge Calculus [Regge, 1961]; Causal Sets [Sorkin, 1983; Henson, forthcoming]; Topological Quantum Field Theory [Witten, 1988]; Generalized Quantum Mechanics [Hartle, 1995]; Group Field Theory [Oriti, 2006]; Causaloids [Hardy, 2007].[50]

However, these are generally not intended to function as whole-sale quantum gravity theories, but as 'ingredients' of some genuine theory of quantum gravity—for the most part, they do not involve the quantization of general relativity. Their importance should not be downplayed though; it is through the inspiration from these alternatives that many of the ideas of the main approaches were derived.[51] They also frequently forge new connections between mathematics and physics (such as the link to knot theory which is now a central component of several approaches—see [Baez and Munian, 1994]).

Conclusion

What is interesting to note about this brief depiction of the approaches, is that during the first forty or so years, there are researchers who straddle the various research methodologies.[52] Twenty years later this is virtually unheard of, with just one or two exceptions. This is one of those aspects that is of sociological as well as historical interest. However, it should be clear that though current researchers tend to divide themselves fairly rigidly according to the categories mentioned here, the methodological divides are no such thing: there are many points of contact between the various approaches, and there is, as has happened many times in the past, and as Lee Smolin argues in his *Three Roads to Quantum Gravity* [2002], the very strong possibility for convergence between approaches.

5 The Ingredients of Quantum Gravity

As we have seen, to make a quantum theory of gravity we need to take into account both quantum theory and general relativity. These are the *ingredients* of quantum gravity.[53] At present they ignore each other: general relativity deals only with the interactions of

[50] An interesting collection of 'iconoclastic' approaches can be found in the *International Journal of Theoretical Physics*, Vol. 45, No. 8, 2006.

[51] For example, the concept of a 'spin network' used to label the (kinematical) states in loop quantum gravity is a direct descendent of Roger Penrose's early attempt to construct a combinatorial notion of quantum space in his 'Theory of Quantized Directions' [Penrose, 1971], which morphed into his 'twistor theory' programme [Penrose, 1979]. The concept was then 'covariantized' in the 'spin foam model' approach, which seeks to describe the evolution of spin network states. Twistor theory itself has recently merged with string theory, giving birth to 'Twistor string theory' [Witten, 2004] (see also: $\mathrm{http : //gallery.math.ucdavis.edu/albums/mathphyscon/16_0 4_E dward_W itten.mp4}$)—hence, this version of string theory and loop quantum gravity have a close direct descendent!

[52] For example, Dirac did work on the field theory of extended objects (what would nowadays be called '2-branes') and early work on the Hamiltonian formulation of general relativity that forms the bedrock of loop quantum gravity. He also laid the formal foundations for the path-integral approach ready for Feynman to develop it into a self-contained approach—see §32 of [Dirac, 1958a].

[53] I borrow the term 'ingredients' from [Butterfield and Isham, 2001].

classical things and quantum field theory deals only with non-gravitational interactions. The different approaches can be viewed as different 'recipes', some using more of one of these ingredients than the other, some adding different ingredients to the mixture: extra dimensions, supersymmetry, complexification, discreteness, etc. Some, as we have already seen with Penrose's ideas, think that entirely different ingredients may be required to get a truly fundamental theory with general relativity and quantum field theory as limits.

Since David Wallace has already given us an excellent account of quantum theory and quantum field theory (see, e.g., §**??**), we do not need to spend too much time going over the details again. Instead, we focus on extracting just those details that are relevant. We look at general relativity, quantum theory (in general) and quantum field theory. We will also briefly need to say something about the process of *quantizing* a classical system to get a corresponding quantum system. Again, our task here is made easier thanks to Roman Frigg's excellent account of classical mechanics in the Appendix to his chapter.

5.1 General Relativity

General relativity is primarily a theory describing the classical gravitational field. Let's begin by giving a nutshell definition of general relativity:

- The gravitational field is the metric field, and affects all other fields and objects. It is itself affected by mass-energy. General relativity is the theory of this field.

In other words, the gravitational field supplies structures generally associated with spacetime: spacelike and timelike separation, causal structure, etc. The reason for this dual function is that the metric field is taken to represent gravitational field structures and spacetime structures. We are led here by the equivalence principle which tells us that gravitational mass and inertial mass are the same. This thought prompts the idea that objects that fall freely in a uniform gravitational field are following geodesics in curved spacetime. By adding the local equivalence to Minkowski spacetime (i.e. in small neighbourhoods of the points of the manifold) and adding the condition that the spacetime should satisfy a set of field equations relating curvature to matter-energy sources we get Einstein's theory—naturally, this is drastically simplified!

A simple inspection of Einstein's field equations of general relativity already points towards the need, or at least the consideration of a quantum theory of gravity, in some form of other. The simplest way to present general relativity in a short space is using models.[54] General relativity has models of the form $\mathsf{M} = \langle \mathcal{M}, g, T \rangle$. To be models of general relativity the two tensor fields g and T must satisfy the Einstein field equation at every point of the manifold $\mathcal{M}$:

[54] For more extended coverage, investigate the following books (organized according to difficulty: hardest first): [Wald, 1984], [Misner et al., 1973], [Carroll, 2003], [Schutz, 2003]. Another very interesting and highly original presentation of general relativity (though very hard to come by) is [Kopczyńscki and Trautman, 1992]—this book contains the most elementary and condensed treatment of advanced topics from general relativity that I have seen; it also have numerous useful 'conceptual asides'. The general mathematical background required for studying general relativity (differential geometry, topology, etc.) can be found in the *Les Houches, Relativity, Groups, and Topology* lectures [DeWitt, 1964; Stora and DeWitt, 1986]. Alternatively, a simpler genera relativity 'toolkit' is [Poisson, 2004].

$$G_{\mu\nu} \equiv R_{\mu\nu}[g] - \frac{g_{\mu\nu}R[g]}{2} + \Lambda g_{\mu\nu} = -8\pi G_N T_{\mu\nu}[\Phi] \tag{2}$$

$G_{\mu\nu}$ is the Einstein tensor describing the curvature of spacetime, and $T_{\mu\nu}$ is the stress-energy tensor describing (the stress-energy-momenta of) various possible sources Φ of the gravitational field, such as particles, fields, dusts, strings, branes, etc.[55] The term $-8\pi G_N$ (sometimes written κ) is the coupling constant, proportional to Newton's universal constant of gravitation, determining the strength of gravitational interactions (in the sense that when $\kappa = 0$ there are zero interactions). The problematic term that involves quantum theory is, of course, the stress-energy tensor of matter. Our best theories of matter are quantum theories, which, prima facie, implies that $T_{\mu\nu}$ should best be represented by a quantum operator, a q-number rather than a c-number. If this is the case, and the success of the standard model of particle physics suggests that it is, or at least a good approximation (certainly better than classical physics!), then we have to face the issue of the coupling between the geometry of spacetime and this quantized matter source—however, we are getting ahead of ourselves here. In vacuum general relativity (i.e. when $T_{\mu\nu} = 0$) the equation is simply $R_{\mu\nu} = 0$. Those distributions of the tensor fields over the manifold that satisfy this equation of motion correspond to the *dynamically possible* histories; those distributions that are possible in a merely 'formal' sense are *kinematically possible* trajectories. Only the former represent physical possibilities.[56]

The standard assumption (made to fit what we observe) is that spacetime $\mathfrak{S} = \langle \mathcal{M}, g \rangle$ is represented by a real, four-dimensional connected, C^∞ Hausdorff manifold $\mathcal{M}$ on which is defined a tensor field g of Lorentzian signature. The metric $g_{\mu\nu}$ is a sixteen component symmetric tensor, which means that Einstein's equation has ten independent components.[57] In a manifestly covariant formulation, these are unified. However, if we follow the canonical procedure of splitting spacetime into space and time then only six of these ten components drive the metric, telling us how it evolves in time. Four of the components (or equations) are *constraints* that the metric on a spatial slice, and its first derivative, have to satisfy at any and all times.

An alternative formulation involves looking at the Einstein-Hilbert action functional for general relativity (this is the action that would be used to weight the paths in the Feynman quantization approach mentioned in the previous section):

$$S[g] = \frac{1}{16\pi G_N} \int d^4x - \sqrt{\det g}\, R \;\; (+ \text{ surface terms}) \tag{3}$$

[55]Note that Einstein was dissatisfied with the 'phenomenological' nature of his field equation. He compared it to "a building, one wing of which is made of fine marble (left part of the equation), but the other wing of which is built of low grade wood (right side of equation). The phenomenological representation of matter is, in fact, only a crude substitute for a representation which would correspond to all known properties of matter" ([Einstein, 1956], p. 83).

[56]As John Wheeler helpfully puts it, "[k]inematics describes conceivable motions without asking whether they are allowed or forbidden. Dynamics analyses the difference between a physically reasonable and a disallowed history" ([Wheeler, 1964b], p. 65).

[57]The tensorial nature of the metric means that the values of these components depend on a particular coordinate system. However, regardless of the coordinate system used, the lengths of worldlines in spacetime are assigned the same value—that is, the length between a pair of spacetime points is an *invariant* quantity.

This action is invariant under the symmetry group of general relativity, namely the group of four-dimensional diffeomorphisms of the spacetime manifold. This gives us an alternative way of understanding the constraints: the basic idea is that the dynamical equations we get from this action contain 'surplus', unphysical structure—i.e. not all of the degrees of freedom are physical. Instead, there are variables that are deemed physically equivalent if they are connected by an element of the invariance group (i.e. by a 4-diffeomorphism). In this case the transformation is called a *gauge transformation*, and in the present case we would have two (gauge-equivalent) metrics that describe one and the same spacetime geometry.

There are then, as with most theories, multiple ways to formulate general relativity. What these have in common is, in some sense (and with very varying degrees of explicitness), the idea that the gravitational field dynamics are given by the dynamics of the geometry of space or the spacetime geometry. A full spacetime, equipped with a gravitational field, is a bunch of spatial geometries stacked up in a certain way. Note the emphasis on the 3-geometry rather than the 3-metric here: the 3-metric represents a 3-geometry, but the relation between metrics and geometries is many-to-one: a geometry is an equivalence class of metrics with elements related by a diffeomorphism. Now, if Riem(Σ) is the space of Riemannian 3-metrics on a spatial hypersurface then we can get the space of 3-geometries ('superspace' $\mathcal{S}(\Sigma)$) by 'quotienting out' the group of diffeomorphisms of Σ, i.e. Diff(Σ):

$$\mathcal{S}(\Sigma) = \frac{\mathrm{Riem}(\Sigma)}{\mathrm{Diff}(\Sigma)}. \tag{4}$$

There are many interesting and intricate mathematical features of superspace; for example, although the space of Riemannian metrics on a manifold is a manifold, superspace is not (it possesses 'kinks'), as was proved by Fischer [1970]. However, one can set up dynamics in superspace. What one needs is a way of 'drawing' a curve connecting distinct points of superspace (each representing an instantaneous space) so as to generate a spacetime. This is performed by a Hamilton-Jacobi equation. This is the starting point for canonical quantization along geometrodynamical lines: the quantum dynamical equation is the notorious Wheeler-DeWitt equation.

There are also many interesting technical differences between general relativity and pre-general relativistic theories. Notably, the invariance group of general relativity, being the diffeomorphism group of the manifold, is not a finite-dimensional Lie group. This feature has been used to underwrite the 'specialness' of general relativity, namely its background independence.[58] Much is made in the context of quantum gravity of the background independence of general relativity, and the imposition of background independence as a requirement of a theory of quantum gravity. As Unruh points out:[59]

> In all other quantized theories, one can assume that the space-time manifold structure can be defined by some matter which does not interact with the field of interest. It is precisely the universality of gravity which

[58]Note, however, that some physicists do not see this as a good thing. Vladimir Fock [1976], for example, proposed a 'bi-metric' theory in which a secondary metric is included in the theory as a background structure.

[59]See [Weinstein, 2001] for a similar perspective of the nature of the background independence of general relativity and the problems it poses for quantum theory.

prevents us from doing this for the gravitational field. ([Unruh, 1984], p. 242)

We return to this subject in §7.2. For now it suffices to say that the geometry of spacetime is dynamical in general relativity; its value depends on the solution to the field equations. This is quite unlike anything encountered in any quantum theory to date where the geometry of space and time have their values fixed *ab initio*.

5.2 Quantum Field Theory

In this section we outline only the skeletal framework of quantum theory: we shall not be concerned with such things as entanglement and non-locality. The main aspect we wish to highlight here is the relationship between the structure of quantum theory and that of general relativity.[60] Let us begin with the quantization of a generic classical system.

The first step is to define a system with a certain number of degrees of freedom n. The dynamical variables $q_k (k = 1, ..., n)$ associated to these degrees of freedom then span a configuration space $\mathcal{Q}$. The dynamics of this system is given by the Euler-Lagrange equation, $\delta S = 0$ (where $S = \int_{t_1}^{t_2} dtL$), which is derived from the Lagrangian $L(q, \dot{q})$. A Legendre transformation gives one the coordinates $< q_k, p_k >$ (where $p_k \equiv \partial L / \partial \dot{q}_k$) of a phase space Γ. The Lagrangian may then be written in terms of canonical variables as $L = \Sigma p_k \dot{q}_k - H(q, p)$. In this case, the dynamics is given by the Hamiltonian $H(q, p)$, where the time-development of q and p are given by:

$$\dot{q}_k = \{q_k, H\} \equiv \partial H / \partial p_k$$

$$\dot{p}_k = \{p_k, H\} \equiv -\partial H / \partial q_k$$

For functions (i.e. observables) on the phase space, one computes their Poisson bracket as:

$$\{F, G\} := \Sigma \left(\frac{\partial F}{\partial q_k} \frac{\partial G}{\partial p_k} - \frac{\partial F}{\partial p_k} \frac{\partial G}{\partial q_k} \right)$$

The brackets for the 'fundamental' variables are $\{q_k, p_l\} = \delta_{kl}$ (where δ_{kl} is the Kronecker delta: 1 when $k = l$ and zero otherwise). Now, in order to *quantize* such a system, one applies the following set of rules, derived for the most part from the symplectic geometry of the phase space. Firstly, Poisson brackets become commutators: $[\hat{q}_k, \hat{p}_l] = i\hbar\delta_{kl}$—with $\hat{q}_k$ and $\hat{p}_l$ now understood as operators. Secondly, the state of the system is given by a complex function $\Psi(q)$ on the configuration space, whose properties make it a Hilbert space (i.e. a normed vector space with an inner product, standardly taken to be positive-definite to forbid negative energy values). The inner product structure makes the dynamical variables Hermitian operators on the state

[60] A more general treatment, with an eye to conceptual issues, is [Isham, 1995].

space. The dynamics (the time-translation operator) is given by the quantum Hamiltonian via the Schrödinger equation $\hat{H}\psi = i\hbar\partial\psi/\partial t$ or via Heisenberg's equation of motion (for some dynamical variable $\mathcal{O}$) $[\mathcal{O}, \hat{H}] = i\hbar\frac{d\mathcal{O}}{dt}$.

However, for general relativity (and many other systems) this simple series of steps is not possible. General relativity is a constrained theory, a gauge theory—as exemplified by its general covariance—and so the step from the Lagrangian to the phase space, and the Hamiltonian description does not go smoothly: the Hessian of the Lagrangian (namely the matrix $\partial^2 L/\partial\dot{q}_j\partial\dot{\mathrm{q}}_k$) is singular, and not all of the variables are physical—some are gauge degrees of freedom or 'surplus'.[61] The problem, then, is the presence of constraints on the variables. These come in two flavours in general relativity: there is the diffeomorphism constraint (three of them at each point of an initial spatial slice) which maps a $x^0 = c$ hypersurface to itself, and there is the Hamiltonian constraint which maps a $x^0 = x$ hypersurface onto other hypersurfaces—we do not need to view these hypersurfaces as existing in a pre-given block of spacetime; indeed, in the canonical (geometrodynamical) approach there is just a single 3-manifold to work with. These constraints taken together make up the full Hamiltonian of general relativity. Now, a natural choice of configuration space, given general covariance, is the space of 3-geometries (or 3-metrics modulo the diffeomorphism symmetry). Given this, any wavefunctions defined over this space will automatically satisfy the diffeomorphism constraint: $\Psi[^3g] = \Psi[\phi(^3g)]$ (where $\phi \in \mathrm{Diff}(\Sigma)$). The Hamiltonian constraint has proven much harder to satisfy, and indeed to define in a consistent manner.[62]

Let us briefly turn to the particle physicists understanding of interactions. The central idea of quantum field theory is that forces between particles are mediated by the exchange of field quanta. The type of force (what it acts on, what its sources are, and how it acts) is determined by the spins and masses of the particles. For example, Maxwell's (classical) theory of electrodynamics is the classical limit of the (relativistic) quantum theory of a massless spin-1 particle, the photon. In the case of the gravitational field we must select mass and spin on the basis of observed properties of gravitational interactions: long-range, static, attractive, macroscopic, etc. This leads one to postulate a massless spin-2 (self-interacting) particle: the graviton.[63] The Lorentz invariant theory of gravitons propagating on a flat background has general relativity as a low energy limit. In this sense the classical theory of general relativity is implied by a specially relativistic quantum particle theory. However, serious problems emerge when this scheme is extended into high frequency domains (where quantum field theory proper is required), as we sketched in §3.4. (But recall that sense can still be made

[61]This is a general problem for gauge theories. See [Henneaux and Teitelboim, 1992] for a thorough treatment of this aspect of gauge theories.

[62]This is, of course, just one way to understand quantization (namely, canonical quantization): as Wallace outlined in §**??**, there are many formulations of quantum field theory. We introduce the details of these other approaches when we discuss the various approaches to quantum gravity. (There is another approach to quantum field theory known as 'axiomatic quantum field theory' (also sometimes called 'general quantum field theory') since this approach is concerned more with conceptual clarity and formal precision than non-axiomatic approaches.There are many excellent texts on this approach to quantum field theory. My personal favourite is [Baez et al., 1992])—the book is out of print as of writing, but it can be obtained perfectly legally from John Baez's website: http://math.ucr.edu/home/baez/bsz.html.)

[63]For a detailed account, see [Deser, 1975b] (especially §2) or [Deser, 1975a]. Or, for the 'horse's mouth' arguments, see [Fierz and Pauli, 1939], [Feynman, 1995] and [Weinberg, 1964].

of the approach in terms of effective field theory: see below.)

General relativity is, of course, usually considered to be a *geometric* theory in the sense that gravitation is deemed a manifestation of curved spacetime as determined by its energy content—(test) particles will then follow geodesics within this curved spacetime. The key point to take from the particle physics approach is that spacetime is decidedly flat (or at least fixed in place independently of the processes occurring within it). Geometrical features of spacetime are not dynamical. In the case of gravity, understood as a quantum field theory, particles will always *really* be moving around in spacetime with a fixed metric; however, it will *appear* that they are following geodesics in curved spacetime because of the graviton exchange going on between them. This approach views gravity much as any other interaction according to which interactions between two (charged) objects is achieved through the exchange of field quanta.

There are severe mathematical problems facing quantum field theories (and indeed field theories in general) with interactions turned on (including self-interactions): given that the interactions are taken to happen at the same point of spacetime, one has to consider products of operators at one and the same point. There is a way around it: perturbation theory. One pretends that the complicated interactions are perturbations of a well-defined free (= without interactions) field theory. More technically, one expands the physical quantities of the theory as a Taylor series in the coupling constant—the latter determining the strength of the interaction concerned. This is where the famous divergences come from: when the various terms in the series are evaluated, they spew out infinities.[64] We don't measure infinite values! Hence, we have a problem. This was resolved, after a great deal of hard labour and not to everyone's satisfaction[65] by the mathematical magic of renormalization theory. Let us say some more about renormalization and its problems.[66]

Quantum field theory provides our present theoretical framework for describing the interaction of charged point particles with non-gravitational fields: the electromagnetic field, the weak field, and the strong field. The quantum field theories that describe these interactions are all *local* in the sense that the field interactions occur at individual points of spacetime. Making the interactions local allows for the peaceful coexistence of special relativity and quantum theory, thus preserving causality. However, as we saw in §3.4, this locality (involving the piling up of field interactions at the same spacetime point) leads to infinities in the theory: the locality leads to singularities which in turn lead to divergences. The renormalization programme led to a finite version of quantum field theory for electromagnetic interactions, known as renormalized QED. The path to this theory involves the introduction of a cutoff so that wavelengths (resp. energies) shorter (resp. higher) than the cutoff are ignored (thus rendering the divergent terms

[64]Note that we are talking about the individual terms of the power series diverging here, not the whole series when summed. Proving converge or divergence of the full perturbation series is a seriously hard task: string theory, and many quantum field theories defined in this way, have question marks over the nature of the full series.

[65]Dirac is a case in point here: [Dirac, 1951; 1987]. Feynman too was not convinced that the renormalization was the last word on the divergence problems: $\mathrm{http://nobelprize.org/nobel_prizes/physics/laureates/1965/feynman-lecture.html}$.

[66]Renormalization has received a fair amount of interest from philosophers: [Huggett and Weingard, 1995; 1996; Cao and Schweber, 1993; Teller, 1989]. For an exceptionally clear, elementary guide to renormalization, see John Baez's entry at: http://math.ucr.edu/home/baez/renormalization.html.

finite).[67] Depending on the cutoff chosen, we will get different values predicted for the various physical quantities. In order to get rid of this unwanted dependence, and get the theory predictively back on track, one performs a readjustment manoeuvre called renormalization as follows. The parameter-values of this modified theory are inserted from their experimentally observed 'dressed' values—dressed, that is, by the swarm of virtual particles that are produced in line with the time-energy uncertainty relations. However, the theory and the parameters at this stage are dependent on the cutoff scale, which is arbitrary, so we must take the continuum limit, letting it go to zero (or the momentum go to infinity). When we do this we get renormalized QED, with quantities that are independent of the cutoff.

To eradicate the divergences of QED one needs to perform renormalization of both charge and mass. Broadly speaking, if one needs to redefine only a finite number of parameters to absorb the infinities then the theory is renormalizable. Otherwise it is non-renormalizable. In the early days of quantum field theory non-renormalizability was considered to be the death-knell of a theory, implying at best its being non-fundamental and at worst its formal inconsistency. Later, renormalization *group* techniques led to a revision of this 'selection principle' interpretation of the significance of non-renormalizability. Instead, a more pragmatic interpretation was adopted according to which a theory is 'sensitive' to scale, so that as the energy is varied the theory may or may not cease to be useful. This domain dependent approach is known as the effective field theory: a theory will be effective only in a certain range. The reason that theories can be effective in a certain range is that they are 'insensitive' to what is going on at other scales (especially at higher energies) and so are rendered relatively free from 'interference'. It is perfectly possible that quantum gravity is an effective field theory in just this sense—i.e. not a theory of everything in the sense of §2.1. This is just how string theorists view perturbative string theory—see §6.3.

5.3 Conclusions

Given the various similarities between Maxwell's theory of the electromagnetic field and Einstein's theory of the gravitational field, one might expect to gain some limited insight into what quantum gravity has in store for us, by comparing it with the quantum version of Maxwell's theory. In the classical theory one deals with electric and magnetic fields, which are defined at each point of spacetime. On quantizing these fields we find that the fields must obey the uncertainty relations (thus forbidding simultaneous specification of their values).

However, this expectation, though apparently borne out by many approaches, is a little premature: there are features of general relativity that are simply not shared by Maxwell's theory, or indeed any other classical field theory. General relativity, as we have seen, does not involve a background metric manifold. This alone muddies the waters immensely, as far as simple extrapolations of the above kind are concerned. What

[67]This cutoff can be understood as slicing off frequencies of waves in the field that are higher than some chosen value, in the Lorentzian formalism. Alternatively, if we use the map $t \to it$ (= Wick rotation), which transforms Lorentzian spacetime into Euclidean spacetime, it can be understood as a distance cutoff which allows one to ignore any behaviour of the fields happening at scales shorter than the chosen cutoff, the distance D.

this background independence implies, amongst other things, is that one cannot simply localize the fields in the theory; one cannot define a simple expression for the energy; the propagation for the fields is more complicated; and, in the realm of the quantum, one cannot postulate the microcausality axiom, nor can one formulate a Schrödinger equation, for there is no external notion of space and time to ground these features (one has instead a constraint equation). These differences suggest that the whole conceptual structure of quantum gravity will be radically different from anything we have had experience of before. One might even legitimately question whether the theory need be a quantum theory at all.

