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Quantum Gravity Meets Structuralism: Interweaving Relations in the Foundations of Physics

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In this introductory chapter we aim to provide some of the technical and philosophical background to the issues discussed in this volume. We hope that, together with the other chapters, it will motivate the view that 'going structural' is well supported by this most pressing area of physics.

1.1 QUANTUM GRAVITY: BACKGROUND, CONCEPTS, AND METHODS

The physics of gravity is inextricably connected to the geometry of space and time. In Einstein's theory of general relativity—the best theory of *classical* gravity that we have—the geometry (curvature) of spacetime, as encoded in the metric tensor $g^{\mu\nu}$, is *identified* with the gravitational field. But the metric field is also responsible for the characteristic structures of space and time too (causal structure, notions of distance, and so on). Hence, the metric plays a dual role in general relativity: it serves to generate both the gravitational field structures and the chronometric, spatio-temporal structures (cf. Stachel 1993). In the context of general relativistic physics, of course, the metric—and, therefore, the geometry of space—is *dynamical*: the metric on spacetime is not *fixed* across the physically admissible models of the theory (as it is in, for example, Newtonian and specially relativistic theories). The geometry of spacetime is affected by matter in such a way that different distributions of matter yield different geometries—the coupling and the dynamics is described by Einstein's field equation. In other words, general relativity does not depend on the fixed metrical structure of spacetime; rather, the metric itself, and hence the geometry, comes only once a matter distribution has been specified (and the dynamical equation has been solved). Classically, this feature, called *background independence*,[1] is rather

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[1] Background independence is, more properly, defined as the freedom from 'background structures', where a background structure is some element of the theory that is fixed across the

remarkable, but it is, at least, fairly easy to make physical and conceptual sense of. We can draw, for example, the following features from background independence in general relativity: the geometry of spacetime satisfies equations of motion; its curvature produces the gravitational force; since it produces a force it has energy momentum; and so on.

However, in the quantum theory of gravity, the spacetime metric will most probably have to be quantized, so that we will have to consider it a quantum theory of spacetime (or quantum *geometry*), and will need to make sense of superpositions of macroscopically distinct spacetime geometries.[2] This is *not* so easy to make *any* kind of sense of; prima facie quantum gravity faces all of the technical and interpretative problems of quantum theory, and then some. However, there are real interpretative problems even at the classical level; most notably, the 'hole argument' (Earman and Norton 1987). The hole argument has played an important role in the small portion of work that exists on the interpretation of quantum gravity, at least in its canonical (i.e. Hamiltonian) guise. Let us begin by saying a little about this argument, its root and its significance—for it is central to the claims being made about the 'structural' and 'relational' aspects, and features quite heavily in what follows. We then discuss the impact of quantum gravity (including a few words about the relevance of the hole argument in this context), and say something about the various methods and concepts employed in the field of quantum gravity. The emphasis throughout will be on the notion of background independence (and the related notions of 'background structure' and 'background dependence').

1.1.1 The Hole Argument and Spacetime Ontology

The hole argument is most easily couched in terms of models $\langle \mathcal{M}, \mathcal{D} \rangle$ (where $\mathcal{D}$ is a set of dynamical fields on $\mathcal{M}$—any further background fields are, of course, absent in general relativity[3]). Let us restrict ourselves, purely for simplicity, to the vacuum case and therefore assume that $\mathcal{D} = g$, so that the (Lorentzian) metric is the only dynamical field on $\mathcal{M}$. The models $\langle \mathcal{M}, g \rangle$ then minimally correspond to

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models of a theory—this 'fixity' can be cashed out in a variety of ways, a common one of which is the idea that a structure is fixed if it is not varied in the action of the theory. However, background independence, when used in the context of quantum gravity, is usually meant in a restricted sense, covering the freedom from a background metric alone. The other side of the coin is, of course, background *dependence*, which is simply a dependence on background structures. See §1.1.7 and the contributions of Baez and Smolin (in this volume) for more details. See also Butterfield and Isham (1999) for a very nice disentangling of the various notions of 'fixity' in this context.

[2] Though several authors have argued that gravity might in fact act so as to collapse wavefunctions that would result in such geometric superpositions—see Károlyházy et al. (1986) and Penrose (1986).

[3] It is important to note that the manifold and the topological and differential structure of the manifold *are* background structures in the theory—we can, in other words, 'factor' the manifold into these other structures and when we do we find that they appear in the theory as background structures. Though one may choose different manifolds and topologies (spaces of dimension other than four, for example) once chosen they remain fixed in place, and are not sensitive to the dynamical goings on in that space. Again, see the contributions of Baez and Smolin for more on this issue.

a 'bare' manifold possessing only topological and differential structure along with geometrical structure determined *dynamically* (i.e. post-solution) by g in accordance with the vacuum Einstein equation:

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}R^{\alpha}_{\alpha}g_{\mu\nu} = 0. \tag{1.1}$$