6 The Manifold Methods of Quantum Gravity

Both strong contenders from the catalogue of methods presented in §4 (i.e. covariant and canonical) do violence to general relativity in some way: the covariant methods break the background-independence of the theory; canonical methods break the manifest spacetime covariance of the theory. Note also that string theory—belonging to the covariant methods, historically at least—is an all out modification of general relativity, in both the quantum and classical domains (cf. [Witten, 1989]). The idea is that it is a successor to general relativity, rather than a quantization of it. A central idea of string theory is that general relativity's being perturbatively nonrenormalizable simply rules it out as a consistent theory at the quantum level: one has to look elsewhere. Loop quantum gravity argues that the perturbative analysis contains fundamental flaws, involving the assumption of a fixed continuum spacetime to get things going. To an outsider, the battles between these two sides (covariant and canonical) may look rather strange. The current animosity—mainly, it has to be said, between string theory and loop gravity—is a fairly new development. In the past there have been suggestions to examine closely the relations (on both a formal and conceptual level) between the canonical and covariant approaches in order to bring them closer together—see e.g. [Hartle and Kuchař, 1984]. Hopefully this attitude will reemerge at some point.

We saw in our brief browse through the historical development of quantum gravity that there are three main methodological approaches, and a family of 'external' approaches that do not readily fit into any of these three categories. In this section we will examine these approaches in more depth by focusing on specific implementations: we look at covariant perturbative quantization in §6.2 and consider string theory independently of this in §6.3. In §6.4 we discuss canonical approaches, particularizing to loop quantum gravity in §6.4.3. We then consider the path-integral (or Feynman quantization) approach in §6.5, followed by a series of external approaches in §6.6. Philosophical ramifications will be integrated *en route*. The natural, logical place to begin, however, is with an approach that isn't really a 'full' theory of quantum gravity at all, but is instead a half-classical-half-quantum 'hybrid' theory. This will lead us in to the philosophically interesting terrain of whether we even *need* to quantize the gravitational field.

6.1 Semiclassical Quantum Gravity

At first sight, it isn't clear that one needs to *quantize* gravity in order to get what one requires from a quantum theory of gravity, namely a framework that can deal with both general relativity and quantized matter fields—after all, we have good empirical evidence about these two aspects of the world *taken in separation*, but no empirical evidence whatsoever about quantized gravity itself. Given the experimental data, then, all one would seem to require is some way of accounting for gravitational interactions between quantized matter-energy: so *prima facie*, the way is open for a theory involving quantized matter-energy interacting through a *classical* gravitational field.[68] This would give us a hybrid 'half and half' or 'semiclassical' theory of gravity. Whether or not this is possible—that is, whether or not there *is* a necessity to quantize the gravitational field given the quantized nature of matter fields and the universal coupling of gravity—has led to a fairly sizeable philosophical literature (sizeable, that is, given the general paucity of philosophical material on quantum gravity). The reason for this philosophical interest is that given the lack of experiment to decide the issue, "we can only attempt to shed light on such a question [whether gravity should be quantized—DR] from the epistemological side" as Rosenfeld puts it ([Rosenfeld, 1966], p. 599). Here we outline the main ideas of semi-classical gravity, and then discuss some of the arguments contained in this literature.

Firstly, let us again write down the (abbreviated) central equation of (classical) general relativity:

$$G_{\mu\nu} = -8\pi G_N T_{\mu\nu}[\Phi] \tag{5}$$

As we said above (in §5.1), the left hand side of this equation is a classical term representing the geometry of spacetime while the right hand side represents any matter-energy within the universe and thus, given what information we have about the nature of matter, ought to be considered as dependent on quantum operators rather than classical functions. We have, then, a formal mismatch: a c-number field on one side and a q-number on the other, an apples and oranges equation. Either we turn the left hand side into a q-number field, which would involve a quantization of the gravitational field, or else we can try to turn the right hand side into a c-number. One early approach along the latter lines—of Møller [1962] and Rosenfeld [1963]—involves coupling a classical gravitational field to a quantized source, satisfying the *semiclassical Einstein equations*:

$$G_{\mu\nu} = -8\pi G_N \langle\psi \mid \hat{T}_{\mu\nu}[\Phi] \mid \psi\rangle \tag{6}$$

Hence, only the stress-energy tensor becomes a quantum operator and the gravitational field interacts with the expectation value (a c-number) of this tensor (henceforth abbreviated to $\langle T_{\mu\nu}\rangle$), rather than directly with the quantum fields. The solution would

[68]This could be accomplished in two broad ways: (1) by formulating a quantum field theory on a curved spacetime in which the spacetime is dynamically decoupled from the matter (i.e. unresponsive to its evolution); and (2) by formulating a quantum field theory in which the state of the matter influences the spacetime geometry. In both cases the geometry remains classical. We discuss approach (2) in this section since it is closer to quantum gravity.

involve a classical spacetime $\langle \mathcal{M}, g_{\mu\nu} \rangle$, a matter field Φ with stress-energy tensor $T_{\mu\nu}$, and a quantum state ψ of the matter field. Hence, roughly, we will be dealing in models of the form $\langle \mathcal{M}, g_{\mu\nu}, T_{\mu\nu}[\Phi]_\psi \rangle$ satisfying eq.6. If this framework makes sense, then there would appear to be no quantization routes to quantum gravity. The industry of approaches that do *not* quantize general relativity points to the fact that many researchers do not think that quantization is necessary—though this does not mean that they think *quantum gravity* is not necessary.[69] However, one often finds arguments that claim to demonstrate the opposite.

6.1.1 Arguments for the Necessity of Quantization.

Bergmann and Komar refer to the idea that the gravitational field must be quantized on pain of violating the uncertainty relations as "the principal argument in favour of quantization" ([Bergmann and Komar, 1980], p. 228). If gravity were kept classical then that means that it isn't subject to the uncertainty relations like quantum quantities are: coupling the two types would appear to open the door to using the classical gravitational field to circumvent the uncertainty relations. Eppley and Hannah extend this to include momentum conservation and relativistic causality [Eppley and Hannah, 1975]. The basic idea is that since all mass generates a gravitational field, then particles generate a gravitational field. These particles obey the uncertainty relations. However, if we retain the classicality of the gravitational field that these particles generate then we can, by simultaneously measuring the components of the field, determine the precise values for positions and momenta of the particles, thus violating the uncertainty principle. Thus, we have a reductio: the gravitational field *must* be quantized to avoid this violation.

The details of Eppley and Hannah's thought experiment are rather involved. A simpler approach is described by Unruh [1984].[70] Here the idea is to connect a Cavendish balance to a Schrödinger's Cat type setup. The prediction of the semi-classical theory is supposed to be at odds with our expectations for what should happen. The details are as follows. We begin with a sealed box in which there are the following elements: a pair of masses connected by a stretched spring and being held apart by a rod; on the rod there is a bomb, itself connected to a detonator which is linked up to a geiger counter, which is beside a radioactive source (which leads the counter to click, on average, once a day). When the geiger counter clicks, the explosive device will detonate the bomb,

[69]However, as we saw in §3, there were problems in making that case completely watertight, there being many and varied arguments of varying strength.

[70]This gedanken-experiment appears to be a variation on the theme of one initially offered up by Kibble [1981]; though Kibble used it to argue that semiclassical gravity *is* viable. Kibble was followed by Page and Geilker [1981], who attempted to actually perform a version of Kibble's experiment. See Mattingly [2006b] for more discussion. Leslie Ballentine writes of the Page-Geilker experiment "A less surprising experimental result has seldom, if ever, been published!" ([Ballentine, 1982], p. 522). Of course, we know that if we perform a macroscopic measurement of the kind carried out—gravitational measurements of two lead balls with two possible position states—then we know that individual measurements will track the definite, individual configuration, not the average of all possible configurations. Not surprising, perhaps, but it makes its point well: in the Everett picture, for example, if the gravitational field were not quantized, then the measurements to determine its values in the case of a mass in a quantum superposition of position states would track the average centre of mass. Naturally, this is a variation on the measurement problem, and gives some of the motivation for Penrose's collapse approach discussed in §3.7.

resulting in the breaking of the rod and the two masses being pulled together. Outside the box is a Cavendish balance whose equilibrium position depends on whether the masses in the box are together or apart—hence, the position will depend on whether the radioactive source decays. There is also an observer outside of the box. This setup is represented in fig. 1.

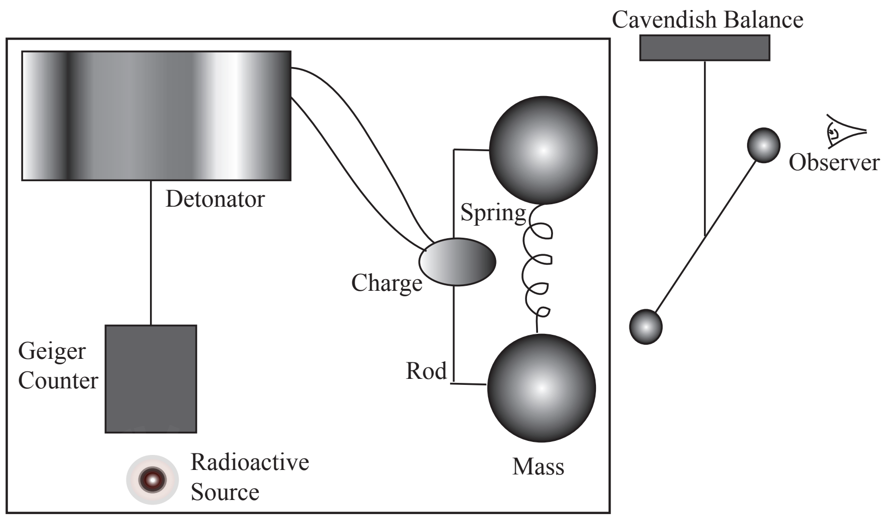

Figure 1: Unruh's Schrödinger-Cavendish experiment: initial state

Now, according to the semiclassical quantum gravity approach, the gravitational field outside of the box is described by the (here abbreviated) semi-classical field equations: $G_{\mu\nu} = 8\pi\langle T_{\mu\nu}\rangle$. Given the dependence of the balance on the positions of the masses, its state is determined by that of the system inside the box. The states of the box are split up into two types: those for which the masses are held apart $|{\Leftarrow}{\Rightarrow}\rangle$; and those for which they are together $|{\Rightarrow}{\Leftarrow}\rangle$. The initial expectation value will be:

$$\langle T_{\mu\nu}\rangle_0 = \langle{\Leftarrow}{\Rightarrow}|\; T_{\mu\nu}\; |{\Rightarrow}{\Leftarrow}\rangle \tag{7}$$

Time evolution will take this state into a linear superposition of both kinds of states (masses apart and masses together):

$$\langle\phi\rangle = \alpha(t)\; |{\Leftarrow}{\Rightarrow}\rangle + \beta(t)\; |{\Rightarrow}{\Leftarrow}\rangle \tag{8}$$

The squared moduli of the coefficients are:

$$| \alpha(t) |^2 \approx e^{-\lambda t} \tag{9}$$
$$| \beta(t) |^2 \approx 1 - e^{-\lambda t} \tag{10}$$

The expectation value after the system has been evolved is:

$$\begin{aligned} \langle \phi \mid T_{\mu\nu} \mid \phi \rangle = | \alpha |^2 \langle \Leftarrow\Rightarrow | \, T_{\mu\nu} \, | \Leftarrow\Rightarrow \rangle \\ + | \beta |^2 \langle \Rightarrow\Leftarrow | \, T_{\mu\nu} \, | \Rightarrow\Leftarrow \rangle \\ + 2\mathrm{Re}[\alpha^* \beta \langle \Leftarrow\Rightarrow | \, T_{\mu\nu} \, | \Rightarrow\Leftarrow \rangle] \end{aligned}$$

Substituting the (empirically observed) values for the coefficients, and taking the final 'interference' term to be negligible, we have:

$$\langle t \mid T_{\mu\nu} \mid t \rangle = e^{-\lambda t} \langle \Leftarrow\Rightarrow | \, T_{\mu\nu} \, | \Leftarrow\Rightarrow \rangle + 1 - e^{-\lambda t} \langle \Rightarrow\Leftarrow | \, T_{\mu\nu} \, | \Rightarrow\Leftarrow \rangle \tag{11}$$

The formalism leads us to predict that the Cavendish balance will slowly (and continuously) shift from one equilibrium position, where the masses are apart (as in fig. 1) to another, where the masses are together (as in fig. 2). However, as Unruh points out, this is at odds with what we expect to happen: rather than a smooth swinging around of the balance, we expect a sudden swing when the counter clicks. If it does move like this, then given the 'slow swing' prediction, the semi-classical equation cannot be correct (not even as a good approximation).

This 'discontinuity problem' forms another problem, connected to the quantum measurement problem. According to collapse interpretations, when we make an observation of the sealed system (by peeking into the box) the state changes discontinuously from a superposition $\alpha \; |\Rightarrow\Leftarrow\rangle + \beta \; |\Leftarrow\Rightarrow\rangle$ to a state with definite positions for the masses: $|\Rightarrow\Leftarrow\rangle$ or $|\Leftarrow\Rightarrow\rangle$, with probabilities $| \; \alpha \; |^2$ and $| \; \beta \; |^2$ respectively. But this discontinuous collapse translates into a discontinuous shift in $\langle T_{\mu\nu} \rangle$, so that the conservation law $\langle T^{\nu}_{\mu} \rangle_{;\nu} = 0$ is violated (where '$;\nu$' denotes the covariant derivative with respect to ν). This violation can be exploited for superluminal signalling—this latter problem forms the much cited thought experiment by Eppley and Hannah.

Eppley and Hannah's argument is intended to show that the gravitational field has to be quantized. It is set up as a *reductio ad absurdum* argument: assume that semiclassical gravity is a consistent and physically reasonable theory. One then uses a gravity wave to simultaneously measure both the position x and momentum p of some putatively quantum body at a level of precision that violates the uncertainty relations: i.e. $\Delta x \cdot \Delta p \geq \frac{\hbar}{2}$. In other words, although the quantized matter source is subject to the uncertainty relations, the classical wave is not, and hence it can be exploited (so the argument assumes) to get around the uncertainty in the quantized system. Therefore, the original assumption, that semi-classical gravity is consistent and physically reasonable, must be false.

James Mattingly [2006] has objected on a variety of grounds to the drawing of the "necessity of quantization" conclusion from such thought experiments. Firstly,

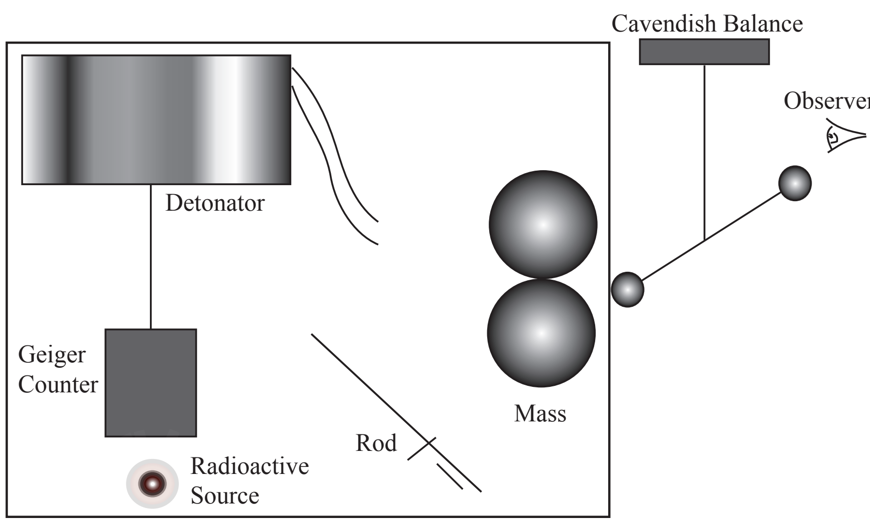

Figure 2: Unruh’s Schrödinger-Cavendish experiment: final state

when tested in the way suggested—*per impossible* as Mattingly argues in a different paper [Mattingly, 2006] (see below)—the uncertainty relations *might* be found to be violated. In other words, checking for such violations is something to be determined by experiment, not from the comfort of one's armchair. Secondly, he argues that the power of the uncertainty relations is interpretation-dependent: in some interpretations, the uncertainty relations reflect our ignorance of the 'real stuff' that is going on in the world.

Mattingly takes issue, then, with the tenability of the thought-experiment invoked by Eppley and Hannah and those like it. However, Unruh's experiment is nearer to actual performability than is Eppley and Hannah's. Indeed, Unruh writes that the Page and Geilker experiment illustrates "the ease with which such a gedanken experiment could be made real" ([Unruh, 1984], p. 237). Mattingly's complaint against these thought experiments has to do with their *physical realizability*: far from being performable, Mattingly argues that they are in fact nomologically and, indeed, metaphysically impossible. The basic idea at the core of his argument is an old and well known one: measuring position (i.e. localizing a particle) requires a concentration of energy; as this energy is forced to occupy smaller and smaller volumes, a black hole will form and swallow up any measuring equipment! This seems to be a strong argument against the Epply-Hannah experiment; however, Unruh's experiment appears to be unaffected.

Rosenfeld, who is often aligned with the 'necessity of quantization of the gravitational field' view, in fact dismissed such arguments (see [Rosenfeld, 1963], for example). The idea, in more intuitive terms, is that quantumness spreads like a virus through classical systems, so that a classical system interacting with a quantum system and remaining classical is impossible—since gravity couples to *all* mass-energy sources, it has to be quantized. Rosenfeld was surely right in thinking that the decision to quantize some object has to come from empirical evidence not *a priori* considerations. The issue of whether the gravitational field *has* to be quantized remains an open one.

I should, however, point to a recent proposal by Adrian Kent that might serve to close the issue up.[71] Kent [2005] proposes a simple (and 'doable') experiment to test the local causality of spacetime. That this experiment is feasible points, at least, to the fact that the question of the quantum properties of the gravitational field is indeed an empirical one. The experiment is a variation on Page and Geilker's experiment, only now involving a pair of Cavendish bars coupled to a pair of spacelike separated detectors used to perform a standard Bell-type experiment.

General relativity is locally causal (or stochastic Einstein local in Butterfield's terminology). This is understood to mean that the probability distribution of metric and matter fields in a region of spacetime is determined only by events in the past of the region (i.e. not a spacelike separated points or regions). The straightforward implication is, then, that any theory formulated with respect to a spacetime background described by general relativity (i.e. classical and geometric) would also have to be locally causal: this would include semiclassical theories of gravity. However, one of the common expectations of quantum gravity is that it should allow superpositions of spacetime geometries: given spacelike separated entangled quantum systems (pairs of photons in

[71] I thank Jeremy Butterfield for bringing this paper to my attention. Butterfield [2007] discusses the experiment under the banner of 'stochastic Einstein locality'.

a polarization singlet state, of the kind found in the wings of Bell experiments), we should be able to render these superpositions macroscopic if we couple the systems at the spacelike wings to some macroscopic device, such as a Cavendish balance, that displays different mass configurations depending on what is measured on the quantum system. Given the entanglement, this should then lead to a violation of local causality by spacetime: the quantum correlations of the photons will be mimicked by the states of the Cavendish balance (four permutations of the states of the masses on the torsion balance). This is the raw outline of Kent's experiment.

If we measure a violation (the intuitively expected result), then general relativity cannot provide a universal description of gravity and spacetime: we need a quantum theory of gravity. However, it is clear that this result is not the kind of thing we can know *a priori*: it might be the case that we *don't* detect any violation at all. In this case quantum theory would fail to describe all possible Bell-type experiments. Alternatively, we might find "the coexistence of a quantum theory of matter with some classical theory of gravity which respects local causality, but which has the surprising property that classical gravitational fields do not couple to classical matter in the way suggested by general relativity" (p. 3). This is simply more grist for Rosenfeld's mill.[72]

6.1.2 Important Results in the Semi-Classical Theory.

There is a natural inverse relation between semiclassical gravity and the theory of quantum fields on curved spacetime: the former describes the way in which quantum fields act as *sources* for the gravitational field, and the latter describes how gravity impacts on quantum fields. This framework, though relevant to the construction of a full-blown quantum theory of gravity, leads to certain results that function as benchmarks for these theories. The most important such result, as mentioned earlier, is the Hawking effect, which exposes connections between quantum field theory, general relativity, and thermodynamics. By considering the behaviour of quantum fields near black holes Hawking discovered that they (that is, black holes) radiate. The radiation is in the form of outgoing particles that are created in the exterior of the black hole, and have the effect of carrying mass-energy away from the hole, resulting in black hole 'evaporation'. The spectrum of black hole radiation must be a prediction of any viable quantum theory of gravity, for, given the ingredient theories, there will be a dynamically possible scenario in which such effects are manifested. Both string theory and loop gravity can—albeit with some difficulty—get the correct value. Let us take a brief detour into black holes and their quantum behaviour.

Black holes provide a central testing ground for up and coming quantum gravity theories. The quantum theory of black holes is especially interesting because it includes aspects of gravitation, quantum theory, and thermal physics. There is an immediate and intuitive connection that is easy to see if one considers what happens when something falls into a black hole (now understood in the old-fashioned way for the purposes of the example): whatever goes in or, (given what we said above), *most* of what goes in (past

[72] See Wüthrich [2007] for an excellent examination of the metaphysical issues surrounding semi-classical theories of gravity, including the impact of some of the most recent debates in this area (connected to viewing general relativity as an effective field theory—Wüthrich ultimately argues that the alternative accounts "at least prove the tenability of an opposition to quantization" (p. 777).

the event-horizon), never comes out again. What goes in is 'lost' because black holes have no internal structure. Throw whatever you like in, the black hole just increases its mass. In particular, throw an object that has a high entropy into a black hole and it appears that you can thereby eliminate the entropy, effectively reducing the entropy of the rest of the Universe. *Prima facie*, this is, of course, a clear violation of the second law of thermodynamics. However, the connections go much deeper than this: Hawking [1971] proved that the total area of a family of event horizons associated to a family of black holes will always increase. This makes the area sound like entropy: that too always increases, or at least it seemed to until we started thinking about throwing things into black holes. This gives an analogy with the second law of thermodynamics, only this time involving the area of horizons. Of course, if entropy just *is* area then entropy doesn't decrease when we throw something in to a black hole: area increases and, therefore, so does entropy!

There are more connections one can make between thermal physics and black hole physics: the mass M of a black hole is analogous to energy E; the surface gravity of a black hole κ is analogous to the temperature T; likewise, there are analogies for the other laws of thermodynamics. Jacob Bekenstein was the first to take this analogy seriously and argue that entropy really is just proportional to area. That is, the area of black holes is another source of entropy that has to be added when we consider the total store of entropy in the world. Hence, we have a simple analogy: entropy is fond of increasing and so is the surface area of a black hole. However, this is, of course, not an identity: black hole entropy is a (monotonically increasing) function of the area. Hence, in order to get the entropy of a black hole from its area we need to know what this function is. Let us briefly review some of the details of the connections.

Quantum black holes emit (approximately) thermal radiation at temperature:

$$T \sim \frac{\hbar c^3}{G_N M} \tag{12}$$

where M is the mass of the black hole. Notice that setting $\hbar$ to zero (i.e. in the classical limit) the temperature vanishes, as we would expect—that is, this is a *quantum* effect. The thermal nature of black hole radiation leads to the idea that black holes have an entropy (called the 'Bekenstein-Hawking entropy'):

$$S = \frac{Ac^3}{4G_N \hbar} \tag{13}$$

where A is the area of the black hole's horizon (i.e. the surface area).[73] The general expression for the entropy of a system is written in terms of the number N of quantum states (microstates) of the system:

$$S = \ln N \tag{14}$$

Given eq.13 this leads us to the following (rough) value for this number of microstates:

$$N \sim e^{\frac{Ac^3}{4G_N \hbar}} \tag{15}$$

[73]Note that we can set $c = G_N = \hbar = 1$ to get the simple expression whereby entropy is just a quarter of the surface area.

This is a huge number, implying that black holes have enormously high entropies.[74] As I mentioned earlier, one of the 'viability tests' of a quantum theory of gravity is to compute the Bekenstein-Hawking entropy using materials internal to the approach, so as to give a microscopic description of black holes. That is, one should be able to use the theory to compute the quantum states of a black hole and, hopefully, find that it matches the Bekenstein-Hawking entropy. This has been done in a number of approaches, albeit with varying degrees of generality and success.

6.2 Covariant Quantization

Much of the early work in quantum gravity has followed the route of 'covariant quantization', largely as a result of the astonishing successes involving the quantization of the other forces using such methods. The viewpoint of covariant approaches is that gravitation is simply a gauge field theory which describes the behaviour of massless, self-interacting, spin-2 bosons. The theory is in principle of a kind with the field theories for the other interactions. The fundamental particles of the theory, namely gravitons, are treated as no different in principle from other particles such as photons and electrons. Crucially, these particles are taken to move in a flat, fixed Minkowski spacetime. Hence, gravity is no longer considered to be a geometric theory, in which gravitation is a result of curved spacetime; rather, the particles behave as though they were moving in such a curved spacetime when 'in reality' they are moving in such a way in virtue of graviton exchange. It is this feature that is responsible for the animosity often shown between the relativistic and particle physics communities: the difference is between quantizing fields *in* spacetime and quantizing spacetime itself.[75]

Often, when some computations are too complex for a theory's equations to be solved exactly, one resorts to approximation methods. One such method, at the heart of quantum field theory, is perturbation theory. Here one calculates physical quantities of interest as power series expansions in the relevant coupling constant of the theory. Consider again the case of QED. Here a coupling constant is the electric charge on electrons, e. This determines the strength of interactions involving electrons. In fact, one works with the (dimensionless) number $\alpha = 2\pi e^2/hc \approx 1/137$, known as the fine structure constant. The small size of this number, much less than unity, allows one to approximate the probability amplitude for some process in QED (such as electron-electron scattering, $S(\alpha)$) using the first few terms of a power series in α—these terms one represents using (families of) Feynman diagrams:

$$S(\alpha) = S_0 + \alpha S_1 + \alpha^2 S_2 + \cdots \tag{16}$$

In the case of QED as we add more terms to the series the contributions reduce substantially, so one can work the first few terms and ignore the rest. However, if we

[74] Note, however, that this large entropy is a property of black holes that holds independently of whether entropy really encodes a count of the number of microstates. It is also noteworthy that the entropy scales with area as opposed to volume, as one might more naturally expect. For a discussion of the significance of this 'holographic' property see [Susskind and Lindsay, 2005].

[75] Note that wave-particle duality provides a correspondence between the massless spin-2 particles propagating on flat spacetime and gravitational waves moving in flat spacetime. Or, in other words, quantized versions of these waves are the gravitons.

crank up the strength of the coupling, the perturbation scheme begins to fail. Already in the physics of strong interactions (where the coupling approaches unity) this scheme falters (new physics can appear at high coupling).[76] This failure necessitates the introduction of alternative approximation schemes, or else *exact* methods. Since we turned to perturbation theory in the first place because of the computational complexity, it goes without saying that these alternative methods are very hard indeed. This didn't stop particle physicists from applying the arsenal of their approximation methods to the gravitational field. Even in this case where the coupling constant is relatively small we still face the fact that such expressions as eq.7.3 are divergent.

The programme of conventional quantum field theory is in many respects an exercise in perturbation theory. This is formulated in a four-dimensional covariant manner. The covariant quantization method involves the application of the particle physicists' machinery of perturbative quantum field theory to gravity. The key step in this approach is to split the spacetime metric g_{ab} into two pieces:

- a kinematic part that functions as the *background* against which quantization is defined (giving us machinery such as microcausality, inner product, and so on), generally chosen to be the flat Minkowski metric η_{ab}.
- a dynamical part, h_{ab}, that will represent the dynamical field to be quantized—this is understood as measuring the 'deviation' of the physical metric from the chosen background.

The original spacetime metric g_{ab} is then written as:

$$g_{ab} = \eta_{ab} + G_N h_{ab} \tag{17}$$

Where G_N, Newton's constant, functions as the coupling constant with respect to which one expands in the perturbation series. The idea, then, is to view only the part h_{ab} as the physical gravitational field, and one disconnects this from the dual rôle it plays in determining the spacetime geometry in the context of Einstein's theory of general relativity. *This* gravitational field lives on the background geometry defined by η_{ab}. Hence, quantization occurs with respect to a fixed spacetime, just as in standard quantum field theories. What we get, as a result of this quantization, is a theory of massless, spin-2 particles: the quanta of the gravitational field, namely *gravitons*. The interactions of these gravitons is determined by the Einstein-Hilbert action. Given this definition of the fields on a background and the action, one can engage in perturbative methods—i.e. compute graviton-graviton scattering, and so on.

Being a perturbative approach it is an approximation rather than an exact theory—as Mandelstam points out, it can only be regarded as a "provisional solution of the problem [of quantum gravity]" ([Mandelstam, 1962], p. 346).[77] Reading the litera-

[76] I should point out that this is not 'globally' true: there are certain 'asymptotically free' sectors of the theory of strong interactions (i.e. quantum chromodynamics, or QCD) where perturbation theory is applicable. The reason is that asymptotic freedom implies the existence of a fixed point as the momentum goes to infinity; at this fixed point the coupling constant vanishes.

[77] The canonical quantization approach if successful would provide us with an exact quantization, though one has to trade in the manifest covariance of the perturbative approach—see §6.4. Note that string theory is, thus far, only known through its perturbation expansion, though the more recent work tackles its non-perturbative features—see §6.3.

ture on perturbative quantization methods would, however, often lead one to believe otherwise.

It isn't hard to see why many general relativists dislike this approach. It does away with what is usually seen to be the defining feature of general relativity: background independence. One has separated out the dual function played by the single object in general relativity. In general relativity the metric determines the gravitational field structures *and* the geometry of spacetime. Not so in the covariant approach; here a separate object performs each function. However, this approach certainly has a strong pedigree (as we saw in §4): Rosenfeld, Gupta, Feynmann, DeWitt, and other luminaries of physics all did serious work on it—as with the canonical quantization method (discussed in §6.4), pursuing such a path was perfectly natural at the time: it is rational to use the methods one already has at one's disposal before breaking with tradition and following an entirely new path).

As we mentioned earlier, the theory is not renormalizable—i.e. the quantum theory possesses infinitely many undetermined parameters.[78] The standard take on such theories is that they are not able to make predictions. What it signifies is that the perturbative expansion is not proving to be a good approximation to the physics at short distances/high energies. Note, however, that many string theorists view the perturbative non-renormalizability of general relativity as evidence that the quantum theory is inconsistent.[79] This motivates their shift to an alternative theory, and their claim that string theory is the *only* viable quantum theory of gravity. Such claims are simply not true: loop quantum gravity shows quite clearly that the nonperturbative theory can make sense, and be finite, despite the perturbative problems. What this shows is that there must have been assumptions going into the perturbative methods that caused the failures. One such assumption is that of smoothness of spacetime structure at arbitrarily small distances. Being a background independent approach, loop quantum gravity seeks to uncover this structure rather than imposing it at the outset.

The diffeomorphism invariance of general relativity is in large part at the root of the problems with the covariant perturbative approach to quantum gravity. Recall that diffeomorphism invariance is a gauge freedom in the theory that derives from the multiplicity of representations by localized metrics of one and the same geometry. This results in a breakdown of unitarity in diagrams containing closed graviton loops. The unitarity of the theory can only be restored by adding correction terms (corresponding to 'ghost particles'). However, adding the ghost particles still leaves another problem: there are divergences in the Feynman diagrams. The absence of a dimensionless coupling constant in general relativity means that the standard renormalization procedures can't work in this context: the divergences are logarithmic. This problem leads the co-

[78]The technical explanation for why things go wrong with gravitation when we try to quantize it in this way is that gravity is described by a non-Abelian gauge field theory. The quanta of the field, gravitons, self-interact; they exchange gravitons with themselves! However, some non-Abelian gauge feld theories *are* renormalizable: the work on the covariant quantization of gravity, of Feynman and DeWitt, was instrumental in t'Hooft and Veltman's later (Nobel prize winning) work on the quantization of gauge field theories. This is quite unlike the electromagnetic field and its quanta, photons; here we have a field described by an Abelian gauge field theory.

[79]This is not just a string theoretic response; there were many pre-string efforts to find an alternative to general relativity (or modifications thereof) that recovered the physics of general relativity 'in the large', but that involved new physics at small distances, such that these modifications cured the ultraviolet divergences.

variant approach down several distinct avenues: supergravity and superstrings are the two main lines (with M-theory containing both as limiting cases). Another option was to treat general relativity as an 'effective field theory'. That still leaves one with the problem of specifying the theory to describe the physics at scales beyond the effective range of this approach to quantum gravity. Hence, though it has proven useful, leaving many tools that form a vital part of many other approaches to quantum gravity, the covariant perturbative approach is no longer pursued, and is generally considered to be a dead-end.

6.3 String Theory

String theory is, as Ed Witten concisely puts it, "a quantum theory that looks like Einstein's General Relativity at long distances" ([Witten, 2001], p. 1577). Despite its present status as the leading candidate for a quantum theory of gravity—and indeed a unified theory of all interactions—string theory did not begin life as a quantum theory of gravity. Rather, it began as a framework for modelling the strong interactions in the 1960s (the 'dual resonance model' suggested by Gabriele Veneziano, where 'resonance' refers to the fleeting nature of certain hadrons), in response to the profusion of hadrons that were being thrown up by the new high-powered accelerators—these particles had spins greater than 1 and the corresponding theory was, therefore, non-renormalizable (in four spacetime dimensions).[80] It was discovered that the various oscillation modes of strings corresponded to the great variety of hadrons; hence, the dual models were reinterpreted as string theories—the initial argument behind string theory was, then, of the 'inference to the best explanation' kind (there wasn't any other viable explanation available at the time!). However, it became clear (thanks to 'asymptotic freedom') that standard quantum field theory could account for the strong interaction without recourse to the higher dimensional entities postulated by string theory, the result being quantum chromodynamics. Curiously, the feature that originally led to string theory's rejection, was the same feature that led to its resurgence: the existence of a massless spin-2 particle in the string's spectrum—i.e. there is a quantum state of the string that corresponds to the graviton. Even once it was realized that it had the potential to incorporate gravity (on account of the correspondence between the spin-2 mode and the graviton),[81] as well as the other interactions (demonstrated by Green and Schwartz [Green and Schwartz, 1984]), acceptance was relatively slow, largely as a result of initial inconsistencies in the bosonic theory. But, after various tweaks to

[80]Recall that the strong force holds together protons and neutrons inside the nuclei of atoms, and also holds together the quarks inside the protons and neutrons. The exchange particles that mediate the force are gluons. When we work out the amplitudes for processes involving some hadrons we find that *prima facie* distinct families of Feynman diagrams are equivalent or 'dual' descriptions of the same thing. The strangeness of this, from the perspective of quantum field theory, is what prompted Nambu [1970] to suggest a string model (on the basis of Veneziano's discovery). Apparent distinctness at the particle level becomes obvious (topological) equivalence at the string level, where the Feynman diagrams are Riemann surfaces.

[81]The particle responsible for mediating the gravitational interaction has to be massless to reproduce the (gravitational) inverse-square law. Can't be half-integral because the Pauli exclusion principle renders a large-scale field impossible. Spin greater than 2 rules out a static force. Spin 1 gives a repulsive force (for like particles). Spin-0 gives a scalar field. Narrowing down to spin-2, associated with a symmetric Lorentz tensor field. As Isham ([Isham, 1991], p. 145) points out, the spin-0 case corresponds to Newtonian gravity and the spin-2 case to general relativity.

string theory resulting in improved behaviour[82]—primarily the introduction of spacetime supersymmetry into the theory—it quickly gained momentum. While certainly not regarded as *fact*, string theory is becoming 'mainstream physics', with numerous textbooks and university courses (even at the undergraduate level!).[83]

String theory is considered to qualify as a quantum theory of gravity for two reasons: firstly, as mentioned above, the string spectrum has a vibrational mode corresponding to a massless spin-2 particle, which can be taken to represent a graviton.[84] Secondly, the ambient spacetime containing the string has to satisfy an equation that has Einstein's field equations as a large-distance limit—this equation has to be satisfied in order for the theory to be well-defined. The physics of general relativity appears as a low energy/long distance limit of string theory, but the theory gets modified at higher energies, as one would expect. On this basis, a claim often made by string theorists is that string theory *predicts* general relativity! This is an absurd claim: one make make a case for saying that string theory *explains* gravity and general relativity, by reducing it to strings and their vibrations and interactions, but prediction is essentially a future-directed matter. Alternatively, one finds string theory being motivated through its necessary inclusion of gravity. As it is put in a recent textbook on string theory: "Ordinary quantum field theory does not allow gravity to exist; string theory requires it" ([Becker et al., 2007], p. 4). However, as Rovelli points out "[t]he fact that string theory includes GR is a necessary condition for taking it seriously, not an argument in support of its physical correctness" ([Rovelli, 1998], p. 5); that is, it does not amount to a sufficient condition.

A prominent string theorist takes matters even further, interpreting the necessary inclusion of gravity as providing strong grounds (confirmation!) for belief in the theory:

> A priori, we shouldn't have expected that a randomly chosen framework would correctly predict the existence of spin-0, spin-1/2, spin-1 particles with spin-2 gravity and the right interactions and the right incorporation of the quantum effects. However, string theory is able to do that (and no other theory can), besides dozens of other successes. I think that this result itself is already such a non-trivial confirmation of the theory that it is unreasonable to believe that string theory could be wrong. ([Motl, 2007])

This seems to betray a lack of knowledge of how string theory was discovered; why it was pursued; and how confirmation works. String theory was not quite discovered by accident, or no more so than most theories. As we said, it started as a theory of the strong interaction only to be shelved because of the spin-2 modes, and other 'un-

[82] I should point out, however, that there is as yet no proof that the theory is free of the kinds of UV divergences that plagued the covariant perturbative approach.

[83] Just how this state of affairs was achieved would make an excellent 'sociology of science' case-study, or just an interesting case-study for historians and philosophers of science. One such small-scale study has already been undertaken: [Galison, 1995]. An excellent collection of historical essays on the origins of string theory can be found in [Gasperini, 2008]. More information can also be found in John Schwarz entry at the Caltech Oral Histories Archive: http://oralhistories.library.caltech.edu/116.

[84] For a thorough investigation of the relationship between spin-2 fields and general relativity (general covariance), see [Wald, 1986].

savoury' features. Of course, it was then just this feature that motivated the development of strong theory after its losing out to QCD as a theory of hadrons. It wasn't a "randomly chosen framework". If it didn't have this feature then it would currently join countless other theories on the scrapheap. On the issue of confirmation, one might as well say that general relativity *predicts* Newtonian gravity because it emerges in the appropriate limit.[85]

6.3.1 String Perturbation Theory

String theory, in its original perturbative formulation, was really just a two dimensional field theory on the worldsheet $\mathcal{W}$ traced out by the strings (the quanta of the theory).[86] $\mathcal{W}$ is mapped into the target spacetime manifold $\mathcal{M}$ via a coordinatization function $X : \mathcal{W} \to \mathcal{M}$. This theory is then quantized and one ends up with excitations of the string corresponding to particles propagating through $\mathcal{M}$.[87] In other words, the perturbative description of string theory amounts to a 2-dimensional field theory on the worldsheet of a string, where the coordinates of the string are the field variables. String dynamics is two-dimensional because a one-dimensional object sweeps out a two-dimensional worldsheet. The dynamics must describe how the worldsheet of the string unfolds in spacetime.
In order to get gravity out of this framework a parameter $\sqrt{\alpha'}$ that is related to the string tension, $T = 1/2\pi\alpha'$ (α' = energy per unit of length), needs to be set to the order of the Planck length, namely $10^{-33}cm$. This sets the length of strings in the theory; naturally, they are way too small to be observed in present day experiments.

Important for the mechanism of interacting between strings is a new field known as the 'dilaton'. The dilaton plays a rôle in determining the strength of the interactions through the string coupling constant g_s. This sits at the regions of splitting and joining of strings, much like the coupling constant in QED sits at the vertices.[88] However, the

[85]Note that Joseph Polchinski has suggested that one might qualify the claim that string theory predicts gravity as follows: "once one starts from the principle that the fundamental degrees of freedom are one dimensional, one derives as consequences gravity, a definite dimensionality to spacetime, and completely determined dynamical laws (e.g. no free parameters). This is what one hopes to see in a theory, in the way that the equivalence principle determines Einstein's equations, but more complete in that Einstein's equations govern only the gravitational part of the theory, and only approximately" (email communication). Given this, if we adopt a Hempelian approach, then we can agree that string theory *explains* gravity (since it is deducible as a logical consequence), but it doesn't make sense to say that this constitutes prediction. However, this account of explanation (and prediction) is, in any case, flawed for many reasons—those unfamiliar with these reasons should consult [Salmon, 1984]. Moreover, as Polchinski also notes, the one-dimensionality is itself a derived principle, governing the perturbative description.

[86]The action for this theory follows the action for a simple mass point: $S = m \int ds$ (for mass m and path s). This gives us the motion of the particle. Similarly the defining action for string theory is $S_{NB} = T \int dA$ (where $T = 1/2\pi\alpha'$ is the string tension, where α has dimensions of length squared—in fact $\sqrt{\alpha'}$ is the string length scale—and A is the area of the worldsheet). Introducing a metric h_{ab} $(a, b, = 1, 2)$ on the worldsheet we can rewrite this as: $S_{NB} = T \int d^2\sigma\sqrt{-h}$. This is the 'Nambu-Goto action'. It is generally replaced with the Polyakov action: $S_P = T \int d^2\sigma\sqrt{-h}h^{ab}h_{ab}$ (where $h_{ab} = \partial_a X^\mu \partial_b X_\nu$ and $X^\mu(\sigma_1, \sigma_2)$ is a map describing the embedding of the worldsheet into the target spacetime with dimensions $\mu = 1, ..., D$).

[87]String *field* theory modifies this framework by considering string theory as a theory in spacetime, rather than on the worldsheet. A string field $\Psi[X(\mathcal{W})]$ is a map from the configuration space of strings to the complex numbers.

[88]There are many ways to understand the dynamics of strings: first and second quantized. The first

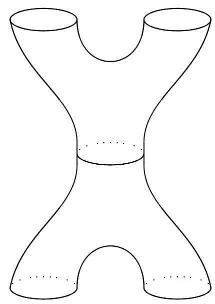

Figure 3: Interactions between strings take place by (local) joining and splitting, i.e. when two points of the strings touch—xy-pic code used with the kind permission of Aaron Lauda.

fact that the splitting and joining is 'spread out', because of the extendedness of the strings, means that the interactions don't involve singularities: the notorious problems of renormalization are avoided.

In string theory Newton's constant G_N is proportional to the string coupling constant and the square of the Planck length: $G_N \sim g_s^2 l_s^2$ (for superstring theory). This series of facts results in the ability to reproduce the low-energy physics of GR by means of a perturbative expansion corresponding to splitting and joining of strings in flat spacetime. In this sense, general relativity looks like an effective field theory, with string theory the more fundamental theory.

When the string is quantized (assuming flat spacetime and no interactions) we find an infinite hierarchy of ever increasing mass modes. It matters whether the string is open or closed. In the case of the closed string, in the massless bit of the spectrum, one finds a mode corresponding to a graviton (a massless spin-two particle). It is for this reason that string theory is taken to constitute a quantum theory of gravity. However, string theory is much more than that since it also contains modes corresponding to all the other force carrying particles. It is in this sense a theory of everything, although the particles and interactions it describes do not quite correspond to those we observe.

To get some physical intuition for string theory, let us give a graphical description. Consider the motion of a string from one embedding in spacetime A to another B. Unlike 0D particles, which trace out 1D *worldlines* as they shift between spacetime configurations, 1D strings sweep out 2D surfaces called *worldsheets*. An amplitude is assigned to the propagation of the string from A to B; this amounts to a sum over all possible worldsheets connecting the A-configuration and the B-configuration—one follows the Feynman path-integral approach of assigning a weight of $\exp(i/\hbar(-S))$ to each worldsheet with the A- and B-configurations as boundaries. The coupling constant determines the probabilities governing string propagation events, such as splitting and joining of strings (that is, it determines the *rate* at which strings interact): for large

quantized formulation focuses on the worldsheet of the string and involves summing over them. The second quantized picture, string field theory, involves field operators that create and annihilate strings.

g_{string} the interactions are strong, which amounts to high probabilities for splitting and joining. Consistency (namely, ruling out tachyons which imply an unstable vacuum) demands that fermionic degrees of freedom are added to the theory. This still does not deliver a unique theory. Rather, there are five distinct string theories living in 10 dimensional spacetime. These are called type I, type IIA, type IIB, $E_8 \times E_8$ heterotic, and $SO(32)$ heterotic.

6.3.2 Residual Dimensions and their Compactification

The consistency of the quantized version of string theory depends on what is called 'the critical dimension' of spacetime. In the case of string theory proper—i.e. *Bosonic* string theory—spacetime must be 26 dimensional for the theory to make mathematical sense. In the case of superstring theory (i.e. with fermions too) the critical dimension is 10. A large part of string theory is devoted to working out how to compactify the residual dimensions, and showing how various properties of our four dimensional world emerge from various kinds of compactification, from the way the strings wind around them, and so on.[89] However, compactification is not the only way to go to account for the four dimensionality of the perceived world. An alternative is what we might call 'branification' (more commonly called 'brane-world scenarios')—see [Randall and Sundrum, 1999] for the original presentation of such models; a lengthy discussion can be found in [Maartens, 2004]. The idea here is to view the world we have access to as a 'slice' (an embedded brane) in a higher dimensional world (an infinite ambient brane), much like Edwin Abbott's Flatlanders!

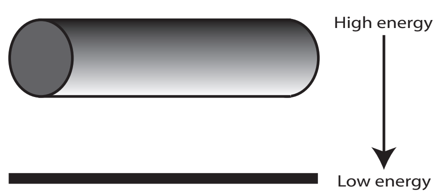

Figure 4: The basic idea of compactification: we have two pictures of a cylinder, but at low energies/small distances the cylinder becomes 'invisible', effectively removing a dimension. Now think of the horizontal dimension as our ordinary 4 dimensional spacetime, and think of the vertical dimension as a 22, 6, or 7 dimensional manifold (manifest at high energies, compactified at low energies). The same reasoning leads to the successful approximation of strings by point particles (in the context of quantum field theory).

Purely for historical interest I note that Einstein (in his 'middle period') would

[89]The idea of compactification has much in common with the old Kaluza-Klein attempt to unify gravity and electromagnetism by postulating a fifth dimension, the curvature of which determines the electromagnetic force, just as curvature in the four spacetime dimensions determines the gravitational force. In Kaluza-Klein theory, the curvature of this extra dimension has to be around the Planck length in order to account for the observed properties.

not have been happy with the higher dimensions demanded by string theory. On the Kaluza-Klein unified model of gravitation and electromagnetism, involving an additional dimension of space, Einstein writes:

> It is anomalous to replace the four-dimensional continuum by a five-dimensional one and then subsequently to tie up artificially one of these five dimensions in order to account for the fact that it does not manifest itself. ([Einstein, 1931], p. 438)

It is not a massive leap to infer that the same would apply to the 26, 10, or 11 dimensions of string theory, superstring theory, and M-theory.[90] But is this good reasoning? In most other situations no doubt it would; it is a simple application of a principle of parsimony or simplicity. But quantum gravity is all about consistency, and if the only way to get a consistent theory is to postulate extra dimensions then should we not accept them? Oskar Klein himself wrote that his unified theory, with its extra coordinate vanquished to the Planck scale, "has such strange features that it should hardly be taken literally" ([Klein, 1956], p. 59). Indeed, he goes on to remark on the "somewhat repellent appearance of the small length just mentioned" (ibid.). Hence, Klein adopted a decidedly instrumentalist approach to the fifth dimension. But, again, what if the extra dimension *did* manifest itself, albeit very indirectly. Of course, this is just what string theorists claim: the extra dimensions, despite being 'curled up' have ramifications for macrophysics; they *explain* the particles and laws that we observe. They can even be called upon to explain the weakness of gravity in branification scenarios. Here is an area that might be profitably studied by philosophers: is this taking the notion of observation one step too far? Some hardened scientific realists might even have trouble taking these extra dimensions as real given the suggested way of making them empirically manifest. But just how different is this case from, e.g. Newton's arguments for the existence of absolute space and time (whereby the *effects* of absolute space and time were taken to point to their existence)? Not really so different in my opinion; however, the question deserves closer scrutiny from philosophers.

Indeed, philosophically interesting issues are never far from the surface in string theory. For example, the freedom in the way the dimensions are dealt with leads to an enormous number of four dimensional theories: quantum string theory doesn't describe a unique theory (or vacuum state), but instead appears to describe a 'landscape' of theories, some of which are good at describing our world, and some which aren't. A serious problem is to find a selection principle to weed out the wheat from the chaff.