The crucial property of Einstein's equations, as regards the hole argument, is that they are *generally covariant*: if $\langle \mathcal{M}, g\rangle$ satisfies (i.e. solves) the Einstein equation then so does the diffeomorphic copy $\langle \mathcal{M}, \phi^* g\rangle$, $\forall \phi \in \mathsf{Diff}(\mathcal{M})$.[4] The 'carried along' field $\phi^* g$ will generally be different in the sense that, given a global chart on $\mathcal{M}$ with coordinates $\{x^i\}$, $\phi^* g(x) \neq g(x)$. When this happens we have the beginnings of a hole argument: there will be many metrics that solve the equations that will give (locally—i.e. at a specific point or within some region) different results. Hence, choose a region of the manifold, $\mathcal{H} \subset \mathcal{M}$ (the hole), and suppose that we can solve completely for all points outside the hole in the region $\overline{\mathcal{H}} = \mathcal{M} - \mathcal{H}$ (i.e. we know $g(x)$, $\forall x \in \overline{\mathcal{H}}$). Now let $\phi_{\mathcal{H}}$ be a diffeomorphism that acts as the identity on $\overline{\mathcal{H}}$ but not within $\mathcal{H}$: then the field equations do *not* uniquely determine $g(x)$ for $x \in \mathcal{H}$; for both $g(x)$ and $\phi^*_{\mathcal{H}} g(x)$ are solutions (thanks to general covariance), and yet $\phi^*_{\mathcal{H}} g(x) \neq g(x)$ for at least one point within the hole. If we put the hole to the future of some initial slice then this signals a violation of determinism: the Einstein equation cannot *uniquely* determine the spread of the metric field over the points of the spacetime manifold.

Earman and Norton argued that this form of indeterminism places the manifold substantivalist[5] in serious trouble: if the points of spacetime are real existents, and are independent of any dynamical goings on at or around them, then he will surely have to view the two solutions above as representing *physically distinct* possible

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[4] Recall that, for a given manifold $\mathcal{M}$, a diffeomorphism ϕ is a smooth (i.e. C^∞), invertible mapping $\phi : \mathcal{M} \to \mathcal{M}$. Diffeomorphisms also act on field structures on $\mathcal{M}$ by 'carrying them along' to new diffeomorphic field structures. Thus, given a field structure $d \in \mathcal{D}$ (e.g. some tensor field) on $\mathcal{M}$, the action of a diffeomorphism ϕ produces a new field structure $\tilde{d} = \phi^* d$ called the *carry along* of d by ϕ. $\mathsf{Diff}(\mathcal{M})$ is simply the group of all such diffeomorphisms on $\mathcal{M}$—this group is usually understood to be the *gauge group* of general relativity.

[5] Following Sklar, let us define substantivalism as that view that takes 'spacetime to be an entity over and above the material inhabitants of the spacetime ... that could exist even were there no material inhabitants of the spacetime' (1985: 8). Relationalism is just the denial of this: what the substantivalist calls 'spacetime' is 'nothing but a misleading way of representing the fact that there is ordinary matter and that there are spatiotemporal relations among material happenings' (ibid. 10). There are two important things to note about these definitions: (1) there is assumed a straightforward distinction between 'matter' and 'space(time)'; (2) the distinction between the positions is grounded in a basic ontological priority claim involving matter or space—in the case of general relativity these distinctions become rather fragile, and this fragility leads to a remarkable degree of resemblance between relationalist and substantivalist interpretations of spacetime in general relativity (compare, for example, Hoefer's (1996) 'metric field substantivalism', Stachel's (1993) 'relationalism,' and Saunders's (2003) 'non-eliminative relationalism'). However, according to Earman and Norton's best choice for the substantivalist (viz. 'manifold substantivalism') it is the manifold of points, along with their topological and differential properties and relations, that best represents spacetime conceived as a substantival entity. At least the distinction between matter and space(time) is rather more robust on this view.

states of affairs (distinct possible worlds, if you prefer); but if that is the case, then the indeterminism that is exposed by the hole argument is genuine and physical. Earman and Norton conclude from this that we should reject substantivalism, for metaphysical positions are not the kinds of thing that should be leading us into such difficulties—only reasons of physics should be doing that, they say. But substantivalists have not been deterred, adopting ever more subtle forms of the basic position than that of Earman and Norton's naive manifold realism. In our view, however, the best way to respect the hole argument, while remaining a realist about spacetime, is to adopt a structuralist position. Many of the more recent positions that call themselves 'substantivalist' (especially the 'sophisticated' ones: e.g. Hoefer 1996; Pooley, this volume) and 'relationalist' (particularly, the physicist inspired ones: e.g., Stachel 1993, this volume; Saunders 2003; Smolin, this volume; and Rovelli 2004) turn out to be of just this kind. The basic idea, to be developed in the following subsections, is that the fundamental ontology of the theory is given by relational structures rather than individual objects; inasmuch as objects exist at all, they derive their properties and individuality from the relational network in which they are embedded. Before we move on to consider quantum gravity, and the structural stance in more generality, let us first pause to consider the nature of the hole argument in a little more depth.

1.1.2 Gauging the Hole Argument

In order to fully appreciate the inner workings of the hole argument (*qua* problem of determinism, at any rate), it is better to shift to the canonical (constrained Hamiltonian) formulation of general relativity, and thus construct its phase space Γ (parts of which are 'unphysical'—see below).[6] Adopting this stance does two things for us: (1) it allows us to make sense of general relativity as a theory about the *dynamics of space*; (2) it allows us to make sense of the way in which general relativity is a *gauge theory*.[7]

First we take spacetime to be a four-dimensional manifold $\mathcal{M}$ diffeomorphic to $\mathsf{S} \times \mathbb{R}$—with S a (compact, orientable) 3-manifold taken to represent 'space' and where $\mathbb{R}$ is taken to represent 'time'. We choose S so that it is spacelike with respect to g and so that it is a Cauchy surface—let's now call this surface Σ. Let t be the function on $\mathcal{M}$ associated with the foliation by Σ and whose level surfaces are the leaves of the foliation. Thus far we have simply defined the background structure of

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[6] Here, we focus on the *geometrodynamical* formulation according to which the configuration variable is the 3-metric q on a hypersurface. There are—as the chapters by Cao, Stachel, and Smolin will highlight—alternative 'polarizations' of general relativity's phase space (one might use, for example, a *connection* on a hypersurface as the configuration variable), but the differences are largely irrelevant for our purposes, and would overly complicate our account (see Rickles 2005a for a discussion of the hole argument transplanted into these different contexts). The chapter by Rickles in this volume offers a more detailed and general introduction to the canonical formalism.