[90] As Joseph Polchinski pointed out to me, Einstein returned to Kaluza-Klein theory in 1938 (working with Peter Bergmann: [Einstein and Bergmann, 1938]) and 1943 (working with Pauli: [Einstein and Pauli, 1943]). In the former paper he writes that "one can assign some meaning to the fifth coordinate without contradicting the four dimensional character of our world" (p. 683). and in the latter paper wrote that "When one tries to find a unified theory of the gravitational and electromagnetic fields, he cannot help feeling that there is some truth in Kaluza's five-dimensional theory" (ibid., p. 131). He even goes so far as to suggest that the problem of the inaccessibility of the fifth dimension might be evaded by taking the fields corresponding to the non-singular solutions to be "linearly extended". They argued in the end that there were no such solutions; however, their paper was incorrect, conflating coordinate and physical singularities. See [Gross, 2005] for more on this aspect of Einstein's work, including details on the identification of the error in Einstein and Pauli's paper, and the solutions (known as 'Kaluza-Klein monopoles') that result once the error has been corrected—these now play a central role in M-theory.

The situation is analogous to the relationship between the 'merely' kinematically possible motions of some system, and the dynamically possible motions: string theory needs a dynamical principle, a criterion for choosing some particular location or region of the landscape. Choosing in such a way so as to fit what we see is open to the charge of ad hocness. What one wants, ideally, is some principle *internal* to the theory, or well-motivated on non-ad hoc gounds. One selection principle that has been utilized to reduce the size of the landscape is the 'Anthropic Principle':[91] choose only those worlds that possess laws of physics capable of supporting us humans! A (better) alternative, I think, is to view string theory as an overarching *framework* in which to construct specific string theories, much as quantum field theory does not name any particular theory but a set of principles that one uses to build such a theory.[92]

6.3.3 The Second Revolution

The 'first revolution' picture was strictly perturbative. It was known that such a framework was an inadequate model. Strings are treated in much the same way as gravitons are treated in the covariant perturbative approach, namely as propagating in an independent background spacetime. That was known to be inadequate too, but the aim was to push for clues about the nature of the right theory, and the kinds of physical quantities it would involve. Hence, the same idealization is present in string theory: though we know (or think we know) that gravitons and strings are really bound up with spacetime—being a *wave* in a geometry in the case of gravitons and maybe in the case of strings too—given the computational complexities, we can ignore this for the time being.

There were two key problems with this first revolution picture of string theory: the residual dimensions of spacetime and the existence of five string theories. These two problems interact in various ways. The residual dimensions—and the fact that we cannot see them—are resolved by compactification (although this leaves the problem of explaining the mechanism behind the compactification). The multiplicity problem is resolved by dualities connecting the various string theories. One kind of duality amounts to an equivalence of string theories using different compactifications. This only partially resolves the multiplicity problem, for associated to the different string theories (in 9+1 dimensions) are a massive number of string theories which amount to yet more distinct theories (in 3+1 dimensions).

A key part of the second revolution, leading into nonperturbative sectors of string theory, was the discovery, by Joseph Polchinski [1995], of D-branes (nonperturbative excitations—the 'D' stands for 'Dirichlet boundary conditions')—discovered by im-

[91] See [Susskind, 2005] for a book-length discussion written at a popular level. [Weinstein, 2006] offers a philosophical discussion of the anthropic principle in string theory and multiverse cosmology.

[92] A potential disanalogy between the string theory and quantum field theory cases is, however, that different quantum field theories are genuinely different theories, in the sense of having different dynamical equations, while in string theory there is just one set of equations and many different solutions. This is viewed as a virtue of string theory since it points to the generation of massive complexity (of solutions) from a handful of central, defining equations—my thanks to Joseph Polchinski for this objection: private communication). However, I would argue that since the solutions are set against different backgrounds, then we have a multiplicity of theories in the string theory case too. In any case, I leave this as a problem for the reader.

posing yet another consistency condition (to avoid yet another anomaly). D-branes are curiously entwined with black hole physics—the directness of this connection is often papered over in advanced string theory texts. The idea is that D-branes are in fact a configuration (microstate) of a black hole, on which strings can have their endpoints—this is the meaning of the Dirichlet boundary conditions mentioned above: the brane is the boundary for the string's endpoints. Now, in a Type II string theory there can be only closed strings. However, the possibility opened up by D-branes is that one can effectively have such a situation. To get a feel for this, imagine a closed string near a black hole—here I borrow heavily from [Witten, 2001]. Now imagine that a portion of the string slips behind the event horizon: we have (from the perspective of an observer outside of the hole) what looks like a string with endpoints on the surface. Now further imagine that the black hole evaporates. It can't evaporate to *nothing* because the string is attached to its horizon, and absolute evaporation would mean that we end up with an open string, which is not possible in Type II string theory. What happens, instead, is that the black hole radiates until it reaches a stable ground-state consisting of a D-brane—in this sense, the D-branes arise from a demand for consistency. A similar situation can happen where there are two black holes and a string plugged into both (i.e. with endpoints in each). The black holes will evaporate again, and each end up in a stable state: a D-brane. This prevents the string having its endpoints in the vacuum.[93]

6.3.4 Duality Symmetries and M Theory

This new work led to the postulation, by Edward Witten [1995], of a new theory labelled $\mathcal{M}$-theory. The central idea of this new theory is that the profusion of different string theories really exist as limiting cases of some more fundamental theory that exists in *eleven* dimensional spacetime. This hypothesis is given support by the discovery that the different string theories are connected to one another by certain symmetries called *dualities*. These various string theories are defined on a variety of spacetime backgrounds, so $\mathcal{M}$-theory is conjectured to be background independent. This seems like a reasonable conjecture since $\mathcal{M}$-theory is supposed to 'incorporate' the various string models that are defined with respect to different backgrounds. However, there remains the pressing problem of actually *defining* $\mathcal{M}$-theory![94]

Edward Witten and others exploited these duality symmetries, and various results from earlier work on supergravity, then, to argue that there was some more fundamental theory that had the five dual string theories as limiting cases. The limits involve the

[93]The end-points can move around on the D-brane, but they cannot leave it unless they join to form a closed string.

[94]There is much excitement at the moment over the status of the so-called 'AdS/CFT' correspondence (aka 'the Maldacena conjecture') which is believed to be a core part of $\mathcal{M}$-theory, and indeed quantum gravity *simpliciter*. This is essentially another duality mapping that would allow one to deal with a background independent theory on the boundary of a spacetime. One can construct a non-perturbative string theory using this duality since the CFT (conformal field theory) side can be algorithmically defined—I owe this point to Joseph Polchinski. This basic idea is known, more generally, as *the holographic principle*, and is believed to be a necessary principle obeyed by any and all viable approaches to quantum gravity. The holographic principle will no doubt be one of the standard hobbyhorses of future generations of philosophy of physics, however, the subject is too advanced for this primer: I refer the interested reader to [Schwarz, 1999], [Di Vecchia, 1999], and [Petersen, 1999]. Some more very brief and technical remarks are contained in the next two footnotes.

postulation of an additional dimension, resulting in eleven dimensions of spacetime. This extra dimension has the topology of a circle. But this isn't all: a new kind of higher-dimensional object, a membrane (a 2-dimensional surface), is introduced into the theory in order to make sense in eleven dimensions (superstring theories demand ten). The membrane wraps one of its dimensions around this circle, leaving one to propagate in the remaining nine spatial dimensions. This reproduces string theory: a one dimensional object moving in ten dimensions of spacetime. Witten noticed that the five consistent string theories are uniquely determined by various ways of wrapping membranes around the dimension. The dualities mentioned above hold for the membrane constrained to the nine spatial dimensions. This new eleven dimensional theory, with its new ontology, was christened $\mathcal{M}$-theory by Witten, where '$\mathcal{M}$' is a placeholder to be filled in once the theory has actually been discovered. Hence, string theory is no longer a theory of strings; rather, it is a theory of p-branes (strings are a special case where $p = 1$: 1-branes).[95] Though these $\mathcal{M}$-theoretic ideas are extremely interesting, they are still very much up in the air (even for quantum gravity research!). This makes it very hard to probe philosophically. However, there are more robust elements: the duality symmetries are a case in point, so we briefly say some more about these.

T-Duality: Equivalent Geometries and Topologies: T-duality (where 'T' stands for 'target space') is a gauge symmetry of classical string theory concerning the propagation of strings in a background metric spacetime. One finds that T-duality connects various prima facie distinct backgrounds so that there is no way to physically distinguish between them—that is, they lead to the same physics. This scenario is similar in many ways to the hole problem in general relativity, where we have distinct metrics that have the same observable consequences. Both are generic problems of gauge symmetries. What it shows is that the background metric is not a measurable thing: T-dual metrics will span the same gauge orbit.

However, though they share this feature, the symmetries have a very different source. In the case of classical general relativity the problem stems from the diffeomorphism invariance, having to do with the dynamical nature of the metric and the unobservability of manifold points. In the case of T-duality the source is the fact that strings have a length, $l_s = \sqrt{\alpha'}$, and can be wound around compactified dimensions—-of course, strings cannot probe distances below l_s (see §6.3.5). Taking a simple case in which we have extra dimensions compactified on a circle of radius R, T-duality says that this scenario is equivalent to the case α'/R, where α' is just the fundamental string length scale l^2. T-duality renders both the two type II theories and the two heterotic theories (exactly) physically equivalent. This implies that T-duality extends over all orders of the string perturbation expansion. T-duality applies to more complex spaces, such as Calabi-Yau

[95] Hence, there is a general class of extended objects: the p-branes. In the branification scenario mentioned previously, the spacetime we inhabit is viewed as a 3-brane. The study of 3-brane physics led to the Maldacena conjecture. The idea is that the 3-brane, specifically our spacetime described by a four dimensional gauge theory ($N = 4$ super Yang-Mills theory) without gravity, is a holographic part of a higher-dimensional theory with gravity (type-IIB string theory compactified on $AdS_5 \times S^5$, with the Yang-Mills theory living on the boundary of AdS_5). They are, in a sense, dual theories.

spaces which are mirror symmetric—these are especially relevant for superstring theory since they form product spaces with four dimensional manifolds to form the string backgrounds.

S-Duality: Equivalent Physics at Strong and Weak Coupling: Like T-duality, S-duality also relates what were previously thought to be distinct string theories. The idea is that the physics of one theory at strong coupling (large g_s) is physically equivalent to that of another theory at weak coupling (for small g_s). This duality holds for string theories of type-I and $SO(32)$ heterotic. Let $O_I(g_s)$ be some observable in the type-I string theory and $O_{SO(32)}(1/g_s)$ be that observable in the $SO(32)$ theory. Then S-duality says:

$$O_I(g_s) = O_{SO(32)}(\frac{1}{g_s}) \tag{18}$$

The type-IIB theory is self-dual, meaning that:

$$O_{IIB}(g_s) = O_{IIB}(\frac{1}{g_s}) \tag{19}$$

This duality enables one to look at the strong coupling behaviour of these string theories using the dual weakly coupled theory.[96] In other words, one is led into distinctly non-perturbative territory. Of particular interest is the fate of the two remaining consistent superstring theories, namely type-IIA and $E_8 \times E_8$ heterotic. If we try to run these theories through the S-duality machine the theories develop an additional spacetime dimension (with a size given by $g_s\sqrt{\alpha'}$). This new eleven dimensional theory has eleven dimensional supergravity as a low-energy classical limit. As we already mentioned, the quantum theory, given the place-holder name '$\mathcal{M}$-theory', is still to be worked out.

One possibility for the $\mathcal{M}$ is 'Matrix': here the idea is to replace string coordinates with matrices that commute at large distances but that fail to do so at short distances. The fact that those working on this approach do not yet know what the fundamental degrees of freedom are renders it unfit for most philosophical analysis: strictly speaking, there is not enough of the theory to analyze! However, one does sense a definite 'circling in' on this unknown theory.

6.3.5 Many Roads to Quantum Geometry

A result of potential philosophical significance is the derivation of a 'minimum length' in the string—see [2]. This minimal length actually refers to the smallest distance that one can experimentally probe using collisions of strings. For a particle, with energy E (and setting $c = 1$), one can probe distances:

[96] Again, this is related to the so-called Maldacena conjecture now relating the weak-coupling limit of a gravitational theory to the strongly-coupled limit of a certain kind of gauge theory *without gravity*. See previous footnote for more details and references.

$$\Delta X \sim \frac{\hbar}{E} \tag{20}$$

The extra dimension that strings possess modify this somewhat to:

$$\Delta X \sim \frac{\hbar}{E} + G_N E' \tag{21}$$

The additional term $G_N E'$ corresponds to the strings' being thrown together at very high energies. This gives as a minimal distance (for stringy scattering experiments):

$$\Delta X_{min} \sim \sqrt{G_N \hbar} = l_P \tag{22}$$

That is, the minimal length in string theory is the Planck length, as one might expect. This provides an intuitive explanation for why there are no ultraviolet divergences in string theory: the minimal length provides a physical cutoff—it also grounds a notion of quantum geometry in string theory.

Likewise, one of the philosophically interesting aspects of T-duality is that it too appears to imply a fundamental length scale $\sqrt{\alpha'}$ for spacetime. To see how this arises simply note that the duality links physics at distance radius R to that at radius $\frac{\alpha'}{R}$. Witten spells out the implications of this:

> What one might imagine would be a world in which at distances above $\sqrt{\alpha'}$, normality prevails, but at distances below $\sqrt{\alpha'}$, not just physics as we know it but local physics altogether has disappeared. There will be no distance, no times, no energies, no particles, no local signals - only differential topology, or its string theoretic successor. ([Witten, 1989], pp. 350–1)

It is a little puzzling why Witten nonetheless insists that there would be 'something' beneath $\sqrt{\alpha'}$ corresponding to physical reality, rather than interpreting the topological structure as mere surplus. This might constitute a fallacy of misplaced concreteness. However, it seems that sub-$\sqrt{\alpha'}$ scales can be probed by D-branes, but they too lead to a form of quantum geometry (see below).

There are many conceptually (and mathematically) interesting features of D-branes. Most interesting, from a philosophical point of view, is that the coordinates of D-branes (when combined into a *system* of such) are non-commutative. Hence, we have a direct connection to noncommutative geometry and quantum theory—quantum geometry of a rather different variety to that found in loop quantum gravity, for example. How does this come about? D-brane positions are represented by matrices rather than numbers or vectors. When we have a system of N (indistinguishable) D-branes, the positions are then given by $N \times N$ matrices. For $N > 1$ these will generally not commute. There is a connection to group theory and gauge theory too: for a system of N D-branes, the physics is given by gauge group $SU(N)$. Now, since D-branes are micro-black holes, if we stack a system of them together then we can create a macro-black hole. This black hole will then be described by the $SU(N)$ gauge theory, where N depends on how many D-branes we stack. In the limit of large numbers of D-branes (to build up size/mass), this method delivers the desired Bekenstein-Hawking entropy.

At least it does for so-called 'extremal black holes', namely those whose charges take the maximum possible value relative to the values for mass and angular momentum—see [Strominger and Vafa, 1996] for details. Any results that string theorists have in this regard, however, are contingent on their extrapolation away from extremal cases.

6.3.6 Conclusions

The second revolution picture amounts to the emancipation from the constraints imposed by string perturbation theory. The incompleteness with which it does this, is a matter of much controversy. Indeed, many outside of string theory complain that what we end up with is not really a theory at all, but a very long, very complex promissory note. Time and experiment will tell. However, it is true that philosophical work, especially of the interpretive sort, is much harder as applied to the non-perturbative approach.

6.4 Canonical Quantization

Canonical approaches to general relativity formulate the theory within the Hamiltonian formalism as a dynamical theory of the basic configuration variable representing space (e.g. spatial geometry, spatial connection, or Wilson loop of a spatial connection). One then attempts to adapt standard quantization techniques to general relativity so formulated. Hence, the fundamental object is space, and general relativity is about its evolution. This is quite unlike general relativity in its standard spacetime formulation. In that case although spacetime is said to be 'dynamical', it itself does not change: spacetime is given once and for all. Of course, in order to *evolve*, a time is needed against which things do their evolving; but in general relativity time is one of the things to be solved for. 'Dynamical' here refers to the nature of spacetime's coupling to matter, to background independence. Canonical approaches do allow us to speak about evolution by setting apart time from space, and allowing space to evolve with respect to it. Hence, one splits spacetime apart so that $\mathcal{M} \cong \mathbb{R} \times \sigma$ (where σ is a compact three dimensional hypersurface). This is achieved by means of a foliation of the spacetime by a family of spacelike hypersurfaces, or leaves:

$$\mathfrak{F}_t : \sigma \to (\Sigma_t \subset \mathcal{M}) \tag{23}$$

Each leaf Σ_t is then taken to correspond to an instantaneous spatial slice (an 'instant of time').[97] Spacetime is recovered as a stack (a one-parameter family) of these slices.

However, there are many ways in which this spacetime recovery can be achieved from stacks of slices. This freedom in the way spaces are stacked corresponds to the diffeomorphism (gauge) symmetry of the spacetime version of general relativity. The symmetry is canonically rendered using four constraint functions on the chosen spatial manifold, a scalar field (known as the Hamiltonian constraint) and a vector field (known as the diffeomorphism constraint). These have the effect, respectively, of pushing data

[97] Each of these surfaces corresponds to the same initially chosen surface in terms of its intrinsic properties. They are distinguished by their extrinsic properties, by the way they are embedded in spacetime.

on the slice onto another nearby (infinitesimally close) slice and shifting data tangentially to the slice. In a canonical approach (to field theories) one writes theories in terms of fields and their momenta. Spacetime covariant tensors are split apart into spatial (tangential) and temporal (normal) components. This naturally obscures general covariance, but the theory is generally covariant despite surface appearances. The general covariance of the Einstein equations, reflecting the spacetime diffeomorphism invariance of the theory, is *encoded* in constraints.[98] Taken together, when satisfied, these constraints are taken to reflect spacetime diffeomorphism invariance; together they tell us that the geometry of spacetime is not affected by the action of the diffeomorphisms they generate. This job is done by two, of course, since the diffeomorphism constraint deals with aspects of the spatial geometry and the Hamiltonian constraint deals with aspects of time. Imposing both delivers the desired full spacetime diffeomorphism invariance.

6.4.1 The ADM Formulation.

The canonical formulation of general relativity depicts the gravitational field and spacetime geometry in terms of the evolution of fields defined on spatial slices (or hypersurfaces) Σ_i, given some foliation of spacetime. In the ADM (geometrodynamical) case, the geometry of the hypersurfaces is described by the 3-metric q_{ab} (induced by the foliation); this is the configuration variable.[99] The configuration space is then the space of Riemannian metrics on Σ, $\mathrm{Riem}(\Sigma)$. Recall that in geometrodynamics (cf. [8]) the points in the phase space of GR are given by pairs (q, p)—where q is a Riemannian metric on a 3-manifold Σ and p is related to the extrinsic curvature K of Σ describing the way it is embedded in a four dimensional Lorentzian spacetime. In GR, the pair must satisfy the constraint equations, and this condition picks out a surface in the phase space called the constraint surface. The observables of the theory are those quantities that have vanishing Poisson Bracket with all of the constraints. According to the geometrodynamical program, each point on the constraint surface represents a physically possible (i.e., by the lights of general relativity) spacelike hypersurface of a general relativistic spacetime. Points lying on the complement of this surface are also

[98]In the Lagrangian formulation of general relativity the spacetime symmetries are manifest. The canonical formulation buries the symmetries in constraints, due to the splitting of spacetime into space and time. The basic idea of a constraint can be best understood with a simple visual example. First consider a particle that is able to move on a plane, with configuration variable (position, specified by a pair of numbers $(x, y) \in \mathbb{R}^2$) and associated momentum variables p_x and p_y. Four degrees of freedom in total. Now suppose that the particle is restricted to a circle, $x^2 + y^2 = r^2$. In this case the particle no longer has the 'freedom to move' that it previously had, so that there are states, previously accessible, that are now inaccessible—hence the terminology, *constraint*. The constraint in this case is: $xp_x + yp_y = 0$. The variables are, therefore, not all independent of one another: we can solve for one in terms of the others. This means that the number of degrees of freedom is reduced by two, so there are just two remaining. The inaccessible states are usually understood as 'surplus structure', and one can move to the 'reduced' formulation with fewer degrees of freedom, taking these as providing the basis of a description without constraints, with the surplus jettisoned.

[99]We can distinguish various approaches through the choice of variables. The earliest attempts used the most obvious choice of a 3-metric q and its conjugate p, giving a theory of geometrodynamics. More recent work has been couched in terms of a connection and its conjugate and the holonomy of a connection (i.e. the path-dependent integration of the connection around a loop in Σ) and its conjugate. The latter choice leads to loop quantum gravity, in which the fundamental classical variables are Wilson loops. See §6.4.2, below, for more details on these alternative polarizations.

3-manifolds, but they do not represent physically possible spacetimes; they have metric and extrinsic curvature tensors that are incompatible with those needed to qualify as a 3-space embedded in a general relativistic spacetime. The constraint surface comes equipped with a set of transformations $\mathcal{C} \to \mathcal{C}$ that partition the surface into subspaces known as 'gauge orbits' (these transformations are the gauge transformations).

To develop a spacetime from an initial data slice (satisfying the constraints), one selects a one-parameter family of gauge transformations by choosing a specific lapse function $N(x,t)$ and shift vector $N^a(x,t)$ and evolving the data with the constraints—varying the action with respect the lapse function gives the Hamiltonian constraint:

$$\mathcal{H}[N] := \frac{1}{\sqrt{\det q}}(q_{ac}q_{bd} - \frac{q_{ab}q_{cd}}{2})p^{ab}p^{cd} - \sqrt{\det q}R \approx 0 \tag{24}$$

where R is the Ricci scalar curvature associated with the 3-metric q. Varying with respect to the shift gives the diffeomorphism constraint:

$$\mathcal{D}[N^a] := -2q_{ac}D_b p^{bc} \approx 0 \tag{25}$$

Where D is the covariant derivative compatible with the 3-metric q.

Conceptual (and technical) problems follow quickly from this formulation. Most obvious is that the imposition of the Hamiltonian constraint implies that we do not have a time coordinate to work with—but see below for a method of extracting a time variable from the field components. Given this, one does not have a Hamiltonian generating the evolution; the Hamiltonian constraint itself delivers the dynamics. The problem is that the deformations it generates are diffeomorphisms, and imposing the constraint amounts to an invariance with respect to such deformations. This is, of course, just what we would expect in a theory without an external, absolute time parameter. But how are we to make sense of a dynamical theory for which this is the case—i.e. how are we to make physical sense of a background independent theory? There is some consensus forming that imposing the Hamiltonian constraint amounts to viewing the dynamics as involving correlations between the physical degrees of freedom of the theory, rather than involving a relationship between some fixed structure and the physical processes. Hence, though evolution with respect to an independent time parameter is ruled out by the Hamiltonian constraint, one can adopt a kind of relational view of evolution according to which a field, say, evolves with respect to another (physical) field rather than an external time parameter. Whether this amounts to *relationalism* or not is not clear. There are two problems here: firstly the manifold still appears as a background structure in canonical approaches. Secondly, one still has the option of interpreting the gravitational field as a substantival space. We return to these issues below. Now let us turn to the quantization of this theory.

There are four quantum constraints in quantum (Hamiltonian) general relativity—or, rather, $4 \times \infty$ (that is four infinite families worth) since these are local in that they sit at every point of the hypersurface. There are three diffeomorphism (or momentum) constraints that render quantum states independent of the choice of coordinates on Σ:

$$\hat{\mathcal{H}}_a(q,p)\Psi(x) = 0 \ \ , \ \forall x \in \Sigma \ \ (a = 1,2,3) \tag{26}$$

and the Hamiltonian constraint:

$$\hat{\mathcal{H}}_{\perp}(q,p)\Psi(x) = 0 \ \ , \ \forall x \in \Sigma \tag{27}$$

The full Hamiltonian for general relativity—the dynamical equation—is then a sum of these constraints:

$$\hat{H}(q,p)\Psi(x) = \int_{\Sigma} d^3x \ (N\hat{\mathcal{H}}_{\perp} + N^a\hat{\mathcal{H}}_a) \approx 0 \tag{28}$$

Given the constraints we get the result that quantum states are annihilated by the full Hamiltonian:

$$\hat{H}\Psi = 0 \tag{29}$$

This equation (known as the 'Wheeler-DeWitt equation') contains all of the dynamics in quantum geometrodynamics.[100] The quantum states (the wave-functionals Ψ) depend only on the 3-metric, not on time—hence, the solutions represent stationary wavefunctions. In fact, the diffeomorphism constraint implies that the quantum states are only dependent on the *3-geometry* rather than the metric—that is to say, the states are invariant under diffeomorphisms of Σ thanks to the diffeomorphism constraint. As mentioned above, the fact that the fundamental dynamical equation does not depend on time has led to much conceptual discussion. However, geometrodynamical approach ran out of steam due to irresolvable technical difficulties. New variables based on a canonical transformation of the phase space of general relativity led to a more tractable formulation.

6.4.2 New Variables

To understand this formulation properly, we must first introduce the concept of a *dreibein* or triad e_i^a (where i indexes an internal space). These are used to give an alternative representation of the geometry of a spatial slice. Each triad corresponds to a triplet of mutually orthogonal vector fields. These fields are sufficient to reconstruct the spatial geometry since we have the relation $q^{ab} = e_i^a e_i^b$ (where q^{ab} is the inverse metric). This change of variables introduces an additional constraint into the theory—the Gauss law constraint generating $SO(3)$ transformations—on account of the freedom to rotate the vectors without altering the metric.

The new variables (A_a^i, E_i^a) introduced by Ashtekar[101] are related to the triad formulation as: $E_i^a = |\det e_j^b|^{-1} e_i^a$ and $A_a^i = \Gamma_a^i + \gamma K_a^i$ (where $K_a^i = K_{ab}e_i^b$, γ is

[100] Note that there is an alternative way to quantize constrained Hamiltonian systems. One can solve the constraints first, rather than solving them at the quantum mechanical level as was done here (this latter approach is known as 'constrained quantization' or 'Dirac quantization'). Maxwell's theory, for example, proceeds by solving the constraints classically, and then quantizes with respect to the reduced phase space (reduced quantization). The virtue of this approach is that one can apply the steps of standard Hamiltonian quantization *without constraints*. However, in the case of general relativity the reduced phase space is much more difficult to work with. Also, since the constraints are associated with dynamics, in eradicating them it looks as if one eradicates dynamics. See [Ashtekar and Tate, 1991] for a superb introduction to these methods and their differences.

[101] The Ashtekar connection A_a^i is responsible for representing the curvature of space (it provides a notion of parallel transport of spinors); the triad E_i^a (the 'electric fields') contains the metric information (i.e. the triad determines the geometry of space), which it describes via a family of local orthonormal frames (geometric observables can be reconstructed as functionals of these fields). The picture of quantum spatial

the Barbero-Immirzi parameter,[102] and Γ is the spin-connection). One recovers the standard geometry of the spatial slice via the relation: $E^a_i E^b_i = q^{ab} \det q$.

One can then rewrite the diffeomorphism and Hamiltonian constraints, $\mathcal{D}[N^a]$ and $\mathcal{H}[N]$, as follows:[103]

$$\mathcal{D}[N^a] = \frac{1}{8\pi G\gamma} \int_\Sigma d^3x N^a F^i_{ab} E^b_i \approx 0 \tag{30}$$

As before, the diffeomorphism constraint will, when satisfied, insure that the theory is independent of a background spatial geometry, or, in other words, that it is spatially diffeomorphism invariant. Solving this constraint (and the Gauss Law constraint below) provides the arena for loop quantum gravity: quantum spatial geometry. There are objects that solve these constraints in a fairly natural way.

The Hamiltonian constraint responsible for the dynamics, leading to spacetime geometry, is written:

$$\mathcal{H}[N] = \frac{1}{16\pi G\beta} \int_\Sigma d^3x \, N |\det E|^{-\frac{1}{2}} [\epsilon_{ijk} F^i_{ab} E^a_k E^b_k - 2(1+\gamma^2) K^i_{[a} K^j_{b]} E^a_i E^b_j] \approx 0 \tag{31}$$

The additional Gauss law constraint is written:

$$\mathcal{G}[\Lambda] = \frac{1}{8\pi G\gamma} \int_\Sigma d^3x \Lambda^i (\partial_a E^a_i + \epsilon_{ijk} A^j_a E^a_k) \approx 0 \tag{32}$$

This constraint, when satisfied, ensures that the theory is independent of arbitrary rotations of the dreibeins (which we desire, since the spatial geometry, as encoded in the 3-metric, is invariant with respect to such rotations).

6.4.3 Loop Variables

The modern incarnation of canonical quantum gravity is 'loop quantum gravity'. The loop variables are based on connection variables: one takes the path-ordered integral of the connection around a closed curve (i.e. a loop α) in Σ. This is the holonomy $U[A, \alpha]$ of the connection:

$$U[A, \alpha] = \mathcal{P} \exp \, (G \int_\alpha A) \tag{33}$$

geometry is very well-understood. However, the geometry of spacetime is much more complex because it requires that one solve the dynamical equation, the Hamiltonian constraint.

[102] The exact value of this parameter (a dimensionless constant) has to be put in by hand (i.e. it is a *free* parameter). It was set positive by Ashtekar. There is a method to set the value by calibrating loop quantum gravity's expression for the entropy of a black hole with Hawking's formula. However, recently Olaf Dreyer showed how its valued can be computed using the quasi-normal modes (i.e. the vibrational modes) of classical black holes [Dreyer, 2003]—he obtains $\gamma = \ln 3/2\pi\sqrt{2}$. The details are rather complicated: for an elementary discussion see [Baez, 2003].

[103] In the equations that follow, F^i_{ab} is the curvature of the Ashtekar connection. These equalities vanish on the constraint surface, hence the use of '$\approx$' (weak vanishing) as opposed to '$=$'. The presentation here follows Bojowald [2005].

The conjugate variable is then the *flux* of the 'electric field' E_i^a through a strip $\mathcal{S} \in \Sigma$ (where $\mathcal{S} : [0, 1] \rightarrow \Sigma$).[104]

Much of the work achieved so far in loop quantum gravity has been carried out in the context of 'kinematics'—i.e. without solving the quantum constraints, or at least not all of them: the Hamiltonian constraint is the problem. However, interesting results have been found in the kinematical sector which are argued to be robust enough to carry through into the full theory, where all of the quantum constraints are implemented. Perhaps the most interesting result is the discovery of discreteness of geometric operators on the space of states. We have to be rather careful with this result though; the operators do not commute with the constraints, and therefore do not class as *genuine* observables. Only when the surfaces and volumes in question are *physical* (the surface of *this* piece of paper, for example), do we get the possibility of a genuine observable, that is a gauge-invariant quantity (or a quantity represented by an operator on the physical Hilbert space). Attempts have been made to solve all of the quantum constraints using a modified (discrete) covariant methodology: this is the way of spin-foam modelling, on which see §6.6.8.

To quantize this theory one first isolates the Poisson algebra between the fundamental canonical variables—in this case we have as the basic configuration variable of the gravitational field the holonomy $H_A(\gamma)$ of an $SU(2)$-connection A_a^i on 3-space and, as the conjugate momentum variable, the flux of the electric fields E_i^a over a 2-surface S. From their Poisson algebra, one then defines an abstract algebra $\mathcal{A}$ of quantum operators—i.e. at this stage, there is no concrete representation of the operators on a Hilbert space; that is the next task. Once armed with a representation of $\mathcal{A}$ on Hilbert space $\mathcal{H}$ one then has the kinematic backbone of a quantum theory of gravity based on loops.[105] Elements of $\mathcal{H}$ are wave-functions of the connections (square integrable with respect to a diffeomorphism-invariant measure). This space forms an overcomplete basis (the space is too big), something which is cured by shifting to the 'spin-network' basis (see [Rovelli and Smolin, 1995]). The subspaces of this space are labelled by graphs whose links are then labelled by spins (half-integers). This framework gives us a notion of quantum geometry: the geometric operators constructed in this approach serve to 'deposit' a quantum of area on a 2-surface that it intesects. One finds that the spectra of eigenvalues of geometrical operators (such as area and volume) constructed from the fluxes are discrete. Whether this result has physical significance is another matter—see §6.4.5.

6.4.4 Holes and Determinism in the Canonical Approach.

We have already touched upon the steps involved in canonical quantization. Here we develop this some more. The first step is to cast a theory in Hamiltonian form. This is

[104]The use of path-dependent variables to aid in the quantization of the gravitational field was in fact suggested many decades ago by Mandelstam [1962]—Mandelstam points out that Bryce DeWitt and David Pandres made similar suggestions. These ideas were developed in great depth in [Gambini and Pullin, 1996].

[105]Astute readers might be concerned about this stage of the quantization procedure since in systems with infinitely many degrees of freedom one generally faces the problem of inequivalent representations. However, here the novelty of general relativity, its background independence, comes to the rescue, serving to uniquely determine a representation (known as the 'Ashtekar-Lewandowski representation')—see [Lewandowski et al., 2006] and [Fleischhack, 2007] for details.

immediately problematic in general relativity because it does not have the structure of a standard Hamiltonian system—its phase space is not a regular symplectic manifold. What this means is that, given a specification of the values of the canonical variables at an initial time, the equations of motion of the theory are not able to propagate all variables: the future values of the variables cannot be determined uniquely. A simple reductio can show why this has to be the case: assume that the components of the metric *can* be uniquely determined given their initial specification (along with their first time derivatives). In this case there is a single, unique way that the metric will develop in the future. But this violates the general covariance of general relativity. Hence, the original assumption was wrong. Instead, the theory permits arbitrary coordinate transformations to the future of some initial time (and which is the identity at all times before this time). Hence, there are multiple solutions (ways of developing the data) compatible with some initial specification. Determinism appears to be threatened, but this is eradicated imposing a gauge principle which considers these distinct solutions to represent one and the same physical situation (this is the *3-geometry* that was mentioned earlier). This is analogous to the problem that arises in the case of Maxwell's theory of electromagnetism (written in terms of potentials $\mathbf{A}$ and ϕ) for which the future values of these quantities are determined only up to an arbitrary function of spacetime.[106] Again, the indeterminism can be washed away by treating the multiple futures as gauge-equivalent, representing one and the same *physical* configuration of fields. This non-uniqueness, then, does not imply that general relativity does not have a well-posed initial value problem: it does. The Einstein field equations comprise a second order system of hyperbolic equations, so that in this sense, in general, a specification of the metric and its first time derivatives on some spacelike hypersurface will deliver a unique solution. The problem is that the diffeomorphism invariance of the spacetime formulation of the theory leads to the presence of constraints on the initial data. We find that the solution is uniquely determined *up to a diffeomorphism*. This is basically the issue underlying the hole problem, along with its standard solution.

This problem plays a key role in the quantum theory of canonical gravity since one needs to make a decision about whether to remove the gauge freedom before or after quantization (or before and after the constraints have been solved). Loop quantum gravity, and most other modern canonical approaches, adopt the method of Dirac quantization according to which the constraints are imposed as operators at the quantum level. Since symmetries (such as the gauge symmetries associated with the constraints) come with quite a lot of metaphysical baggage attached, such a move involves philosophically weighty assumptions. For example, the presence of symmetries in a

[106]There is a disanalogy between these two cases: Maxwell's theory faces the Aharonov-Bohm effect. Here we modify the double-slit experiment to include a solenoid (long—ideally, infinitely so—and thin) sitting beyond and in between the slits. This produces a magnetic field confined within the solenoid when it is turned on. Outside of the solenoid the value of the magnetic field is zero. Electrons are fired through the slits at the screen, and when the solenoid is turned on, they undergo a phase shift—this is manifested by a shift in the interference pattern on the detection screen. This phase shifting is known as the "Aharonov-Bohm effect". The magnetic field is zero in the path taken by the electrons, but the vector potential is non-zero. This appears to show that the gauge potentials are real, so that gauge equivalence does not imply physical equivalence. Either that, or there is some non-local action being performed at a distance by the magnetic field on the electrons. See [1] for the original presentation or [Feynman, 1962], Chapter15, for an exceptionally clear presentation.

theory would appear to allow for more possibilities than one without, so eradicating the symmetries means eradicating a chunk of possibility space: in particular, one is eradicating states that are deemed to be physically equivalent, despite having some differences somewhere or other. Hence, imposing the constraints involves some serious modal assumptions. Belot and Earman [2001] have argued that since the traditional positions on the ontology of spacetime (relationalism and substantivalism) involve a commitment to a certain way of counting possibilities,[107] the decision to eliminate symmetries can have serious implications for the ontology one can then adopt.

6.4.5 Is Quantum Geometry Discrete?

In loop quantum gravity, as we saw, the geometric operators are not physical observables: they are operators on a kinematical state space that is far too big! The diffeomorphism and Hamiltonian constraints have not been factored out of the space, though the Gauss law constraint is satisfied. One forms a state space with the configuration variable as an SU(2) valued connection. This gives $\mathcal{L}^2(\mathcal{A}/\mathcal{G})$ (with $\mathcal{A} \in$ SU(2)-connections on Σ and where $\mathcal{G}$ is the Gauss constraint). Quantum states are given by spin networks, which form a basis for $L^2(\mathcal{A}/\mathcal{G})$. Recall that in order to get solutions to the diffeomorphism constraint one has to factor out the diffeomorphism freedom. This involves taking equivalence classes of spin-networks under diffeomorphisms of Σ, giving us the s-knots (i.e. the orbits of spin-networks by the action of the diffeomorphism constraint). Finding solutions to the constraints would give us states of quantum gravity that are invariant under diffeomorphisms of spacetime. These would be the physical states that the theory would be about and that the experimentalists would try to find out about.

One of the main claims of loop quantum gravity is that it makes a genuine physical prediction about the nature of space; one that is, in principle, testable. The theory says that surfaces of space are discrete; or rather, the operators corresponding to the measurements one would perform to determine the properties of space (area, volume, etc.) have a discrete spectrum which can be computed and which forms the basis of the prediction. Hence, this property of discreteness of geometry at the Planck scale forms the core of the potentially predictive basis of loop quantum gravity. Loop theorists also use it to compute the entropy of quantum black holes. To do this one views the surface area (i.e. the horizon) of a black hole as being determined by the number of spin network links intersecting the surface, each one depositing an area quantum of $8\pi l_P^2 \gamma \sqrt{j(j+1)}$. However, given the problem presented above, these cannot be viewed yet as genuine physical predictions of the theory.[108] As potentially revolution-

[107] Roughly, substantivalists countenance more possibilities than relationalists because they count states that differ only in how the physical stuff is distributed over a set of spacetime points. Relationalists will count these as the same physical possibility.

[108] It is generally assumed that discreteness transfers from the gauge variant (kinematical, unphysical) to the gauge invariant (dynamical, physical) cases, so that the genuine physical geometrical operators possess discrete spectra too. However, Dittrich and Thiemann [2007] demonstrate that discreteness at the kinematical level does not always transfer into the physical level for the case of partial and complete observables. Their examples are based on models with few degrees of freedom. It is possible that their result is an artifact of this restriction; in the case of general relativity, you will recall, there are infinitely many constraints. The burden of proof is, however, clearly on the loop programme to demonstrate the transference of spectral properties.

ary and philosophically exciting as the spectral discreteness of geometric operators is, it has to be conceded that there is, thus far, no firm *proof* of Planck scale discreteness. The discreteness result has been shown to hold only for operators on the kinematical Hilbert space: that is, for gauge variant quantities. It is still an open question whether this result transfers to genuine observables (i.e. operators that satisfy all of the constraints and are defined on the physical Hilbert space). This means that the results of discreteness does not imply that this is what would be measured in a real physical experiment (such measurements will presumably be described by gauge invariant, Dirac observables). Hence, the loop gravity programme still needs to solve the dynamics because Dirac observables must commute with *all* of the constraints. *If* the theory is then found to retain this discreteness, then the result is clearly one of tremendous physical significance. Unpacking the meaning and implications of this kind of discreteness is a task philosophers could be engaging in now.

6.4.6 The Problem of Time.

Conceptual problems are much more transparent in canonical, non-perturbative approaches (1) because the full metric is quantized and (2) because $g_{\mu\nu}$ is understood to perform its dual function of both describing the gravitational field and as being the determinant of the spacetime geometry in virtue of its status as a metric field. Naturally, if we adopt this viewpoint, then a quantization of $g_{\mu\nu}$, so that the components become quantum field variables, will, in some sense, involve a quantization of spacetime geometry. Unpacking this notion will be a job for philosophers as well as physicists. One potential consequence—hard to prove for the physical case, as we saw above—is that spacetime (or, rather, space) is discrete. Another is that spacetime seems not to be involved as a background, rather it is what one gets out of the theory (at least, that's the hope).

Arguably, however, the main philosophical problem of all canonical approaches is the problem of time, which also manifests itself as a problem of change, and is buried in the problem of observables. All of these relate back to the diffeomorphism invariance of Einstein's theory, and the way in which this invariance principle is encoded in the constraint equations, especially the Wheeler-DeWitt equation. In order to keep this chapter at a reasonable length we focus on just few aspects of this very large, much discussed problem.[109]

As Ashtekar and Geroch point out, "[s]ince time is essentially a geometrical concept, its definition must be in terms of the metric. But the metric is also the dynamical variable, so the flow of time becomes intertwined with the flow of the dynamics of the system" ([9], p. 1215). The problem of time (and change) is that the dynamics of the system is contained in the constraints, and these are taken to generate gauge motions. But gauge motions correspond to no change in physical state! Further problems naturally arise when we take the metric to be a quantum variable, in which case there are

[109] More details, from a philosophical point of view, can be found in the review articles [Belot and Earman, 2001; Rickles, 2006]. An excellent pair of classic reviews is [Kuchař, 1992; Isham, 1993]. For a philosophically astute review of the problem of the emergence of time in quantum gravity, covering a range of approaches to quantum gravity rather than just canonical approaches, see [Butterfield and Isham, 1999].

fluctuations in the geometry (including temporal geometry). This gives us a variety of interrelated problems, both classical and quantum, to do with time and change:

- Prima facie, the genuine observables of the theory don't change from one hypersurface to the next since they must commute with all of the constraints (which take the data from one hypersurface to another)—the constraints generate gauge, so this motion is pure gauge.
- Displacement in time is just a diffeomorphism and, therefore, also a gauge transformation. The physics needs to be independent of such transformations, and so must be time-independent.
- In the quantum theory, when we impose the constraints we get a Hamiltonian that necessarily annihilates physical states.

One response to these problems, adopted by Karel Kuchař [1992] is to distinguish *physically* between the Hamiltonian and diffeomorphism constraints, so that only the latter is viewed as a generator of gauge transformations. One then has to find a 'hidden' or 'internal' time among the phase space variables.[110] Now, the configuration variable in canonical quantum gravity, in the geometrodynamical formulation, is the 3-metric which requires 6 numbers per space point.[111] By gauge fixing and selecting a particular coordinate system three more degrees of freedom can be disposed of, leaving three—this is just to impose invariance under the spatial diffeomorphism group $\mathrm{Diff}(\Sigma)$. As we saw earlier, general relativity has two degrees of freedom corresponding to the two helicity states of a massless spinning graviton. One way to resolve the discrepancy is to impose invariance under *normal* deformations of the hypersurface (from the perspective of the ambient spacetime in which the hypersurface is embedded). This seems reasonable on account of the fact that we need to reflect the full spacetime diffeomorphism group in the formalism, and $\mathrm{Diff}(\Sigma)$ isn't by itself sufficient. This is encoded in the Hamiltonian constraint (or Wheeler-DeWitt equation).

Of course, the Wheeler-DeWitt equation does not contain a time variable. The residual degree of freedom has been identified as a 'hidden' time variable known as 'internal time'. The time is, then, buried in the gravitational field, and appears as a function of the field's variables. When this time is isolated from the variables, one can consider the evolution of the other variables (the two physical degrees of freedom) against this internal time. This does not violate the condition of no preferred reference frames, since the choice of internal time is not unique: time is 'many fingered', as one would expect. The invariance principle encoded in the Wheeler-DeWitt equation is a reflection of the fact that there is no privileged way of slicing spacetime into instants of time. Alternatively, one can view the invariance as pointing to the *eradication* of a fundamental notion of time.

[110] Several authors have suggested that the non-local hidden variables theory of Bohm may offer a way out of the trouble by dispensing with the Schrödinger equation entirely in place of another that has a nonzero quantum dynamics—see [Callender and Weingard, 1996] and [Goldstein and Teufel, 2001]. However, I have yet to see this proposal worked out beyond the basic idea; certainly not into something that could deliver a quantum theory of gravity.

[111] Three degrees of freedom are removed by the symmetry of the metric: $g_{ab}(x) = g_{ba}(x)$.

A problem (or feature) that emerges from the internal time approach is that, since time is bound up with the gravitational field, it is a semi-classical or *emergent* feature. One begins with a notion of space and then develops a notion of spacetime from this. However, because spacetime trajectories are subject to the uncertainty principle, just like particle trajectories, the notion of spacetime breaks down.[112]

Hence, there are various proposed resolutions of this problem: some retain time as an intrinsic feature of the world; others deny any fundamental reality to time. Following Karel Kuchař's terminology, these broad responses are called 'Heraclitean' and 'Parmenidean' respectively.[113] The latter category of responses, the time deniers, follow Einstein's dictum that "if physics wants to use time, it first has to define it" [Einstein, 1916b]. This leaves us a certain amount of freedom in 'recovering' a notion of time. We briefly look at several proposals that have a more philosophical flavour.

Julian Barbour [2001] bites the bullet and defends the view that time, as a dimension against which things evolve, does not exist. This is based on the fact that canonical quantum gravity uses just the 3-space. Jeremy Butterfield [2001] describes Barbour's position as "a curious, but coherent, position which combines aspects of modal realism *à la* Lewis and presentism *à la* Prior" (p. 291). While there is a whiff of these positions in Barbour's position, his brand of timelessness is more directly connected to a denial of *persistence*—and, as such, is not timeless at all. Rather, it is changeless. Far from denying time, then, Barbour has in fact *reduced* it (or, rather, the instants of time) to the points of a relative configuration space. This is, however, very different from time as is standardly conceived, and how it is modelled in quantum mechanics, for example.

The central structure in Barbour's vision is the space of Riemannian metrics mod the spatial diffeomorphism group (known as "superspace"): $\mathrm{Riem}(\Sigma)/\mathrm{Diff}(\Sigma)$. Choosing this space as the configuration space of the theory amounts to solving the diffeomorphism constraint; this is Barbour's *relative configuration space* that he labels "Platonia" (ibid., p. 44). The Hamiltonian constraint (i.e. the Wheeler-DeWitt equation) is then understood as giving (once solved, and "once and for all" ([Barbour, 1994], p. 2875)) a *static* probability distribution over Platonia that assigns amplitudes to 3-geometries (Σ, q) in accordance with $\|\Psi[q]\|^2$. Each 3-geometry is taken to correspond to a "possible instant of experienced time" (ibid.) The very real *appearance* of change is explained by introducing the notion of a 'time capsule', or a 'special Now', by which he means "any fixed pattern that creates or encodes the appearance of motion, change or history" ([Barbour, 2001], p. 30). Barbour *conjectures* that the relative probability distribution determined by the Wheeler-DeWitt equation is peaked on time capsules; as he puts it "the timeless wavefunction of the universe concentrates the quantum mechanical

[112]Recall that Kant argued that space and time were necessary conditions for experience. Presumably this implies that any adequate physics must include them amongst its fundamental categories. But this is denied by many quantum gravity researchers, not just canonical theorists. But there need not be a clash: the claim is generally that time and space do not exist at the microscopic level, not that they do not exist *simpliciter*. It is possible, for example, that spacetime is an emergent or collective property that is manifest only at certain scales. This viewpoint can be seen by remembering that the features of space and time are determined by the (classical) gravitational field.

[113]It is important to note that the debate here is not directly connected to the debate in the philosophy of time between 'A-theorists' and 'B-theorists' (or 'tensers' and 'detensers', if you prefer). Both of these latter camps agree that time exists, but disagree as to its nature. By contrast, the division between Heraclitean and Parmenidean interpretations concerns whether or not time exists *simpliciter*!

probability on static configurations that are time capsules, so that the situations which have the highest probability of being experienced carry within them the appearance of time and history" (ibid.).