[7] Recall that a gauge theory is one whose *physical* content is captured by those dynamical variables, the observables, that are invariant under the action of the (gauge) symmetry group, i.e. those unchanged by gauge transformations (these are those transformations generated by the first class constraints—see below, and see Dirac 1964, for the classic exposition).

the theory. A phase space Γ is then constructed using this background by taking the basic dynamical variables of the theory to be the 3-metric q_{ab} on Σ (playing the role of canonical 'position' variable) and p^{ab} (playing the role of canonical 'momentum' variable conjugate to q_{ab})[8]—both are induced by the $3+1$ 'split' together with g. Thus, an instantaneous state of the gravitational field is given by pairs $(q, p) \in \Gamma$. However, not any old pairs will do—i.e. not all points in Γ are physically 'kosher'. The reason for this has to do with the four-dimensional diffeomorphism invariance of the covariant theory which is 'translated' into a pair of constraints on the initial data (Σ, q, p) so that, in order to count as *physically admissible* (i.e. dynamically possible), they must satisfy both the *diffeomorphism* (or *vector*) constraint and the *Hamiltonian* (or *scalar* constraint). We can express these formally—with ${}^3\mathsf{R}$ being the Ricci curvature scalar of q on Σ—in the geometrodynamical formulation as follows:

$$\mathcal{D}_a(q, p) = -2q_{ac}\nabla_b p^{bc} = 0 \tag{1.2}$$

$$\mathcal{H}_\perp(q, p) = \mathsf{det}(q)^{-1/2}\left[q_{ac}q_{bd} - \frac{1}{2}q_{ab}q_{cd}\right]p^{ab}p^{cd} - \mathsf{det}(q)^{1/2}\,{}^3\mathsf{R} = 0 \tag{1.3}$$

This analysis brings out some of the gauge-theoretic aspects of general relativity—though, it has to be said, these aspects are at their most transparent in the connection formulation. In phase space terms we see that the full phase space Γ does not correctly represent the physically possible worlds of general relativity, for not all points will satisfy the constraints. However, the points that *do* satisfy the constraints form a submanifold $\mathcal{C} \subset \Gamma$ known as the *constraint surface*. The crucial feature of this setup, vis-à-vis the hole argument, is that the constraint surface is partitioned into gauge orbits whose elements (phase points) correspond to those states related by the symmetries (i.e. the diffeomorphisms) generated by the constraints—see the essays by Dorato and Pauri and Rickles (in this volume) for more details.

The connection to the hole argument is now obvious: the spacetime diffeomorphisms utilized therein correspond to 'unphysical' gauge motions generated by the constraints. The relevant constraint for the hole argument is $\mathcal{D}_a$ since this generates *spatial* diffeomorphisms of Σ.[9] (This distinguishing of the constraints may seem a little unnatural, since the hole argument calls upon the *full* group of spacetime

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[8] The momentum variable is related to the extrinsic curvature K^{ab} of Σ by $p^{ab} \equiv \mathsf{det}(q)^{1/2}(K^{ab} - K^c_c q^{ab})$, where K_{ab} describes the embedding of Σ in $\langle \mathcal{M}, g \rangle$.

[9] However, an analogous problem also holds for the Hamiltonian constraint, though its treatment and interpretation leads to even thornier issues connected with time and change (known as the *problem of the frozen formalism* in the classical theory and the *problem of time* in the quantum theory). Very roughly, the problem is that if we interpret the Hamiltonian constraint as both the generator of time evolution (as is standard) *and* a generator of gauge transformations (and being a first class constraint, following Dirac 1964, we should indeed view it as such—but see Kuchař (1992) for a view to the contrary), then it seems as if there is no change, for time evolution corresponds to an unphysical gauge motion. The quantum version of the problem simply follows from the fact that if the classical Hamiltonian is zero, then the Schrödinger equation for relevant wave functions Ψ (e.g. 'the wave function of the universe') will be $i\frac{\partial\Psi}{\partial t} = \hat{H}\Psi = 0$, and we will be without quantum dynamics. See Belot (1996), Belot and Earman (1999, 2001) and Rickles (this volume) for more details.

diffeomorphisms. However, in the canonical formalism, we can envisage the normal deformations generated by the Hamiltonian constraint to be zero and yet still generate hole argument situations, and likewise, in setting the tangential deformations generated by the diffeomorphism constraint to zero, we can still generate 'problem of time' situations—whether anything of real significance rests on this fact we leave to the reader to decide.) The gauge motions—the transformations generated by the constraints—act on all points of Γ *including* those points lying within $\mathcal{C}$. In fact, the constraints have the effect of shifting phase points along orbits of the gauge group. Distinct points lying on the same gauge orbit are physically indistinguishable, representing equivalent (with respect to the 'genuine' observables) descriptions of the same physical state. Hence, even after disposing of the physically impossible states (by focusing on the constraint surface), there is something of an overabundance of physically possible states; this surplus structure is known as 'gauge freedom', and it is this that is responsible for the indeterminism that the hole argument exposes so well.