Barbour's approach is certainly timeless in this sense: it contains no reference to a background temporal metric in either the classical or quantum theory. The metric is defined by the dynamics, in true Machian style. Butterfield mentions that Barbour's denial of time might sound (to a philosopher) like a simple denial of temporal becoming—i.e. a denial of the A-series conception of time. He rightly distances Barbour's view from this B-series conception. Strictly speaking, there is neither an A-series nor a B-series on Barbour's scheme. Barbour believes that space is fundamental, rather than spacetime. This emerges from his Machian analysis of general relativity. However, according to Barbour, there are *many* Nows that exist 'timelessly', even though we happen to be confined to *one*. The following passage brings the 'Lewis/Prior' hybrid flavour of Barbur's view that Butterfield mentions out:

> All around NOW ... are other Nows with slightly different versions of yourself. All such nows are 'other worlds' in which there exist somewhat different but still recognizable versions of yourself. (ibid., p. 56)

Clearly, given the multiplicity of Nows, this cannot be presentism conceived of along Priorian lines, though we can certainly see the connection to modal realism; talk of other nows being "simultaneously present" (ibid.) surely separates this view from the Priorian presentist's thesis. That Barbour's approach is not a presentist approach is best brought out by the lack of temporal flow; there is no A-series change. Such a notion of change is generally tied to presentism. Indeed, the notion of many nows existing simultaneously sounds closer to eternalism than presentism; i.e. the view that past and future times exist with as much ontological robustness as the present time. These points also bring out analogies with 'many-worlds' interpretations of quantum mechanics; so much so that a more appropriate characterization might be a 'many-Nows' theory.[114]

There is a view, that has become commonplace since the advent of special relativity, that objects are four-dimensional; objects are said to 'perdure', rather than 'endure': this latter view is aligned to a three-dimensionalist account according to which objects are wholly present at each time they exist, the former view is known as 'temporal part theory'. The four-dimensionalist view is underwritten by a wide variety of concerns: for metaphysicians these concerns are to do with puzzles about change; for physics-minded philosophers they are to do with what physical theory has to say. Change over time is characterized by differences between successive temporal parts of individuals. Whichever view one chooses, the idea of *persisting* individuals plays a role; without this, the notion of change is simply incoherent, for change requires there to be a *subject* of change. Although Barbour's view is usually taken to imply a three-dimensionalist interpretation (by Butterfield for one), it is perfectly compatible with a kind of temporal parts type theory. We see that the parts of Platonia, the Nows, do not change or endure and they cannot perdure since they are three-dimensional items and the parts occupying distinct 3-spaces (and, indeed, the 3-spaces themselves) are not genidentical;

[114] Indeed, Barbour himself claims that his approach suggests what he calls a "many-instants ... interpretation of quantum mechanics" (ibid.). However, it seems clear that the multiplicity of Nows is as much a classical as a quantum feature, so we have a definite disanalogy.

rather, the quantum state varies from Now to Now in accordance with the Hamiltonian constraint in such a way that the parts (specifically, the time capsules) contain records that 'appear' to tell a story of linear evolution and persistence. Properly understood, then, Barbour's views arise from a simple thesis about identity over time, i.e., a denial of persistence:

> We think things persist in time because structures persist, and we mistake the structure for substance. But looking for enduring substance is like looking for time. It slips through your fingers. (ibid., p. 49)

In denying persisting individuals, Barbour has given a philosophical grounding for his alleged timelessness. However, as I mentioned earlier, the view that results might be seen as not at all timeless: the relative configuration space, consisting of Nows, can be seen as providing a *reduction* of time, in much the same way that Lewis' plurality of worlds provides a reduction of modal notions.[115] The space of Nows is given once and for all and does not alter, nor does the quantum state function defined over this space, and therefore the probability distribution is fixed too. But just like modality lives on in the structure of Lewis' plurality, so time lives on in the overall structure of Barbour's Platonia. For a good philosophical examination of this view, see [Butterfield, 2001]; for a recent more technical account, placed in historical context, see [Barbour, forthcoming].

Richard Healey [Healey, 2004] is not convinced by the 'no-change' argument in classical general relativity. He questions the claim that Dirac observables exhaust general relativistic worlds arguing that this is overly restrictive. *Observing* change involves the introduction of 'frames': genuine change is frame-dependent. Once we have frames on top of the unchanging structure given by Dirac observables then a coherent notion of change emerges—indeed *supervenes* on the structure formed from the Dirac observables. Of course, if we are to have an account of these frames that is internal to general relativity, then it will surely be the case that they are built up from physical degrees of freedom of the theory. If this is so then we have a position that begins to resemble the relational-type responses according to which change, at a fundamental level (in the sense of a change of the fundamental variables with respect to a time parameter) does not exist, but evolution does take place with respect to other physical degrees of freedom of the theory. That this is in fact the case can, I think, be inferred from Healey's example of the detection of gravitational waves using LIGO. Healey wants to align the notion of frame with the notion of a foliation. It is difficult to see how calling this a frame takes one beyond ordinary Hamiltonian general relativity which, of course, is based on just such foliations. Perhaps Healey's basing foliations on physical observers is supposed to add some extra ingredient (see pp. 410–1). However, the invocation of the conscious states of observers looks like a restatement of the problem: we appear to observe change, and yet general relativity appears to rule it out on account of the fact that the basic observables of theory cannot take on different values on different time slices relative to any foliation (given some initially chosen topology for the slices). The basic idea that one can have 'change without change' (i.e. change at one level but not

[115] Roughly, Lewis' idea is that the notions of *necessity* and *possibility* are to be cashed out in terms of holding at all or some of a class of 'flesh and blood' worlds.

at a more fundamental level) does deserve the close scrutiny of philosophers. Indeed, many of the Parmenidean views espouse this view in some form or another.

Carlo Rovelli has attempted to resolve the problem of time in several different ways, similar to Healey's in the basic approach. His most recent attempt involves the utilization of his own 'partial observables' framework [Rovelli, 2002]—his textbook on loop quantum gravity [Rovelli, 2004] contains a very readable account of the partial observable framework. Partial observables are contrasted with *complete* observables. This distinction keys into the division between gauge-variant and gauge-invariant quantities. In the constrained Hamiltonian formalism of Dirac only the latter are genuine, physical observables. The former are unphysical surplus; useful perhaps, but ultimately doing no direct representational work. Rovelli modifies this framework so that complete observables are viewed as correlations between partial observables. Let's spell this out in more detail.

A *partial* observable is a physical quantity to which we can associate a measurement leading to a number and a *complete* observable is defined as a quantity whose value (or probability distribution) can be predicted by the relevant theory. Partial observables are taken to coordinatize an extended configuration space $\mathcal{Q}$ and complete observables coordinatize an associated reduced phase space Γ_{red}. The "predictive content" of some dynamical theory is then given by the kernel of the map $f : \mathcal{Q} \times \Gamma_{red} \to \mathbb{R}^n$. This space gives the *kinematics* of a theory and the *dynamics* is given by the constraints, $\phi(q^a, p_a) = 0$, on the associated extended phase space $T^*\mathcal{Q}$. There are quantities that can be measured whose values are *not* predicted by the theory; yet the theory *is* deterministic because it does predict correlations between partial observables (which form complete observables). The dynamics is then spelt out in terms of *relations* between partial observables. Hence, the theory formulated in this way describes relative evolution of (gauge variant) variables as functions of each other. No variable is privileged as *the independent one* (cf.. [Montesinos et al., 1999], p. 5). The dynamics concerns the relations between elements of the space of partial observables, and though the individual elements do not have a well defined evolution, relations between them (i.e. correlations) do: they are independent of coordinate space and coordinate time.

Rovelli suggests that we can use this to resolve the problem of time as follows: let $\phi = T$ be a partial observable parametrizing the ticks of a clock (evolving out across a gauge orbit), and let $f = a$ be another partial observable (also stretching out over a gauge orbit). Both are gauge *variant* quantities: their change is purely gauge dependent. A gauge *invariant* quantity, a complete observable, can be constructed from these partial observables as:

$$\mathcal{O}_{[f;T]}(\tau, x) = f(x') \tag{34}$$

These quantities encode correlations. They tell us what the value of a gauge variant function f is when, under the gauge flow generated by the constraint, the gauge variant function T takes on the value τ. This correlation is gauge invariant. These are the kinds of quantity that a background independent gauge theory like general relativity is all about. We don't talk about the value of the gravitational field *at a point of the manifold*, but where some other physical quantity (say, the electromagnetic field) takes on a certain value. Hence, evolution is relational.[116]

There are issues remaining over the interpretation of these correlations. Rovelli claims that "the *extended* configuration space has a direct *physical* interpretation, as the space of the partial observables" ([Rovelli, 2002], p. 124013-1, my emphasis). *Both* spaces—the space of genuine (complete) observables and partial observables—are invested with fundamental physicality (or ontological primacy) by Rovelli; the partial observables, in particular, are taken to be physical variables. Einstein, it seems, argued that only the correlation (between the gravitational field and other data) is physically real; the relata are secondary, unable to exist independently. This fits the Dirac picture better, but to adopt it one must fill in an account of the relationship between the partial and complete observables in such a way that the complete observables have ontological primacy. In [Rickles, 2006; 2007; 2008] it is argued that the proper interpretation of Rovelli's approach is structural. That is, the partial observables have no intrinsic properties, but gain their properties from the correlation they find themselves in (the complete observable). One must also adapt the approach to mesh with quantum theory—see [Weinstein, 2000] for a philosophical discussion of this problem; [Hájiček, 1996] gives a more technical discussion.

Belot and Earman [2001] argue that these problems of time and change may serve to reinvigorate the listless debate between substantivalism and relationalism—that is, the debate concerning whether spacetime is a 'substance' (ontologically independent of matter) or not—by furnishing *physical* reasons for deciding one way or the other. They believe that substantivalism and relationalism are aligned to particular ways of canonically quantizing gravity (specifically with how one deals with constraints) so that if one approach were successful, and the other not, then that would give a principled reason for accepting the aligned spacetime ontology. I have argued elsewhere that this is not the case (see [Rickles, 2005b; 2006; 2007]). The problems and responses to time and change are analogous to the problems and responses to the hole argument, and the solution to the latter, vis-á-vis spacetime ontology, is far from decided.

6.4.7 Conclusions

Philosophers have debated geometrodynamics since the early 1970s—e.g. [Graves, 1971]. Moreover, the physicists involved with geometrodynamics have contributed to the philosophical debate—e.g. [Misner, 1972]. This is a testament to the fact that canonical approaches have been more fruitful for philosophical research. Whether this is due to some deep reasons or whether it is because it is just simpler to understand is debatable. Whatever the reasons are, it seems that canonical quantum gravity is a very fit vehicle for philosophical research.

6.5 Feynman Quantization

In the previous sections we have looked at covariant and canonical quantization techniques applied to the gravitational field. Of course, Richard Feynman developed an-

[116] This view is broadly in line with Einstein' own view of the physical content of general relativity. Indeed, he is very modern-sounding on this point, writing that "the gravitational field at a *certain location* represents nothing 'physically real', but the gravitational field together with other data does" ([Einstein, 1918], p. 71).

other form of quantization using functional integral (or path-integral) techniques. Here we will follow Charles Misner [Misner, 1957] in speaking of the functional integral or path integral approach as 'Feynman Quantization'.[117] This too has been applied to gravity in the hope of constructing a quantum theory of gravity. If successful the approach would be able to generate solutions of the Wheeler-DeWitt equation. According to Misner, the Feynman quantization of general relativity involves the following series of steps:

- A 4-manifold $\mathfrak{M}$ of points—where the $x \in \mathfrak{M}$ have "no physical significance in themselves" (p. 501) and serve a purely convenient purpose ("as handles for stating the significant mathematical relationships"). No definite metric for $\mathfrak{M}$ is chosen, nor will it be.

- A family of hypersurfaces 3-dimensional submanifolds $\sigma \subset \mathfrak{M}$.

- Define the metric at a point to be the inner product of a pair of tangent vectors at the point. However, the metric at a point is not to be viewed as a distance interval, only as useful in the computation of such intervals.

- Introduce a 'field history' $f(x)$ over all points of $\mathfrak{M}$ that gives a definite value for the field (including the metric field) at the point. When the x ranges over the points of a hypersurface $\sigma_1 \subset \mathfrak{M}$, the field history is a 'field configuration' f_1 at σ_1.

- Define a 'state functional' ψ_σ for the hypersurface σ: the state functional ψ_1 at σ_1 is given by the complex number $\psi_1(f_1)$ (the value of ψ_1 when the field is in configuration f_1); one does this for each field configuration on σ_1. The state functional ψ_1, then, completely characterizes the physical state of the field system—i.e. given ψ_1 (and the theoretical apparatus appropriate to the field concerned) one can compute expectation values for all observables.

- The 'Heisenberg formulation' versus 'Schrödinger formulation' distinction amounts to choosing a representation of states ψ either as a state functional on some particular hypersurface or as a representation by a *family* of state functionals on different hypersurfaces (satisfying the Schrödinger equation).

- However, Misner uses what he calls the "Feynman principle" in place of the Schrödinger equation: a state functional on a particular hypersurface, one can find the other members of the family of states on other hypersurfaces via the functional integration over the field configurations f_0 at the initial hypersurface σ_0: $\psi_a(f_a) = \int K(f_\sigma, \sigma; f_0\sigma_0)\psi_0(f_0)\delta f_0$ (where K is the Feynman propagator).

- Misner notes that gauge invariance implies that there is an overdetermination of physical states by the state functionals on hypersurfaces. In the context of general relativity this gauge invariance is diffeomorphism invariance. It has the fur-

[117] Misner credits John Wheeler with suggesting the idea of attempting a Feynman quantization of general relativity via the formula $\int \exp\{(i/\hbar)(\text{Einstein action})\}d$ (field histories).

> ther implication that pairs of manifolds diffeomorphic (i,e, topologically equivalent) to one another should have equivalent Feynman propagators: "the Feynman propagator connecting equivalent hypersurfaces is trivial" (p. 507).[118]

According to this approach, in the context of the quantum field theory of particles, one computes the probability for a particle to go between two states by summing over all possible trajectories (histories) that *could* connect the states—with an assignment of two numbers (the amplitude and the phase) to each possible path—by adding together the squares of those amplitudes. Hence, Misner proposed that one apply this method to the gravitational field. Here the histories would be the 'trajectories' followed by spatial geometry, which of course amount to a spacetime (or a 'segment' of such). Let us spell this out.

Recall that in the classical theory of general relativity we are dealing with the metric as a classical degree of freedom. Once we have supplied the initial conditions, the metric is propagated uniquely[119] in accordance with the Einstein equations (relating the metric to the stress-energy tensor representing the matter source of the gravitational field. This uniqueness (up to gauge) in the evolution of the metric is in line with the classical nature of the theory, in much the same way as a classical particle follows a unique trajectory in spacetime (of course, in the case of the metric the evolution is not in spacetime, but in superspace). Quantization forces us to replace these unique trajectories with amplitudes. In other words, if in the classical case we are interested in the motion of some object from $x(0)$ to $y(t)$, then the quantum scenario will be given by the sum over all possible paths connecting these points:

$$\langle y,t|x,0\rangle = \int_{paths} \exp(iS_{path}/\hbar) \tag{35}$$

Here, 'paths' ranges over the (infinite) set of possible trajectories with identical extremities, initial point $x(0)$ and end point $y(t)$. The full amplitude is computed by adding the various paths together, where each path contributes an amplitude $\exp(iS_{path}/\hbar)$.

In the gravitational case, the action S will be the Einstein-Hilbert action and the space of paths will contain 4-metrics that have coincident 3-metrics on the initial and final time-slices. Recall that the Einstein-Hilbert action is:

$$S[g] = \int_{\mathcal{M}} R \text{ vol} \tag{36}$$

'R' is the Ricci scalar of the metric and 'vol' is the volume form, $\sqrt{-g}$ (where g is the determinant of the metric)— 'R vol' is the Lagrangian of general relativity. Hence, one can consider the path integral formulation of general relativity by substituting its action in the above expression, giving us:

[118]Of course, this is simply a recasting of the hole problem and problem of time issues only now in the Feynman description—however, this does show that those problems are *not* artifacts of the canonical formulation, as is sometimes supposed (see, for example, [Maudlin, 2004]). This train of thought can also be seen in the context of topological quantum field theories, where the dynamics is trivial.

[119]Of course, there is the hole problem to contend with, generating infinitely many diffeomorphic evolutions, but that is easily resolved by viewing them, quite naturally since they are generated by constraints, as gauge equivalent.

$$\langle h_2, t_2 \mid h_1, t_1 \rangle = \int e^{\frac{iS[h]}{\hbar}} d\mu[g] = \int e^{\frac{i(\int_{\mathcal{M}} R \text{ vol})}{\hbar}} d\mu[g] \tag{37}$$

Where we now consider the amplitude for the induced 3-metric h_0 on an initial hypersurface to go to another 3-metric h_1 on a later hypersurface. But we quickly run into trouble: although the times t_0 and t_1 denoted something physical in the case of standard quantum field theories (since we had a fixed spacetime to work with), in this case the time labels are gauge artifacts. In this case the amplitude gets tarnished with the gauge character of these labels.

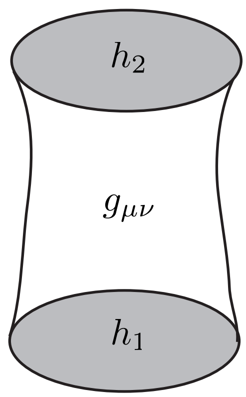

Figure 5: Representation of the gravitational path integral as a gravitational propagator from an initial 3-geometry h_1 to a final 3-geometry h_2, interpolated by the 4-geometry $g_{\mu\nu}$

Even supposing these problems can be resolved, there are other complications. For example, as before we include paths that are not considered to be dynamically possible by the lights of the classical theory. In the case of general relativity this will include interpolating metrics that correspond to different underlying topologies (i.e. that are compatible only with different topologies). However, the topological structure is fixed in all known approaches to general relativity, and it is fixed in covariant and canonical approaches. Note, however, that many view the dynamical topologies as a *virtue* of the approach (and a vice in those approaches, such as the canonical approach, that fix it): the idea of fluctuating topologies keys in to Wheeler's notion of spacetime foam.

The Euclidean approach took the topology change on board and firmed up the Feynman quantization approach. The basic idea is the same: the probability amplitude to go from an initial configuration (of metric h_{ab} and of, now, of matter Φ) on a hypersurface Σ to another configuration $(h^{'}_{ab}, \Phi^{'}, \Sigma^{'})$ is computed by the functional (path) integral of $\exp(-iS)$ over all possible interpolating configurations:

$$\langle h^{'}_{ab}, \Phi^{'}, \Sigma^{'} | h_{ab}, \Phi_{ab}, \Sigma \rangle = \Sigma_{\mathcal{M}} \int \mathcal{D}(g, \phi) e^{-iS(g_{\mu\nu}, \phi)} \tag{38}$$

The Euclidean, path integral approach was taken up primarily for its cosmological applications: (1) in the context of black hole physics (see [Hawking, 1979; 1978]); (2) in the context of providing solutions to the Wheeler-DeWitt equation (wave-functions of the Universe—see [Hartle and Hawking, 1983]). Solutions to $\mathcal{H}\Psi = 0$ are given by a path integral (over spacetime histories). The 'no-boundary proposal' of Hartle and Hawking for initial conditions of the universe is given by taking the path integral to range over (closed) Riemannian 4-metrics, C, with just one boundary (i.e. no initial boundary):

$$\Psi[h_{ij}] = \int_C \mathcal{D}[g_{\mu\nu}]\exp(-S[g_{\mu\nu}]) \tag{39}$$

If the metric manifold has only one boundary, as in the Hartle-Hawking no-boundary proposal, then the path integral is taken to represent a quantum tunneling effect: 'tunneling from nothing'. The solution is taken to provide the wavefunction for the Universe, the so-called 'Hartle-Hawking wavefunction'. As mentioned previously, this approach still faces a version of the problem of time found in the canonical approach: there is no reference to time here, the wave-function depends only on 3-geometries.

Although this approach has filtered in to many other approaches, it is no longer pursued in its raw state as a contender theory of quantum gravity. The primary problems have to do with the definition of the integral itself and the measure space $\mathcal{D}[g_{\mu\nu}]$. There are also interpretive issues to do with the very basis of the Euclidean approach: for example, the formalism involves Wick-rotation which turns t into $-it$ ('imaginary time'). There are two basic problems with this procedure: (1) the physical interpretation is not forthcoming—Deltete and Guy [2004] argue that the idea of "emerging" from imaginary time is simply incoherent.[120] (2) spacetime is Lorentzian, not Euclidean—Gibbons and Hartle [1990] have argued that the metric signature changes dynamically so that in the early Universe the metric is Riemannian, and then later it became Lorentzian.

Hence, there are both technical problems and interpretive problems facing Feynman quantization approaches. However, as we will see in the external methods section, §6.6 below, the basic idea of summing over topologies and geometries is fairly ubiquitous, though the integral has to be tamed in various ways. Feynman quantization has, *mutatis mutandis*, become a central part of several approaches to quantum gravity.

6.6 External Methods

Here we look at several interesting and/or promising research directions that do not fit into the methodological triplet: 'Covariant, canonical, path-intergral'. One feature of the triple is that they involve *quantizations* of general relativity (or some other classical theory). Naturally, this involves a substantial amount of conceptual and formal baggage from the classical theory. The external methods often depart from quantization, and thereby detach themselves from (possibly misleading) assumptions of classical theories. Quite often, however, these external methods will overlap significantly with multiple methodologies.

[120]See also [Butterfield and Isham, 1999], pp. 161–5, for a discussion of this problem.

6.6.1 Regge Calculus and Discrete Methods.

We have seen how the idea of quantum geometry seems to be a fairly generic feature of the main approaches to quantum gravity. Regge calculus allows one to deal with such possibilities—as utilized, for example, in Wheeler's notion of 'spacetime foam'.[121] In the Regge calculus, continuous space is decomposed into discrete chunks called *simplices*. These are stuck together along their faces. The edges (or "bones" in the jargon) are responsible for the gravitational field: the curvature resides here.

One uses these chunks to see what the geometry is like at an approximate level (with the approximation being dependent on the size of the chunks). As with many discrete methods one takes some continuum limit. Hence, the idea is to produce a discrete approximation of (continuum) general relativity. A spacetime is taken to be a simplicial 4-complex (a network of edges, faces, and vertices: basically, geometry of solids in four dimensions), where the lengths of the edges are the dynamical (gravitational variables). Quantization follows the Feynman quantization method: one sums over lengths.

An alternative discrete approach to quantum gravity known as the method of Dynamical Triangulations involves keeping the sizes of the building blocks fixed, but vary the way they are combined. In this case one sums over the ways that the blocks could be combined—see [3] for a book-length introduction; for the state of the art, see [5] or [Loll, 1998].

As seems to be the norm in quantum gravity research, the concepts and methods crops up in various guises. We find that the covariant extension of loop gravity leads to something like these approaches in the context of discrete spin foams. The methods here take discreteness as an input, rather than an output as was the case with loop quantum gravity. One is trying to match what one *expects* quantum spacetime to be like. However, one would like to solve for as much structure as possible.

6.6.2 Quantum Topology and Topological Quantum Field Theory.

Related to Feynman quantization methods is the notion that topology becomes a dynamical variable too. Given this one is led to consider quantizing it too, so that one quantizes below the metric. A firm proposal for making sense of this is topological quantum field theory.[122] The basic insight of topological quantum field theory is that the minimal constraints of quantum gravity can be met by producing a quantum field theory on a non-metric, differentiable manifold. These will be diffeomorphism invariant quantum theories. Naturally, such theories do not possess local degrees of freedom (i.e. no properties *here* or there); but there are global degrees of freedom that do not refer to specific points or regions of the manifold. Most work on this approach has been carried out by mathematicians where a firm axiomatic framework is known. This involves (2) the assignment of Hilbert spaces to spatial manifolds, whose

[121] The original motivations in [Regge, 1961] were also practical: Regge wanted to find ways of making general relativity more computationally manageable. Making the scheme discrete allows one to do numerical relativity. One can solve the Einstein equations for a larger class of models (without symmetry assumptions, and so on).

[122] Of course, the Euclidean programme allowed for topology change to occur, and there is a sense, in that approach, of what Wheeler called spacetime foam, since one can sum over different topologies.

rays will represent states of the universe that are possible relative to the given manifold. (2) The assignment of linear operators to cobordisms (corresponding to spacetime segments joining spatial boundaries) representing how states change given the interpolating manifold. The problem is, though topological quantum field theories share some of the properties we expect a quantum theory of gravity to have, they do not constitute quantum theories of gravity since gravity does not make an appearance. See [Baez, 2005] for more details.