Now, the view that the constraints generate gauge motions—so that the diffeomorphisms utilized in the hole argument are gauge—leads to a natural resolution (that we might refer to as 'the physicist's resolution'[10]) of the hole argument: the indeterminism is simply unphysical, it is gauge. All that the hole argument shows us is that there are no observables of the form '$F(\mathbf{x})$': since points of space or spacetime are not diffeomorphism invariant, neither are quantities defined with respect to them. Hence, the value of the metric field at a certain *independently specified* spacetime point is not admissible; that we can talk about such a thing at all is merely the result of the surplus degrees of freedom (the gauge freedom) in the mathematical framework we use to formulate the theory. Thus, the observables of the theory should not distinguish between gauge-equivalent states (i.e. states lying within the same gauge orbit); rather, they should be constant along gauge orbits (so that their Poisson bracket with the constraints vanish) and dependence should be at the level of entire gauge orbits.[11] There are a number of ways of cashing this out, both formally and technically. For example, we might see it as motivating (or, perhaps, as being underwritten by) an anti-haecceitistic metaphysics, according to which there is no physical difference (i.e. a difference between possible worlds) without a qualitative difference (this is the line of Stachel and Pooley in this volume). The natural formal setup for making sense of the 'eradication' of the unphysical gauge degrees of freedom is to construct the *reduced* phase space $\overline{\Gamma}$ (roughly, $\overline{\Gamma} = \mathcal{C}/\mathsf{Diff}(\Sigma)$, where $\mathcal{C} \subset \Gamma$ and $\mathsf{Diff}(\Sigma)$ include the diffeomorphisms tangent and normal to the

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[10] See, for example, Wald (1984: 259–60) and Hawking and Ellis (1973: 227–8) for a pair of classic statements of this viewpoint.

[11] Note, as hinted at in the previous footnote, that Kuchař argues that the constraints of general relativity should be distinguished: the diffeomorphism constraint, generating spatial diffeomorphisms, should be viewed as a gauge transformation, so that observables should be insensitive to their action, but the Hamiltonian constraint is a different matter for it generates changes in the variables from one hypersurface to another. This is, of course, related to the problem of the frozen formalism: if the Hamiltonian constraint is taken to generate gauge transformations, then observables must be constants of the motion, which, Kuchař maintains, is absurd. Rickles reviews the interpretative options in his contribution to this volume.

hypersurface Σ) with phase points given by equivalence classes of models under all the diffeomorphisms. Earman and Norton (and, more recently, Belot and Earman 1999, 2001) took this space to be out of bounds for substantivalists; after all adopting it is, more or less, tantamount to implementing Leibniz equivalence (i.e. the idea that diffeomorphic models represent one and the same physically possible world). But they view the adoption of Leibniz equivalence (or, equivalently, commutation of physical quantities with all of the constraints) as underwriting relationalist (or, at least, *anti*-substantivalist) positions. We don't wish to enter this debate here; it is well trodden and many of the chapters in this volume cover the central issues. What we want to suggest is that structuralist views sit nicely in this space, and avoid the (often seemingly *verbal*) dispute between relationalists and sophisticated substantivalists (i.e. substantivalists who endorse Leibniz equivalence). Indeed, as mentioned previously, we say that these latter positions sit very happily under the more general banner of 'structuralism' (see §1.2). Let us now turn to the subject of quantum gravity, and consider the bearing of background independence in this context. We shall then connect this to structuralism.

1.1.3 Enter Quantum Gravity

The problem of quantum gravity involves finding a way of describing the gravitational field in those high-energy, small-scale regimes in which its quantum mechanical features cannot be swept under the carpet. However, *quantum gravity*, as a label, does not yet denote any existing theory; rather, there are a number of distinct research programmes in competition for that title. There are certain minimal constraints that these approaches must satisfy to qualify, or at least be in the running. How and to what extent these constraints are met, and indeed *what* the precise constraints are is a matter of debate between the various camps. Minimally, though, it seems that what is required is a quantum theory that has general relativity as a classical limit, so that the success of general relativity can be explained from the perspective of the new theory. We might understand this in terms of a *synthesis* (or unification) of quantum field theory and general relativity (say, a generally relativistic quantum field theory); but even if we can make sense of such a notion, it is not clear that synthesis or unification is a *general* requirement.[12] For one, it has never been decisively demonstrated that there is an a priori conflict between the *formalisms* of classical general relativity and quantum field theory.[13] It should be noted, also, that there is no clear empirical problem that requires quantum gravity for its resolution, nor is there, at present, any way to probe quantum gravitational sectors empirically (though, recently, there has

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[12] This 'synthetic' view seems to be the one adopted by those working on loop quantum gravity, and the canonical approaches more generally—this picture seems to correspond to that favoured by Cao (2001, and in this volume). The string theorist, by contrast, appear to follow a more 'accommodationist' line: quantum gravity is contained in the general framework of the theory in virtue of there being a massless spin-2 particle (the graviton) in the string spectrum.

[13] On the other hand, there does appear to be a 'conceptual mismatch' at the level of the views of spacetime that each calls upon: general relativity is not set against a background spacetime, whereas all quantum theories constructed so far, have been—see p. 13.

been some progress in this latter respect: see Amelino-Camelia 1999). In light of this, let us begin by assessing the possible reasons for wishing to construct a quantum theory of gravity—this brief detour will act as a primer on the kinds of issue and areas that a theory of quantum gravity might be expected to deal with. We shall then sketch in *very* broad brushstrokes the kinds of methods that have been employed to implement a theory of quantum gravity, and then finally indicate the way in which structuralism enters the picture by appealing to background independence. The following sections will then attempt to consolidate this suggested 'structuralist turn' in quantum gravity by situating it within wider historical and philosophical issues pertaining to structuralism.