6.6.3 Non-Commutative Geometry.

Given a real manifold $\mathcal{M}$ one can form an algebra consisting of the scalar functions on it. Given this algebra alone, one can reconstruct the manifold from whence it came. There is an isomorphism between the (commutative) algebra of functions $\mathcal{A}$ and $\mathcal{M}$. This suggests the following possibility: if we can use a commutative algebra to reconstruct a space, then can we do the same thing with a non-commutative algebra? Of course, such non-commutative algebras are a feature of quantum mechanics; for example, the algebra of observables satisfying the canonical commutation relations. The answer is Yes, and the structure that is reconstructed is called a non-commutative geometry. Though the idea has features we might expect in a quantum theory of gravity, it does not have the resources to function as a self-standing approach.

6.6.4 Group Field Theory.

The group field theory method aims to instill as much generality as possible in quantum gravity, dispensing with both background geometry and topology. Hence, all spacetime concepts are dispensed with during the initial formulation. It is intended to be a quantum field theory *of* spacetime. It blends elements of the path-integral approach, the loop quantum gravity approach, and discrete methods (simplicial methods, dynamical triangulations). Indeed, it has hopes to be a unifying, overarching framework for all of these methods. Group field theory is perhaps the newest approach that is intended to provide a full 'fundamental formulation' quantum theory of gravity. The details are still in the early stages of development and we will have to wait for more concrete results into which philosophers can dig their teeth (see [Oriti, 2006; Friedel, 2005] for good reviews).

6.6.5 Twistor Theory.

Twistor theory is the brainchild of Roger Penrose. One of its primary motivations is, as he puts it, "the thought that there should be a more intimate union between spacetime structure and quantum mechanics than exists in conventional theory" ([Penrose and Ward, 1980], p. 283). Hence, the twistor programme involves the forging of mathematical links between the formal structures of quantum theory and general relativity. The structures of general relativity are, it seems, usually privileged somewhat more than those of quantum theory; that is, it is manifolds rather than vector spaces that take center stage. Twistor theory reverses this, connecting the mathematical structures of quantum theory with spacetime. For example, the complex number field does the work in the context of quantum theory and this is taken up in the construction of spacetime in twistor theory. In this way one achieves some kind of unification between quantum theory and spacetime: one and the same mathematical framework applies to both.

The approach is based on two philosophical principles: (1) that the use of a spacetime continuum is an unjustified assumption in physics; (2) that the use of real-number structures in physics is an unjustified assumption.[123] It is based on the space of light rays, rather than point-events. The latter are then formed from the coincidences between the former. Connecting this up to the problem of quantum gravity, we can notice that the usual methodology is to quantize on at least a fixed manifold structure—i.e. keeping the points well-defined. Then the metric (responsible for the light cone structure: the null cones) is quantized, and thus becomes 'fuzzy'. In twistor theory the situation is reversed: the null cones are well-defined, and the point structure becomes fuzzy.

The central mathematical idea of the 'twistor' programme is a complexification of spacetime. The idea is supposed to be taken seriously, rather than simply as a heuristic device; naturally, this increases the dimensionality of spacetime (4D real Minkowski spacetime is a subspace of an eight real dimensional manifold, namely complexified Minkowski space). In twistor quantization, the twistor space forms the arena in which quantum processes occur, and at whose points quantum fields are defined.

We leave the subject of twistor theory without going into the formal details—the theory is, mathematically, extremely complicated. Indeed, as Penrose admits ([1999], p. 607), despite its ultimate aim as providing a general framework in which quantum gravity will be formulated, twistor theory has had most success in the area of *pure mathematics* rather than physics. It remains to be seen whether Witten's [2004] integration with string theory bears fruit in physics.

6.6.6 Supergravity.

Why stop at complex numbers as in twistor theory? Hypercomplex numbers—complex numbers involving more than just pairs of real numbers—might be even more useful from the point of view of quantum gravity since quantum theory involves noncommutativity and hypercomplex numbers have non-commutative products. This connects up to elementary particle physics through the notion of a Grassman algebra.

Supersymmetry increases the number of fields in general relativity. Gravitons get a 'superpartner', the spin-$\frac{3}{2}$ gravitino. These fermionic fields serve to cancel the bosonic fields, thus taming (some of) the infinities that inevitably trouble most field theories. Indeed, the primary aim is to cure these divergences, thus making modified general relativity perturbatively renormalizable. Unfortunately the pure supergravity theory fails at the 3-loop level—general relativity itself fails at the 2-loop level.

[123] Chris Isham has been developing an approach based on similar philosophical principles, though one that implements them in a very different way to Penrose. For example, Butterfield and Isham speak of the "danger of certain a priori, classical ideas about space and time being used unthinkingly in the very formulation of quantum theory" ([Butterfield and Isham, 2000], p. 1711). Hence, though both Isham and Penrose propose a revision of spacetime, Isham's approach is more radical than Penrose's, arguing that it might even be necessary to dispense with set theory in order to get what we want: a quantum theory of gravity.

6.6.7 Causal Sets.

Rafael Sorkin has been developing an increasingly popular approach to quantum gravity known as 'causal set theory'. A causal set is a set $\mathcal{C}$ on which there is defined a relation of precedence $\prec$ that is transitive ($[(x \prec y) \wedge (y \prec z)] \supset x \prec z$), non-circular ($[(x \prec y) \wedge (y \prec x)] \supset x = y$), and finite between any two points ($|Y| = |\{y|x \prec y \prec z\}| < \infty$). Or, in other words, a causal set is a locally finite partially ordered set (or 'poset'). His approach involves utilizing causal sets within a 'sum over histories' type approach so that the histories are built from (discrete) causal sets. One can find hints of a programme of this kind in the mid-50s. D. van Dantzig, for example, suggests, on the basis of the empirical inaccessibility and non-definability of worldpoints, that one deal instead with a "finite set of discrete events with spacetime relations between them" ([van Dantzig, 1956], p. 52).

The basic idea of a causal set was known before Sorkin's work on the subject. The application to gravity was briefly considered by t'Hooft ([t'Hooft, 1979], p. 340), where he was concerned with retaining causality despite losing the metric tensor—he also notes that Lorentz and diffeomoprhism invariance can be preserved on a lattice given an appropriately defined causality relation.[124] Butterfield [2007] has recently argued, however, that Sorkin's causal set theory fails to satisfy stochastic Einstein locality.

The causal set approach, unlike loop quantum gravity, includes spacetime discreteness as an input. The key is to eradicate all traces of continua from the formalism; any such notions are to emerge in an appropriate classical, macroscopic limit. Hence, such things as distance, length, time, and so on are approximate concepts: at a microscopic level, spacetime ceases to means the same thing as at the macroscopic level, one has only a primitive notion of before and after.

6.6.8 Spin-Foams.

There is a covariant (path-integral) version of loop quantum gravity that involves the time-development of spin-networks, a procedure that generates 'spin foams', the cross-sections of which are spin-networks. These are then integrated over, to produce a 'sum over spin-foams' formulation of quantum gravity. The aim of this approach is to resolve the difficulties facing the dynamics of loop quantum gravity: the spin foam formulation deals directly with the dynamics—it is a spacetime formulation of loop quantum gravity, only the spacetime is the object that is solved for (hence, this is still a background independent approach).

Before leaving this section I should mention some very recent work that pertains to the unification of matter and gravity in spin foam models. What this work shows is that some causal spin-foam models possess 'emergent' local degrees of freedom representing particles. Hence, just as string theory has modes of the string corresponding to elementary particles, so the *covariant* extension of loop quantum gravity has too. How

[124] There are precursors too in the philosophical and logical literature: see [Reichenbach, 1969] and [Zeeman, 1964] respectively. One can also find the basic idea of treating the causal structure of spacetime as fundamental in Robb's axiomatization of special relativity: [Robb, 1936]. For a comparison of these approaches with modern causal set theory, see [Sorkin, 2002].

such models bear on traditional debates in metaphysics and the philosophy of space and time remains to be seen.

6.6.9 Generalized Quantum Mechanics.

It seems pretty clear that quantum mechanics is incompatible with the picture of spacetime that general relativity provides us with. Quantum mechanics demands a fixed spacetime geometry. This is essential for the definition of the states, which are given on spacelike hypersurfaces, and that are evolved unitarily onto other hypersurfaces. General relativity does away with this notion, so that any such evolution will be a gauge motion: the spacetime geometry is dynamical. In a quantum theory of gravity we expect that matters will be even worse since the geometry, as a dynamical variable, will undergo fluctuations and so will, in general, be without a definite value. Just as particles don't have definite trajectories in quantum mechanics, so spacetime geometry doesn't have a definite trajectory. Hence, the incompatibility. This is simply to recap what we have said already, of course.

Generalized quantum theory is intended to provide a framework that can cope with such situations. One has to generalize standard quantum mechanics in such a way as to apply to *closed* systems, so that measurement and the notion of observers doesn't play a fundamental rôle. This is so that the theory can be applied to the universe as a whole, enabling quantum cosmological considerations, as should be possible in a theory of quantum gravity. One must also generalize the spacetime dependence so that dynamical geometry can be incorporated. The histories in this case, however, do not involve evolution of quantum systems within spacetime but involve the evolution of spacetime itself. A history, then, could be a spacetime geometry. Essentially one ends up with something similar to the Feynman quantization approach, though one that involves decoherent histories (see §2.2.3 and §2.3.1 of Wallace's chapter for the details of this approach). In any case, we saw earlier, in §2.2, that quantum cosmology, though bound up in various ways with quantum gravity, is a very different enterprise.

6.6.10 Causaloid Quantum Gravity.

Lucien Hardy [2007] has recently begun to work on a new approach to quantum gravity that is intended to provide a 'framework' for quantum gravity theories. The idea is to develop a general formalism that respects the key features of both general relativity, which he takes to be the dynamical (nonprobabilistic) causal structure, and quantum theory, which he takes to be the probabilistic (nondynamical) dynamics. The causaloid (of some theory) is an entity that encodes all that can be calculated in the theory. The causaloid formalism does not depend on background causal structure and it can handle quantum theory. Given his characterization of quantum gravity as a probabilistic theory with a dynamical causal structure, Hardy argues that this might help in the search for quantum gravity. As he admits, there are many technical hurdles to leap: not least of these is the problem of incorporating general relativity in the formalism (beyond the lack of fixed causal structure, which is necessary but clearly not sufficient).

6.6.11 Asymptotically Safe Quantum Gravity.

The standard model contains perturbatively renormalizable quantum gauge field theories of the electroweak and strong interactions. General relativity, when set up as a quantum field theory, is not perturbatively renormalizable (in the coupling constant G_N). The approach known as 'asymptotic safety', associated with Martin Reuter (see [Niedermaier and Reuter, 2006]), attempts to avoid these difficulties by modifying the computational (renormalization) strategies, making them nonperturbative: hence, the idea is to produce a nonperturbative renormalization of quantum gravity. Asymptotic safety, coined in [Weinberg, 1979], refers to the fact that the physical quantities in such a theory will not be affected by divergences (as a cutoff limit is taken). This approach makes use of the Wilson (renormalization) group flow ideas that tell us how the dynamical behaviour of a system changes as the scale (or energy) is varied. The details of which are too complicated to go into here: see [Gross, 1999] for an excellent, concise introduction. However, the results here are philosophically interesting for a variety of reasons. For one thing, it appears to imply that quantum general relativity can be held up as a fundamental theory of sorts (i.e. applicable at all energies/distances). This approach also predicts a fractal-like microstructure of spacetime. Both of these aspects, resulting from the intermingling of statistical physics ideas with quantum gravity research, are ripe for philosophical pickings.[125]

Conclusions

The approaches to quantum gravity that we presented above do not constitute a case of complete underdetermination: they make a number of very different predictions about the world. It is becoming clear that initial pessimistic claims concerning the non-testability of these approaches were not accurate. As we will see in §7.3, recent work has shown that there are tests that might be made in the foreseeable future that have the potential to falsify certain approaches—or at least cast them into a shadow of serious doubt. What makes quantum gravity such (philosophical) fun is that if we can make the connections between philosophical positions, with respect to time, space and change, then some test will also support or undermine these positions too! It seems, moreover, that from what we have seen these connections *can* be forged, leading to the promise of new areas of experimental metaphysics (or, at least, new constraints on old metaphysics).

7 Special Topics

In this section we focus briefly on several topics of especial philosophical interest. We look at interactions and cross-fertilization between the methodologies; background independence, the experimental status of quantum gravity research, and the interpretation of quantum theory. The treatment here very barely skims the surface and is intended purely as a preliminary pointer to the kind of philosophical work that has and could be carried out.

[125] For related work along these lines see: [Volovik, 2003], [Zhang, 2004], and [Laughlin and Pines, 2000].

7.1 Interactions and Cross-Fertilization

The battlefield of quantum gravity research is littered with the corpses of once-promising approaches. Some, badly damaged, soldier on. In certain cases one finds approaches resurrected. In other cases their parts are transplanted onto other approaches. Given this apparent patchwork quality to the approaches, one wonders why there isn't more interaction between the leading approaches, string theory and loop quantum gravity, and with the other approaches. Part of this, I expect, can be put down to the fact that they have different aims: string theory aims to be a theory of all interactions while loop gravity is concerned primarily with the quantization of gravity. There are less charitable reasons one might give: funding demands, arrogance, etc.! Indeed, the field of quantum gravity research has become a rather ugly one in recent years, with string theorists and researchers from other approaches engaged in various 'my theory's better than yours' antics.[126] This doesn't seem a healthy way to do physics. As the brief history of quantum gravity highlights, significant advances appeared to occur when researchers were dealing with multiple approaches with an eye to their connections.

An important example here, mentioned earlier, is Roger Penrose's work on combinatorial spacetime, in which he attempts to construct both spacetime and quantum mechanics from discrete elements [Penrose, 1971]. Now, the approach is certainly not an *intrinsic* approach: it is based on a quantity, angular momentum, that plays a rôle in both spacetime and quantum mechanics, and it has discrete spectrum. Hence, some feature of both spacetime and quantum theory is utilized in a central way to develop a notion of quantum space. This basic idea has infected all of the major lines of research and many 'external' approaches. The notion of spin-network thus functions as a kind of unifying instrument. The ubiquity of such a concept throughout quantum gravity research ought to signal collaboration—however, as philosophers know well, ought does not imply is.

In "How to Be a Good Empiricist—A Plea for Tolerance in Matters Epistemological", Feyerabend writes[127]:

> You can be a good empiricist only if you are prepared to work with many alternative theories rather than with a single point of view and 'experience'. This plurality of theories must not be regarded as a preliminary stage of knowledge which will at some time in the future be replaced by the One True Theory. Theoretical pluralism is assumed to be an essential feature of all knowledge that claims to be objective. ... The function of such concrete alternatives is, however, this: They provide a means of criticizing the accepted theory in a manner which goes beyond the criticism provided by comparison of that theory 'with the facts'. ... This, then, is the methodological justification of a plurality of theories: Such a

[126] One can find this in various books, blogs, and debates: see, for example, http://motls.blogspot.com and http://www.math.columbia.edu/ woit/wordpress.

[127] However, Feyerabend probably isn't the best spokesperson to pick for the point I am making here, since he famously argued that even Galileo resorted to chicanery and propaganda such as one finds amongst quantum gravity researchers. However, the following quote serves my purposes well. Indeed, since there are no such 'facts' (by which he means *empirical* facts, it would seem that the pluralism of which he speaks is demanded more so.

> plurality allows for a much sharper criticism of accepted ideas than does the comparison with a domain of 'facts' which are supposed to sit there independently of theoretical considerations. (Feyerabend 1968, pp. 14–5)

This bears many similarities with Chamberlin's 'Method of Multiple Working Hypotheses' (1965). There the idea is that the use of several methods produces a situation in which "the re-action of one hypothesis upon another tends to amplify the recognized scope of each, and their mutual conflicts whet the discriminative edge of each" (Chamberlin 1965 (1890), p. 756). Feynman too expressed a similar sentiment in his Nobel address:

> For different views suggest different kinds of modifications which might be made and hence are not equivalent in the hypotheses one generates from them in ones attempt to understand what is not yet understood. I, therefore, think that a good theoretical physicist today might find it useful to have a wide range of physical viewpoints and mathematical expressions of the same theory ... available to him. This may be asking too much of one man. Then new students should as a class have this. If every individual student follows the same current fashion in expressing and thinking about electrodynamics or field theory, then the variety of hypotheses being generated to understand strong interactions, say, is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view of field theory - who will find it? (http://nobelprize.org/nobel_prizes/physics/laureates/1965/feynman-lecture.html)

In my view, part of what lies behind the present split in quantum gravity research is a detachment from the historical origins and early trajectory of such research. Never before has there been such a gap between the origins of some research topic and its initial formulation. Many of the early pioneers are no longer with us. As I mentioned above, these early pioneers worked on multiple lines of attack, because they saw that one had to try almost anything at that stage. The problem is, these lines have solidified into well-defined paths that no longer seem to intersect—or if they do it is through dense thickets. In the early period there was no sense that they were on the *right* path,[128] but this is no longer true: a large proportion of string theorists believe they are absolutely on the right track, and so (it has to be said) do many loop theorists. There is no evidence to decide between them or to tell us which, if any, really is right. Given this state of affairs, it makes no (rational) sense to exclude other approaches; certainly not as a matter of ideology. However, this kind of prescriptive preaching has a tendency to backfire: perhaps the ideological (even dogmatic) way in which researchers are glued to their pet programmes, despite the lack of evidence, might very well lead to fruitful results—Thomas Kuhn [1964] argued persuasively for a certain amount of dogma in the practice of normal science. The difference is: quantum gravity is not yet normal science; that is, there is no singe theory that is pursued in virtue of a consensus amongst

[128] This is not true of the very earliest attempts based on the electromagnetic analogy, where it was believed that the quantization of gravity would be a relatively trivial matter.

physicists that they have the *right* theory. Time will tell if the current way of doing physics works: I doubt it though. At the very least, I'm sure it would be far more fruitful if there were more cooperation.

7.2 Background Structure

It is often claimed that the *novelty* of general relativity lies in its (manifest) 'background independence'. However, background independence is a slippery concept apparently meaning different things to different people. The 'debate' between strings and loop on the issue of background independence is severely hampered by the fact that there is no firm definition of background independence on the table. The two camps are almost certainly talking past each other when discussing this issue. It certainly does seem reasonable to assume that in order to reproduce a manifestly background independent theory like general relativity, a quantum theory of gravity should be background independent too. However, so far as I know, there is no proof of this. The problem might be that background independence simply isn't a formal property of theories—Gordon Belot [2007] has recently argued that background independence is an *interpretive* matter.

The debate over background structure is focused around the status of the metric. The metric is a variable that describes the geometry of spacetime. In non-generally relativistic theories it is fixed to a single value assignment for all of the theory's models, constraining the motion of light, particles, and fields, but not itself being in any way affected by these motions. In general relativity, of course, this all changes: the metric is a dynamical variable, which implies that the geometry of spacetime is dynamical. Einstein's insight was to see that this was able to account for gravitational interactions. As Carlo Rovelli expresses it: "What Einstein has discovered is that Newton had mistaken a physical field for a background entity. The two entities hypostatized by Newton, space and time, are just a particular local configuration of a physical entity—the gravitational field—very similar to the electric and the magnetic field" ([Rovelli, 2006], p. 27). In other words: "Newtonian space and time and the gravitational field are the same entity" (ibid.).

However, most of physics ignores this lesson and freezes the metric to a single value once again, in order to simplify calculations. Such a manoeuvre is called a *background field method*. We saw that some approaches to quantum gravity adopted such a methodology; but it can only ever be a stopgap. In some cases it is appropriate (when G is small), but certainly not in cases that we would expect a theory of quantum gravity to deal with (extreme gravitational situations, such as end states of quantum black holes and the initial phase of the universe, close to the Big Bang.

There are certain immediate obstacles that we face as soon as we contemplate a full quantization of a background independent field theory like general relativity. The dynamical nature of the metric field, coupled with its dual rôle, points to a notion of quantum geometry. This quantum geometry differs greatly from other quantum field theories. For example, one of the axioms of quantum field theory (in Minkowski spacetime) is that spacelike separated fields commute:

$$[\hat{\phi}(x), \hat{\phi}(y)] = 0 \quad \forall x, y \in \mathcal{M},\ I(x, y) < 0 \tag{40}$$

That is, whatever field measurements we make at the spacetime point x cannot influence the field values at y whenever these points are at spacelike separation—this still applies if we substitute 'regions' for 'points'. Now consider what happens when we turn the metric field into a quantum gravitational field:

$$[\hat{g}(x), \hat{g}(y)] = 0 \quad \forall x, y \in \mathcal{M},\ I(x, y) < 0 \tag{41}$$

In this case $\hat{g}$ is a quantized metric field, and the metric field determines spacetime geometry as well as the gravitational field. Without a definite metric in hand we cannot say that a pair of points or regions are spacelike separated: such a notion is determined by the metric which is itself determined by field equations. Hence, we get a fuzzy notion of causal structure in this case, and this axiom can't hold: it assumes that the points of spacetime have some independent meaning, when according to general relativity they do not—see [Weinstein, 2000] for a discussion of this problem. This is why the background dependent methods are clung to, despite their failings: they provide useful machinery to aid theory construction.

We face a series of questions when considering background independence: What exactly is it? Why is it considered to be an important principle? What theories incorporate it? To what extent do they incorporate it? In particular, is string theory background independent? If 'clues' from the duality symmetries of $\mathcal{M}$-theory are anything to go by, it looks like string theory might be even more background independent than loop quantum gravity, for the dimensionality of spacetime becomes a dynamical variable too (cf.. [Stelle, 2000], p. 7). Indeed, various string theorists claim that their theory is background independent. In many cases it seems that they have a different understanding of what this entails than loop quantum gravity researchers—this takes us to the first, definitional, question. In particular they seem to think that the ability to place a general metric in the Lagrangian amounts to background independence. This falls short of the mark for how we are understanding it here, namely as a *reactive* dynamically coupling between spacetime and everything else. Though one can indeed place a variety of metrics in the stringy Lagrangian, one does not then vary the metric in the action. There is no interaction between the strings and spacetime. Indeed, this is not really distinct from quantum field theory of point particles in curved spacetimes: the same freedom to insert a general metric appears there too. There is an alternative argument for the background independence of string theory that comes from the field theoretic formulation of the theory: string field theory. The idea is that classical spacetime *emerges* from the two dimensional conformal field theory on the strings worldsheet. However, one surely has to say something about the target space, for the worldsheet metric takes on a metric induced from the ambient target spacetime. Yet another argument for the background independence of string theory might point to the fact that the dimensionality of spacetime in string theory has to satisfy an equation of motion (a consistency condition): this is how the dimensionality comes out (as 26 or 10, depending on whether one imposes supersymmetry). One contender for the definition of background independence is a structure that is *dynamical* in the sense that one has to solve equations of motion to get at its values. In this case we would have extreme background independence stretching to the structure of the manifold itself. However, the problem with this is that this structure is the same in all models of the theory; yet we expect background independent theories to be about structures that vary across models.

Whether background independence will continue to be the divisive principle that many take it to be is not clear. It seems like all of the main approaches are converging onto background independence. This includes string theory, as mentioned. For example, Michael Green, a string theorist, writes:

> One of the most obvious problems is that all the suggested microscopic models of M theory are background dependent. A truly background-independent formulation would not make a distinction between the target space and the embedded objects—both concepts should emerge from a novel kind of quantum geometry. ([Green, 1999], p. A99)

Lee Smolin [Smolin, 1999] acknowledges that recent results into the non-perturbative (strong coupling) aspects of string theory points to existence of an underlying background independent version of string theory known as $\mathcal{M}$-theory. One reason for its alleged background independence is that it includes multiple perturbative string theories defined with respect to a multitude of different backgrounds. There are, as we saw earlier, (duality) symmetries linking these various spacetimes, much as diffeomorphism invariance links the various spatial slices linked by the constraints in the canonical approach.

The issues here are subtle and complex, and philosophers have begun to consider them. The central problem faced, as a philosopher, when trying to make sense of claims such as these is that there is no solid, unproblematic definition of background structure (and therefore background independence and dependence) on the table. Without this, one simply cannot decide who is right; one cannot decide which theories are background independent and which aren't. Hence, an urgent issue in both physics and the philosophy of physics is to work out exactly what is meant by 'background independence' in a way that satisfies all parties. Until this is achieved, background freedom cannot be helpfully used to distinguish the approaches, nor can we profitably discuss its importance. A serious attempt to define background independence in such a way as to make these tasks possible has been made in [Giulini, 2007]—I refer the reader to this excellent article for a review of the various ways of making sense of background independence.