1.1.3.1 Why Bother?

One of the first questions one faces when thinking about quantum gravity is why one should bother constructing such a theory at all. There are, after all, no phenomena that are out of the reach of the theories we have at out disposal already. Why should we require a revolution when there is nothing to *revolt* against? It is true that many times in the history of physics, when a revolution has occurred, it has occurred because of some *lack* with the theories then current. Either there was an inconsistency in the theory, or else the theory could not deal with some new (or old) piece of observational data. However, conflict with the observed data is not necessary for a revolution; in the next subsections we present several alternative reasons for requiring another revolution in physics.

Dimensions of Quantum Gravity

Max Planck demonstrated over a century ago that the three fundamental constants of nature—c (speed of light *in vacuo*), G (the gravitational constant), and $\hbar$ (Planck's constant: the quantum of action)—can be uniquely combined in such a way so as to produce 'natural' units of *length*, *time*, and *mass*. We get:

$$l_p = \left(\frac{\hbar G}{c^3}\right)^{\frac{1}{2}} \approx 1.62 \times 10^{-33} cm. \tag{1.4}$$

$$t_p = \frac{l_p}{c} = \left(\frac{\hbar G}{c^5}\right)^{\frac{1}{2}} \approx 5.40 \times 10^{-44} s. \tag{1.5}$$

$$m_p = \frac{\hbar}{l_p c} = \left(\frac{\hbar c}{G}\right)^{\frac{1}{2}} \approx 2.17 \times 10^{-5} g. \tag{1.6}$$

At these scales, in the 'Planck regime', general relativity and quantum field theory stop working: singularities, and other craziness emerge that lie outside of their domain of applicability. It is here that quantum gravity is expected to reign triumphant, and provide an adequate framework—'formally' adequate, in the sense of providing a consistent mathematical theory (perhaps by eliminating the 'craziness'); and 'experimentally' adequate in the sense of offering up confirming instances of data. Of course, this is not an *empirical* problem with general relativity and quantum field theory simply because these dimensions are 'out of reach' as far as empirical accessibility goes—though we might class it as a 'potentially empirical problem'.[14] Rather, the lack is purely conceptual; it is a problem with the frameworks of quantum theory and general relativity that lies beyond what is empirically accessible. In addressing the issue of what happens in this realm we are ineluctably led to consider what happens at scales when one or the other theory becomes relevant for the other, so that both theories have to be considered acting together. When we do this, then certain other, even deeper, conceptual problems surface, problems to do with the radically divergent conceptual schemes the theories employ.

The Principle of Unification

A great many revolutionary advances in physics have come about by means of a synthesis between two theories that were thought to be disparate. For example, special relativity was conceived by trying to hold the principle of Galilean relativity and Maxwell's theory of electromagnetism together. The problem is that Maxwell's theory is not Galilean invariant. By unifying the two, Einstein realized that electromagnetic phenomena must look the same in uniformly moving reference frames. Quantum field theory was the result of concerted efforts to bring together special relativity and quantum mechanics. General relativity was conceived in an attempt to unify Newton's theory of gravity with the principle of locality of special relativity. In each case there was supposed to be some fundamentally conflicting pair of theories or pieces of data that were both taken 'seriously' for the purposes of unification. The end product is a theory of the piece of data that respects both in some ways, and departs in other ways. If this is the dialectic of progress in physics, then we should expect a theory of quantum gravity to emerge from the unification of quantum field theory and general relativity, the latest in a series of conflicting pairs that physics has presented us with.

However, the concept of unification is not straightforward, and admits certain ambiguities in the context of physical theories. Unification can mean any number of distinct, though often related, concepts. We can range a number of such concepts in order of 'strength' as follows: (1) reductionism, (2) synthesis, or (3) compatibility (encompassing 'accommodation'). It isn't clear that all revolutions in physics occur at the same strength, or even that they involve any kind of unification. Above, we have been speaking of unification as synthesis, whereby two incompatible theories are 'merged', in some sense, into one that takes important features from both, and discards other features. In the case of general relativity, the key distinguishing feature that is expected (by many) to be retained is the diffeomorphism invariance of the theory, and the background independence that it implies.[15] Quantum field

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[14] We should add, however, that the field of 'quantum gravity phenomenology' has gone some way towards demonstrating that features from the Planck scale might be accessible through certain potentially observable effects, such as the violation of Lorentz invariance—see Amelino-Camelia (1999) for a clear review.

[15] The argument, in a nutshell, is that (1) diffeomorphism invariance means that the physical quantities of the theory are insensitive to diffeomorphisms; (2) diffeomorphisms act (inversely) on the dynamical fields of the theory. Therefore, (3) there cannot be a background metric, for if there were then the diffeomorphisms *would* make a difference to the physical quantities.

theory will, most likely, retain the probabilistic structure as encoded in the operator algebraic representation of observables, and the representation of states as elements of Hilbert space (or, possibly, linear functionals over the operator algebra). Thus, what is required is a background-independent quantum field theory, or, equivalently, a quantum theory on a differentiable manifold.[16] In his contribution John Baez presents one such possibility in the form of topological quantum field theory. His idea involves the tools of category theory which he uses to demonstrate certain deep analogies (at the category theoretic level) between quantum theory and general relativity. Such a theory would certainly be structuralist. The reason for this is to do with the absence of a background metric with which to ground absolute locations in spacetime. This leads to the view that spacetime localization is relativized to something other than spacetime points—this may be physical objects or fields, or, if we view the identification of the metric with the gravitational field as marking an ontological identity, then we are able to localize with respect to the metric field itself (or, more properly, the points defined by the metric field).[17]

Coping with Singularities

One area where there does appear to be some breakdown in current physics, albeit in a (currently) non-empirical sense, is black hole physics. We know from general relativity, and the singularity theorems of Penrose and Hawking, that very many admissible initial data sets, for gravity plus matter, will result, under the evolution described by Einstein equations, in a gravitational collapse so extreme that a singularity will be produced. A singularity, you will recall, is (roughly) a region of spacetime at which the gravitational curvature becomes infinitely large; physically this may correspond to, for example, a material body collapsing to a point.[18] Now, a physically reasonable normative requirement on our theories is that infinite quantities should be avoided or, more strongly, that infinities do not correspond to anything physical. Whether one views this constraint as reasonable

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[16] It is for this reason that the hole argument becomes a pressing issue in quantum gravity (conceived of in terms of a background independent quantum field theory). For one must make certain non-trivial choices regarding how one deals with the symmetries utilized in that argument. In capsule form these choices concern the question of whether or not we should quantize *with* or *without* the symmetries generated by the constraints—or, in more technical terms, whether we should use the machinery of non-constrained or constrained quantization. The choice is non-trivial because there will be degrees of freedom being quantized in the unconstrained approach that are not contained in the constrained approach; these can have potentially physical consequences (cf. Gotay 1984).

[17] This isn't quite right. In the case of the topological quantum field theories that Baez discusses, there are no local degrees of freedom at all. This is a problem because general relativity *does* have local degrees of freedom, only they are determined dynamically by solving the Einstein equation. However, the topological quantum field theories Baez presents nonetheless display structuralist tendencies on account of the weight they put on relations as opposed to objects.

[18] This is a rough characterization, and the details are much more complex. Less roughly we can define a singular spacetime to be one containing a geodesic of finite total *affine* length, such that a scalar invariant considered along it becomes infinite (see Earman 1995)—though there are problems even with this 'received' definition: see, for example, Geroch (1968).

or not, however, it seems clear that such singularities would pose a severe problem for our current physical theories. The reason has to do with the simple dimensional argument presented above: when the spacetime curvature is of the order of the Planck length the quantum fluctuations of the spacetime metric would no longer admit a representation by means of a smooth (pseudo-) Riemannian manifold. Thus, some new physics is inevitably required to deal with the gravitational field in such circumstances (cf. Penrose 1978).

Of course, another area in which infinities raise a problem is in quantum field theory. As in classical electrodynamics, in quantum electrodynamics there is the problem of electrons interacting with their own field. To resolve this problem, manifested as divergent integrals, one looks to renormalization theory and, more recently, renormalization group theory, to cope with or make sense of the difficulties. However, when we run general relativity through this sausage machine, we find that more infinities are produced: the theory is non-renormalizable.[19] These ineradicable infinities might be taken as signalling the need for a shift to a new or modified theory; and, indeed, many have taken the lesson of non-renormalizability to be as signalling a shift to a non-perturbative approach.[20]

It might be the case that these two types of infinities can be dealt with together as a package. Indeed, this seems to be the case in some approaches to quantum gravity; certainly it is in string theory and loop quantum gravity (the two main lines of attack): stringy dynamics has the effect of 'delocalizing' interactions (i.e. 'smearing' them out, away from points), so that the point interactions responsible for the ultraviolet divergencies are outlawed. Likewise the singularities of spacetime are avoided in string theory, since there gravity simply corresponds to a certain vibrational mode of the string, and in loop quantum gravity the micro-structure of space is discrete (since the geometry, and therefore geometrical quantities that depend on the metric, are quantized). In this way, the success of renormalization procedures is made a little clearer from a physical point of view. Thus, we might say, roughly, that the loop gravity and string theory programmes avoid the singularities by adding non-locality at the level of 'space' and 'objects' respectively.

Cosmological Quantum Theory

If quantum theory is about observations, then we need observed things and observers. What about the universe as a whole? Bell calls this 'an embarrassing concept' (1981: 622). Why? Because we do not see the universe in a superposition of states. Why not if there is no observer to observe it? Shouldn't the universe be in a grand superposition of, for example, macroscopically distinct volume states? In this case we cannot call

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[19] See Deser and van Nieuwenhuizen (1974) for a classic discussion. However, the pudding is in the proof, on which see Goroff and Sagnotti (1986).

[20] However, we need not desert a theory just because it is non-renormalizable. The theory of the renormalization group (as devised by Wilson and co.—see Binney et al. 1992), and the programme of effective field theories show us how we might view general relativity as an *effective* field theory that is nonetheless capable of making physical predictions (cf. Donoghue 1994, 1996). See Burgess (2004) for a very readable account of this viewpoint. Castellani (2002) offers a nice elementary survey of effective field theories and their philosophical implications.

on environmental effects (and thus modifying the state by including these variables), since there is no environment. But with no measuring 'agency' the universe should be in such a state if quantum theory is universally valid. In typically colourful style, Bell writes that:

> It would seem that [quantum] theory is exclusively concerned with 'results of measurement' and has nothing to say about anything else. When the 'system' in question is the whole world where is the 'measurer' to be found? Inside, rather than outside, presumably. What exactly qualifies some subsystems to play this role? Was the wave function waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some highly qualified measurer—with a Ph.D? If the theory is to apply to anything but idealized laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time more or less everywhere? Is there ever then a moment when there is no jumping and the Schrödinger equation applies? (1981: 611)

This brings into sharp focus the problems that quantum cosmology poses to the interpretation of quantum theory. If it is measurement that prevents the wave function from applying to everything at all times, then what measures the whole universe? The universe is, after all, a valid object of study in general relativity, therefore we should it expect to remain a valid object of study in quantum general relativity. We might expect, then, that no measurement takes place, and that the evolution is plain linear Schrödinger-style evolution—of course, the problem of time, mentioned earlier, becomes highly relevant here. Given this, how can we make sense of the universe's being in a superposition of (e.g. geometrical) states? There are several possibilities: some go down the Everettian route, and some go down the de Broglie–Bohm route. Neither route leads to jumps or collapses.