7.3 The Experimental Situation

As Carlip writes in his recent review of quantum gravity: "The ultimate measure of any theory is its agreement with Nature; if we do not have any such tests, how will we know whether we are right?" ([Carlip, 2001], p. 885). Quantum gravity, of course, reverses the conventional way of doing physics—Green, Schwarz, and Witten write that "[q]uantum gravity has always been a theorist's puzzle *par excellence* ([Green et al., 1987], p. 14). Generally, when attempting to construct a new theory to deal with some novel phenomena, physicists have some experimental data at their disposal to which they will attempt to fit phenomenological models, hopefully leading to a predictive general theory. What is interesting about this methodology, looking at various crucial historical episodes, is that, often, conceptual and formal consistency are bypassed in a bid to gain a good fit to reality. By contrast, quantum gravity is almost entirely based on conceptual and formal consistency, along with constraints imposed by background knowledge and theories. It has, from the beginning, seemed to be out of bounds as far as experimental probing is concerned. This, more than anything else, gave quantum gravity research a bad name (and still does, though to a lesser extent): the litmus test of any scientific theory is an experimental test. Without this one is dabbling in pure mathematics, or worse, metaphysics! Experiment is what makes us willing to brand a theory a *physical* theory. Yet the very possibility of experiments to observe quantum gravity effects seems to be ruled out on simple dimensional grounds: the natural unit of energy in quantum gravity is $\sqrt{\hbar c^5/G} = 10^{22} MeV$, but even the Large Hadron Collider [LHC] will only reach energies of the order 14 TeV (for combined energies of collided particles)—see [t'Hooft, 1979], p. 328 for a stereotypical example of this pessimistic argument.

However, there have been a number of recent developments—beginning in the late 1990s with the work of Giovanni Amelino-Camelia—that indicate that the initial pessimism concerning the testability of the various quantum gravity theories might be unfounded.[129] Indeed, these developments have spawned a whole new research programme called 'quantum gravity phenomenology'. This work, if successful, will transform quantum gravity research into a genuine experimental discipline—it might well wreck the chances of all of the leading theories too. Firstly, let us recall the reasons behind the pessimism.

The scale at which quantum gravitational effects are supposed to appear is set by the various physical constants of fundamental physics: $\hbar$, c, and G. These characterize quantum, relativistic, and gravitational phenomena respectively. Hence, quantum gravitational phenomena will involve all three. By combining these constants we get units of length, time, and mass/energy at which the effects of quantum gravity should make themselves manifest. We gave some of these earlier, but we shall repeat them for convenience:

- **Planck length**: $l_p = \sqrt{\frac{\hbar G}{c^3}} \approx 1.62 \times 10^{-33}\text{cm}$
- **Planck time**: $t_p = \sqrt{\frac{\hbar G}{c^5}} = \frac{l_p}{c} \approx 5.40 \times 10^{-44}\text{s}$
- **Planck mass**: $M_p = \sqrt{\frac{\hbar c^5}{G}} = \frac{\hbar}{l_p c} \approx 2.17 \times 10^{-5} g$ (Planck energy $\approx 1.22 \times 10^{19}\text{GeV}$)

These are very many orders of magnitude beyond current experimental capabilities.[130] They would appear to lie beyond our capabilities in the distant future too. Hence, the pessimism.

[129]The tests devised by Amelino-Camelia and others, however, are doable with present technology. The methodology is the same as Unruh's: don't even think about tying to probe individual events at the Planck scale; instead, look for events that amount to an amplification of the Planck scale effects. For a selection of recent articles on quantum gravity phenomenology, see [6]—a more recent, highly readable review is [Lämmerzahl, 2007].

[130]If the Planck mass looks like rather a reasonable figure, note that one needs to consider it concentrated in a volume (roughly) with sides equal to the Planck length in order to produce quantum gravitational effects.

However, the pessimism seems to have been unwarranted. The problem with the scale argument, as we noted earlier, is that it is applicable to *individual* quantum gravitational events. The key insight of quantum gravity phenomenology is to combine such events, and so generate amplified effects that can be detected with present day equipment, or equipment that can conceivably be constructed now or in the near future. Hence, the irony of quantum gravity phenomenology is that, not only does one not attempt to (directly) probe the very small distances normally associated with quantum gravity, one goes to the farthest reaches of the opposite end of the scale spectrum, using astronomical features as probes. This can be achieved by observing various systems: cosmic rays, gamma-ray bursts, Kaon bursts, particles, light, and the cosmic background radiation. One looks for ways that quantum gravitational effects might manifest themselves in these systems, given that they are such that Planck scale effects will have been able to become amplified in them (because of the very large energies or the vast time/distance-scales they involve—e.g. photons that have travelled vast distances, and so might have been *cumulatively* modified by miniscule Planck-scale effects).[131]

That does not mean we can produce the necessary effects ourselves, in experimental devices on Earth. Instead, one utilizes various 'natural experiments' that the universe itself provides us with. For example, there are particles that have been travelling across vast distances at tremendous velocities, far greater than we could manage. Hence, by trading in control, we can help ourselves to phenomena that can be utilized to test the various proposals.

That quantum gravitational effects will not be measurable on individual elementary particles is intuitively quite clear. Bryce DeWitt devised rigorous arguments to show this to be the case: the gravitational field itself does not make sense at such scales. He showed that the static field from such a particle (with a mass of the order 10^{-20} in dimensionless units) would not exceed the quantum fluctuations. The static field dominates for systems with masses greater than 3.07×10^{-6}. The gravitational field is from this viewpoint an 'emergent' "statistical phenomenon of bulk matter" ([DeWitt, 1962], p. 372).

DeWitt points out that the continuum picture "must persist [even at $10^{-32} cm$] if the general coordinate transformation group is really fundamental" ([DeWitt, 1962], p. 373). That is, the diffeomorphism group depends on the manifold. One might wonder how this squares with the canonical approaches, loop quantum gravity in particular. However, as DeWitt goes on to remark, there need be no conflict since there will be a natural cutoff that allows us to 'ignore' distances below this. I quote him at length:

> Such a "cutoff" would, of course, eliminate the ultraviolet divergences

[131] Very recent results from the MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescope might constitute a genuine example of quantum gravity phenomenology: [MAGIC Collaboration, 2007] (see also http://magic.mppmu.mpg.de). The data reveals an energy-dependent time delay in the photons from the active galaxy Markarian 501—that is, it appears that the photons have different arrival times despite having the same departure times. The best fit of the parameter M under the hypothesis $\Delta c/c = -E/M$ (where E is the energy of photons) is $M = 0.4 \times 10^{18}$ Gev (i.e. the Planck mass). Whether or not this is due to some quantum gravity based corrections to the propagation of particles in a discrete, fluctuating spacetime is not yet clear. However, it does seem to indicate that quantum gravity effects are indeed measurable using currently available technology. (I thank Carlo Rovelli for this observation.)

of field theory and establish a fundamental role for gravitation in elementary particle physics. Moreover, the existence of a "cutoff" at this wavelength is not obviously incompatible with the success of modern field theory in correlating experimental data. ([DeWitt, 1962], pp. 373–4).

> [I]t must constantly be borne in mind that the "bad" divergences of quantum gravidynamics are of an essentially different kind from those of other field theories. They are direct consequences of the fact that the light cone itself gets shifted by the non-linearities of the theory. But the light-cone shift is precisely what gives the theory its unique interest, and a special effort should be made to separate the divergences which it generates from other divergences. ([DeWitt, 1962], p. 374).

> It may ... be worth while to make strong attempts to link the apparent "internal" spaces more directly to the ordinary four-dimensional space-time of everyday experience, even at the risk of resurrecting some long-abandoned so-called "unified field theories" in modified or generalized form. The present unattractiveness of theories of this type is due at least in part to the lack of a quantum formalism for them. If the quantization programme for gravitation can be successfully pushed through then these theories may become more attractive. ([DeWitt, 1962], p. 373).

The proposed effects are expected to flow from the apparently generic modification of spacetime that quantum gravity will herald.

As mentioned, there have been proposals that essentially involve using the universe as an experimental device, by exploiting its age and the ages of certain processes that have been occurring in it. One idea is that, discernibly, light changes its properties over vast distances of travel *in the case of discrete spacetime*. The idea is that the graininess of spacetime causes birefringent effects in the observed light (that has travelled over large distances)—see [Gambini and Pullin, 1999] for an elementary review. According to Maxwell's equations, defined on continuous spacetime, the speed of light *in vacuo* will be independent of its wavelength λ. The expectation is that this will be false if spacetime has a discrete, polymer-like structure. The basic idea here stems from the fact that a wave propagating across a discrete lattice will violate Lorentz invariance: this symmetry breaking is then viewed as a 'probe' to test quantum gravity proposals. Since many approaches involve spacetime (or just spatial) discreteness, this might well afford an experimental test. However, spacetime discreteness is not itself a sufficient condition for Lorentz non-invariance: causal sets are discrete structures that do not seem to violate it. Hence, this evidence would still leave us ignorant on many crucial 'theory-selection' matters. This should not inhibit experiment, of course.

While these experiments would, if successful, generate some qualitatively novel phenomena, the results would be *generic*—amounting to what Smolin [forthcoming] calls 'soft predictions'. That is, they would not allow us to choose between a group of theories that postulated spacetime discreteness. It is possible that one such approach comes up with a particularly accurate specific value for the effect, and this would then be a step towards theory adoption.

Finally, let us consider the issue of the importance of experiment over mathematical rigour. Werner Heisenberg was skeptical of ‘overly rigorous’ mathematical methods in physics. Some of his remarks on this issue are highly applicable to quantum gravity research:

> When you try too much for rigorous mathematical methods, you fix your attention on those points which are not important from the physics point and thereby you get away from the experimental situation. If you try to solve a problem by rather dirty mathematics, as I have mostly done, then you are forced always to think of the experimental situation; and whatever formulae you write down, you try to compare the formulae with reality and thereby, somehow, you get closer to reality than by looking for the rigorous methods. ([Heisenberg, 2005], p. 106)

On the issue of phenomenological methods, however, he was equally cold:

> When you get into such a new field, the trouble is, that with phenomenological methods you are bound always to use the old concepts; because you have no other concepts, and making theoretical connections means then applying the old methods to this new situation. Therefore the decisive step is always a rather discontinuous step. You can never hope to go by small steps nearer and nearer to the real theory; at one point you are bound to jump, you must really leave the old concepts and try something new and then whether you can swim or stand or something else, but in any case you can’t keep the old concepts. ([Heisenberg, 2005], p. 106–7)

Heisenberg’s view of theory-development is more than a little Kuhnian,[132] then. It is highly philosophical too: it blends *interpretive* issues with *constructive* issues. For example, he goes on to say:

> [I]n quantum mechanics ... first we had the mathematical scheme, and then, of course, we had to try to use a reasonable language in connection with it. Finally we could ask what concepts does this mathematical scheme imply and how do we have to describe nature? ([Heisenberg, 2005], p. 107)

Perhaps part of the problem is that many of the old guard who helped found quantum mechanics are now dead. Constructing quantum mechanics was a conceptually taxing venture: it made philosophers of many of those involved—many were already of a philosophical bent, of course. Quantum gravity research is similar in this way, only the times scales involved in its development are much longer.

[132]Indeed, there are many points of overlap between the views of these two men on the subject of scientific devlopment.

7.4 Interpretation of Quantum Theory

I have largely steered clear of issues to do with the interpretation of quantum theory here. However, since, in most cases, we are dealing with quantum theories—in some cases quantum theory will be emergent—then the old troubles will reappear in this context. The question is: are there *additional* worries or complications that quantum gravity might bring to the interpretation of quantum theory? The clear answer seems to be Yes. Recall, for example, that Roger Penrose believes that gravitational effects have an important rôle to play in quantum theory. Indeed, he thinks that the rules of quantum theory will have to be modified in the light of such effects. Note that this is not a general solution of the measurement problem: it applies only to those superpositions of observables that are relevant to gravitational distortions, mass, location, shape, etc.

That there will be implications for the interpretation of quantum theory has been known for some time. This is the case in quantum cosmology too. As John Wheeler explains:

> The quantity ψ [the universe's wave-function–DR] ... is a probability amplitude for something—but for what? and "observed" by whom? ... There is no platform outside the universe on which to stand to observe it. There is no possibility by external observations to produce uncontrollable disturbances and thereby transitions from one quantum state to another. It is not even clear that there is any but a unique quantum state. The tools most useful in other dynamical systems to distinguish one quantum state from another are completely missing here. "Total energy" is a term without meaning for a closed universe. ([Wheeler, 1964a], p. 517)

In the first article from his remarkable triptych on quantum gravity, Bryce DeWitt argues that quantum gravity is best interpreted *à la* Everett:

> Everett's view of the world is a very natural one to adopt in the quantum theory of gravity, where one is accustomed to speak without embarrassment of the 'wave function of the universe'. It is possible that Everett's view is not only natural but essential. ([DeWitt, 1967c], p.1141)

I have yet to see an argument to the effect that Everett's approach is necessary in quantum gravity. One can think of modal interpretations doing the job, or perhaps Bohmian mechanics—though the close relationships between these interpretations are well known. One thing does seem certain, and that is that the Copenhagen orthodoxy is ineffective in such a context since there is no (external) classical observer available. How true is this? Firstly, let us see what motivates this belief. The idea is that the universe, taken as an individual system in its own right, is a closed system, the *only* genuinely closed system there is, since quantum entanglements spread. This spread terminates at the level of the universe, making this a valid object for quantum theory: the universe is a quantum system too. Now, this is the domain of quantum cosmology, and this is clearly what DeWitt has in mind.[133] The connection to quantum gravity

[133] Indeed, the context of the above quotation is a quantization of a closed Friedmann universe containing matter—the first example of quantum cosmology.

results from the fact that the gravitational interaction dominates at such cosmological scales. If the universe is indeed a quantum object, and gravity is in operation here, then quantum cosmology will involve, in some sense, a quantum theory of gravity.

However, collapse interpretations in general do not seem to be at odds with the notion of a wave-function of the universe: a spontaneous collapse interpretation—such as Penrose's that utilizes the instabilities of a superposition of geometries—requires only 'internal' processes. It also seems likely that there will be decoherence effects between the geometry and matter, resulting in an 'effective' collapse.

Moreover, as mentioned earlier, quantum gravity is a separate enterprise from this: one can talk of the measuring of a spatial region (e.g. [Rovelli, 2004]), and bring in all of the machinery and baggage of the Copenhagen interpretation if one is so inclined. We should, then, be careful with the claims that quantum gravity can have any bearing on the interpretation of quantum mechanics (functioning, as some have suggested, as some kind of 'selection principle' on the class of interpretations). However, this issue—of working out the relationships between quantum gravity proposals and interpretations of quantum gravity—would seem to be an excellent one for philosophers of physics to be tackling now.

8 Final Remarks: What Will the Future Bring?

For what it's worth, I'll finish by giving my own views on the status of quantum gravity, and what I see happening.

We have seen that the experimental situation is not quite as dim as is often made out. However, the kinds of experiments that are on the table so far tend to be of the 'generic' sort: they are not very useful for 'weeding out' approaches, but they may enable the demonstration of some of the quantum properties of the gravitational field (or their non-existence!) and so put an end to the steady flow of papers asking whether we really *need* a quantum theory of gravity. It will also provide experimental values that the various approaches can aim for, for once we have secured this initial empirical basis, without further precision tests to separate out the various approaches, non-experimental factors may come into play, as regards theory-selection—notice, for example, how string theory is already becoming entrenched.

However, it is also possible that the near-future will bring more 'approach-specific' tests too. There is some hope that the energies generated by the LHC will be sufficient to test more specific features of the approaches to quantum gravity, such as extra dimensions, supersymmetry, microscopic black hole behaviour, and so on. But one can all too readily envisage situations in which approaches are tweaked to fit. If supersymmetry is discovered to operate then string theory passes what ought to be a 'crucial test'—or as crucial as can be given the 'holistic' lessons of Duhem and Lakatos. But this would not vindicate string theory, for it doesn't uniquely mesh with supersymmetry or, indeed, extra dimensions.

The most likely situation is that one approach may prove to be more heuristically useful, at suggesting promising research and experimental directions, and so on. Hence, we may end up with a family of approaches that can match each other experimentally, and claim compatibility with the results—if not quite able to *predict* the results. This does not imply that they are all ‘equally good’: selection often happens on the basis of more than experimental evidence alone. I don’t think this necessarily implies that the extra-experimental factors are not perfectly rational ones.

Lee Smolin, and many other members of the canonical camps, believe that the future will bring a background independent theory of quantum gravity—though perhaps not loop gravity. One of the arguments Smolin presents is that it would be a step backwards to move to background dependent theories after we have already been presented with Einstein’s background independent theory of gravitation. Since gravitation is universal it infects all other interactions (it can’t be screened off), so background independence should apply across the board. But this isn’t a good argument. The key problem is that it clashes with certain events from the history of physics, as bundled in the pessimistic meta-induction argument. Recall the twists and turns in the fortunes of æther theory, or the wave theory, or the particle theory. The wave and particle debate is particularly interesting here since that involved a tying together of the concepts in quantum theory and special relativity. However, we surely cannot expect a similar duality between background dependence and independence? At least I don’t see how any sense can be made of such an idea.

Background independence appears to be being taken on board by all parties, string theorists included. We need to know how to interpret such theories: without any background how does one understand the ontology? That’s of more interest to philosophers perhaps, but there are related technical issues as well: How does one compute physical quantities, scattering matrices, and so on? More seriously, however, is the problem of working out *what background independence means*!

What will happen in terms of the research environment? If there is to be progress I think it is inevitable that cross-fertilization across the camps will have to begin. Smolin’s book *The Trouble with Physics* [2006], though construed by most string theorists as a venomous attack, at least triggered *some* dialogue, if only negative at this stage. That book was important in that it provided a critical view on string theory, something that has been lacking because of the insular and difficult nature of contemporary quantum gravity research: string theorists don’t want to challenge their theory (given various academic pressures and so on), and non-string theorists usually don’t understand string theory well enough to give a confident reasoned critique.

What of ‘traditional’ philosophy of science issues, such as the ‘realism/anti-realism’ debate? I see no reason to suppose that quantum gravity will have an impact on this debate beyond that of quantum theory, relativity theory, and gauge theory taken separately. There are, for example, issues with quarks to do with their observability (or not) and the fact that they cannot be isolated, and so on. Likewise, our evidence for the existence of extra-dimensions, dark energy, and so on will be indirect too.[134] *More* indirect? This question leads to an unhelpful continuum of ‘directness’ that I think we should not pursue.

Although I have tried to remain reasonably impartial in this review, I should nail my colours to the mast as regards my favoured approach. For several reasons I favour

[134] In this primer the focus has been mainly on space, time, and spacetime, as opposed to matter. Of course, quantum gravity will have things to say about matter too—more or less, depending on the approach taken. However, the choice to limit discussion of matter was guided both by word count and by the fact that most approaches to quantum gravity shelve discussions of matter too.

loop quantum gravity and its covariant spin foam extension. But the more I learn about string theory the more I can appreciate the claims of its beauty and breadth. Moreover, one cannot help but notice the many similarities between strings, loops, and others. Such personal attachments are bound to colour one's judgement and allegiances. But solidified allegiance really ought to wait for experiment to catch up with theory, at least a little. String theory is already being pursued by its adherents as if it were 'normal science', a paradigm set in stone.[135] The revolution in physics remains incomplete. It is, I think, a puzzle that will remain with us for much of the 21st century and fundamentally alter the way we think about the world. Philosophers would do well to catch up while the pieces of the puzzle are still manageable!

9 Resources and Further Reading

Here I supply information that will aid the reader in getting to grips with quantum gravity.

On-Line Talks and Lectures

It is a wonderfully exciting time in terms of learning physics: one can learn mathematics and physics from some of the present masters. There is a wealth of on-line lectures, courses, and seminars.[136] An annotated list of some of the best of these follows:

- A rapidly evolving database of talks on quantum gravity and surrounding research areas from the Perimeter Institute can be accessed at http://www.perimeterinstitute.ca/en/Scientific/Seminars
- A vast repository of talks, many pertaining to quantum gravity, can be found at the Kavli Institute for Theoretical Physics' website: http://doug-pc.itp.ucsb.edu/online.
- Talks from *2001: A Spacetime Odyssey* can be found at http://pauli.physics.lsa.umich.edu/w/arch/som/sto2001/Lect
- African Summer Theory Institute, featuring a variety of excellent introductory lectures leading up to quantum gravity—http://www.asti.ac.za/lectures.php.
- Video of talks from a summer institute on *Gravity in the Quantum World and the Cosmos* can be found at http://www.conf.slac.stanford.edu/ssi/2005/program.htm.
- A vast array of talks, including many on quantum gravity and related areas—http://webcast.cern.ch/Projects/WebLectureArchive/index.html.
- Some high quality quantum gravity talks from seminars and conferences can be found at the Pacific Institute of Theoretical Physics—http://pitp.physics.ubc.ca/upcoming/index.html.
- Video of talks from a summer school on string theory, gravity and cosmology—http://www.pims.math.ca/science/2003/fmp/.

[135]There are two reasons for this, so far as I can see: (1) according to string theorists, quantum gravity demands unification of gravity with matter, so since string theory is the only consistent framework to achieve this, it has to be right. (2) according to string theorists, quantum gravity must be a theory of everything, and if this is the case, it must be unique. Neither is correct, of course, as the alternative approaches reveal.

[136]Of course, though working at the time of writing, these links are not guaranteed to be permanent.

- String theorists hold an annual *Strings* conference; talks from these have been uploaded for several years:
  - http://www.damtp.cam.ac.uk/strings02/speak.html.
  - http://www.yukawa.kyoto-u.ac.jp/contents/seminar/archive/2003/ str2003/speakerspro.html.
  - http://www.fields.utoronto.ca/programs/scientific/04-05/string-theory/strings2005/public_talks.html.
  - http://gesalerico.ft.uam.es/strings07/060_marco.htm.
- An excellent series of talks from the two recent loop quantum gravity conferences (modelled on the Strings conferences), Loops '05 and Loops '07, can be found here:
  - http://www.matmor.unam.mx/eventos/loops07.
  - http://loops05.aei.mpg.de/index_files/Programme.html.

Reading

My advice to those who are coming to quantum gravity afresh, or are fairly new to the area is to read the early papers on the subject, those mentioned in §4. Launching into most contemporary research articles in this area is liable to scare one off. The early papers, especially those which introduce some idea for the very first time, are far easier to make sense of, and will inevitably give one a better physical grasp on some idea. There are several review papers also that provide relatively easy access.

There have recently appeared some general textbooks and collections that contain material of a fairly elementary level: [Ehlers and Friedrich, 1994; Kiefer, 2007; Stamatescu, 2007; Fauser et al., 2007; Giulini et al., 2003; Kowalski-Glikman, 2000]. Specific textbooks on the more heavily researched approaches are also available, mainly on string theory and canonical quantum gravity. An excellent introduction to loop quantum gravity, and canonical approaches more generally, is [Rovelli, 2007]—this book also includes some good discussions of philosophical issues. The best introduction to string theory, for newcomers, is [Becker et al., 2007].

Compared to the wealth of material available on the interpretation of quantum mechanics, there is very little material on the philosophical aspects of quantum gravity. However, if one looks hard enough, there is some to be found. Three books on the subject are: [Ashtekar and Stachel, 1991; Callender and Huggett, 2001; Rickles et al., 2006].

Stephen Hawking once remarked that each mathematical formula in a popular science book halves the number of sales. I think that this pessimism, though it might have been right at the time, is no longer justified. There is a new brand of popular science book, generally written, like Hawking's *Brief History of Time*, by 'insiders'. However, these are not scared to include equations, though they are usually quick to explain their meanings. The first book of this kind was probably Roger Penrose's *The Emperor's New Mind* [2002]—he has written a new 'popular' book *The Road to Reality: A Complete Guide to the Laws of the Universe* [2007] that contains more mathematics (and more complex mathematics) than many physics research monographs.

This book would make an excellent companion whilst trying to get to grips with quantum gravity, and indeed it contains introductory material on many of the approaches delivered with the touch of a true master expositor. There are a few more excellent popular accounts of quantum gravity, written by quantum gravity researchers. In order to get the 'big picture' I highly recommend Lee Smolin's two books: [Smolin, 2002; 2006]. Also, Julian Barbour's book *The End of Time* [2001] is an excellent account of the conceptual problems involved in quantum gravity. For a superb account of string theory, see Brian Greene's two books: [Greene, 2000; 2005].

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