One thing seems certain, however, and that is that the traditional Copenhagen interpretation is put under pressure in this context. Recall that according to this 'orthodox' interpretation of quantum theory, any measurement interaction requires an observer that is *external* to the system that is being measured and is classical. Yet if we want quantum theory to be *universal* (i.e. independent of scale and applicable to all dynamical systems) then this category of interpretation faces a very simple problem. Quantum theory being universally valid means that it applies to systems of any size. The universe as a whole can be viewed as a physical system. Indeed, in cosmology this is a perfectly reasonable object of study. Yet there is, by definition, no observer outside the universe. Moreover, physics on cosmological scales, and so the universe as a whole system, is the domain of general relativity. It seems as though we have wandered into the territory of quantum gravity, and it seems that the Copenhagen interpretation is at a loss to deal with it.

Though many view the problems of quantum cosmology as strictly independent from the problem of quantum gravity, there are some who see the two problems as entangled (e.g. Smolin 1991, 2003). Our view is that there is a definite asymmetry here: a theory of quantum gravity should certainly give us an account of quantum cosmology, but the converse of this need not be true; for example, there are proposals to make sense of quantum cosmology that, strictly speaking, lie outside quantum gravity proper—e.g. consistent histories and Hartle's 'spacetime quantum mechanics' (1995).[21]

Problems with the Semiclassical Theory

There is a fairly simple argument that demonstrates that a semiclassical theory of quantum gravity (that is, a coupling of a classical gravitational field with quantum matter) results in superluminal signalling (Eppley and Hannah 1977). Suppose we have two spacelike separated observers, at sites A and B, and that they are making continuous measurements on the gravitational field. Suppose now that in between A and B we perform a beam-splitting experiment on a photon (let us suppose, for the sake of simplicity, that the photon has a mass of one unit—one pound, say). The experiment results in a probability distribution according to which it is at site A with a probability of a half, and at site B with a probability of a half. Since the gravitational field is classical, this will manifest itself as a warping of spacetime equivalent to half a pound at A and half a pound at B. Now suppose that observer A makes a measurement to determine the position of the photon. If the photon is at A, then the wave function collapses in such a way as to produce a warping equivalent to a one-pound mass, and the gravitational field at B will diminish by an amount equivalent to half a pound. Otherwise, the field at A will be diminished by half a pound of curvature and will increase to a pound of curvature at B. This happens instantaneously. Thus, observer A could use this setup to send a message to B; he could make a measurement to send the message, say, 'Yes, the bomb has been launched,' and not make any measurement to say 'No, the bomb has not been launched.' All B has to do is continue to measure the state of the gravitational field, and watch out for the increase or decrease. This suggests that we have to consider the gravitational field as quantized too, in order to avoid conflict with the principle of locality in general relativity.[22]

Time and Space in GR and QFT

One of the most obvious areas where philosophers can apply themselves is to the radically divergent concepts of space and time that are employed in quantum field theory (QFT) and general relativity (GR). In a nutshell the theories are incompatible because they employ incompatible ideas of space and time: quantum field theory (those forms we have at present) is necessarily background dependent (in order that the states, operators, and even the fundamental axioms can be defined); general relativity is background independent. Many of the problems and issues raised in the contributions in this book can be traced back to this single source. Here we do no more than merely hint at the scope of the problems.

The central point of difference between the two types of theory concerns, of course, the treatment of the metric (or connection) on the spacetime manifold. In existing quantum field theories (and quantum theories more generally), space and

[21] See also Gell-Mann and Hartle (1990) for an attempt to formulate a (non-quantum gravitational) quantum theory capable of dealing with the universe as a whole.

[22] We don't discuss this further, though there has been some recent philosophical work on this argument: see Mattingly (2006); Callender and Huggett (2001); and Wüttrich (2004).

time possess a *fixed* metric and connection structure. That is to say, the metric is imposed prior to solving any equations of motion for the other fields, is not allowed to vary in the action, and so is not affected by the behaviour of the quantum fields defined with respect to it. We hinted above at the fact that the metric is crucial in quantum field theory for the mathematical and conceptual foundations of the theory. For example, it is an axiom of the theory that for any pair of spacelike separated (relativistic) quantum fields (i.e. field operators with support in regions of spacetime that lie at spacelike distances from each other) $\hat{\Phi}(X^i)$ and $\hat{\Phi}(Y^j)$

$$[\hat{\Phi}(X^i), \hat{\Phi}(Y^j)] = 0. \qquad (1.7)$$

This is known as the 'microcausality condition', and it encapsulates the specially relativistic basis of the theory. The fundamental conceptual conflict (vis-à-vis the nature of spacetime) between quantum field theory and general relativity can be captured if we consider the quantum gravitational analogue of the microcausality condition. Recall that in a quantum theory of gravity the spacetime metric will be an operator. Yet the metric field is responsible for chronogeometrical structure in addition to gravitational field structure, which implies that it is responsible for the causal structure too (microcausal structure included). In other words, since the causal structure is dependent on the metric and the causal structure determines whether two events are spacelike or not, and given that the metric is prone to quantum fluctuations, it follows that the notion of spacelikeness, and therefore microcausality itself, becomes subject to quantum fluctuations: one of the fundamental axioms of quantum field theory is thus rendered meaningless (cf. Wald 1984: 381–2). We need, then, a new conception of spacetime that goes beyond the conceptions that we find in quantum field theory and general relativity, and that will take something special indeed: prima facie, we need to either reject background-independence (scrap general relativity) or else find a way to set up a background independent quantum field theory (scrap quantum field theory as it is understood at present).

The question of why we should attempt to construct a quantum theory of gravity duly dealt with (albeit in a very cursory manner), the next question we face is *how* to go about it. The fact that there are many unconnected approaches makes philosophizing about quantum gravity a difficult matter. Of course, in an article of this nature we can barely pay lip service to the welter of methods that have been devised to resolve the problem of quantum gravity.

1.1.4 Categorizing the Manifold Methods

There are so many distinct approaches to quantum gravity that the task of categorizing them is rendered surprisingly difficult. Indeed, there is quite a diverse range of suggestions within the quite substantial literature on the subject. Let us begin by outlining several of these, before we lay down our preferred version.

- Relativity vs Particle Physics based: the various methods are divided according to the principle that there are methods that favour general relativity over quantum field theory, and those that reverse the preference.

- Additional Structure based: the methods are distinguished by various novel elements that are added to the foundations of one or another ingredient theory until quantum gravity is accounted for. Examples might be supersymmetry, extra dimensions of spacetime, and so on.
- Covariant vs Canonical based: methods are distinguished by the method of quantization used.
- Perturbative vs Non-perturbative: methods should be distinguished according to whether they use perturbative or non-perturbative technology.

The latter two taxonomies are often run together, with covariant and perturbative methods set together against canonical and non-perturbative methods. Certainly loop quantum gravity is both canonical and non-perturbative and the first revolution (pre-1995) picture of string theory was covariant and perturbative. However, there is no necessary connection between these distinctions. For example, recent work on string theory, though remaining manifestly covariant, aims to be thoroughly non-perturbative. However, the kinds of connections that *do* hold between these two distinctions certainly deserves some serious attention from physicists and philosophers of physics. Focusing on these two taxonomies independently of one another, they face the same problem; namely that there are methods that simply fall outside their scope.

The first taxonomy appears to be largely based in dogma and prejudice, rather than on any deep underlying divisions concerning the subject matter of the approaches thus divided. The relativists follow their geometric training whilst the particle physicists follow their analytic training. Fortunately too there are signs that this once 'great divide' is eroding, with the appearance of certain researchers who have feet in multiple camps (e.g. Baez 1994 and Smolin 2000). The second taxonomy hardly constitutes a taxonomy at all, since there would most likely be but a single theory or approach to each category. The third taxonomy makes a useful cut between the approaches, but the division is rather weak since one can associate (via a Legendre transformation) a canonical approach to each covariant approach, and vice versa—furthermore, these formulations should be equivalent. Moreover, again, there are approaches that fall outside the remit of this taxonomy—we are thinking of those approaches, such as causal set theory, which do not work by *quantizing* a theory at all. Our preferred way is to focus on background structure and dependence or independence on it and from it. This is related to the fourth taxonomy on our list, since the perturbative approaches tend to be those that make use of a fixed, flat background spacetime, while the non-perturbative ones do not follow this procedure. It strikes us that this division reflects the most fundamental and central division that separates the distinct approaches to quantum gravity. However, it seems that the balance between the two sides of this carving of the approaches is becoming increasingly lopsided, with the majority of physicists acknowledging the importance of having a background-independent theory—the background-dependent approaches appear to be slowly dying off. Let us consider this distinction a little further by exposing the pitfalls of background-dependent methods, and the virtues of the background-independent methods.[23]

1.1.5 What's Wrong with Background-Dependent Methods?

Among the first serious attempts to produce a quantum theory of gravity were background-dependent, covariant perturbation quantizations. This method was generally adopted within the particle physics community. The idea was, as Ashtekar so nicely puts it (1988: 1), to do unto the gravitational field as was done to the electromagnetic field: quantize the gravitational field to get a particle (the *graviton*) that mediates the interaction. However, just as photons require background metrical structure, so does the graviton.[24] One begins the analysis in terms of *weak* gravitational waves moving about in Minkowski spacetime. This is accomplished by splitting the spacetime metric $g_{\mu\nu}$ into a *background* part and a *perturbation*; the background part corresponds to flat Minkowski spacetime, with metric $\eta_{\mu\nu} = \mathsf{diag}(-1, 1, 1, 1)$, and the perturbation term $p_{\mu\nu}$, measures the 'deviation' from the flat (classical) background. Thus, one has

$$g_{\mu\nu} = \eta_{\mu\nu} + p_{\mu\nu}. \tag{1.8}$$

This procedure is done to make the quantization job easier; one has all of the machinery of a fixed spacetime so that, for example, microcausality conditions are defined with respect to this rather than the full metric. The helicity states[25] of the gravitational waves on the background become the quantum states of the graviton. Utilizing the representations of the Poincaré group, one is able to define the graviton as a spin-2 particle. We know, also, that this particle must be massless because the gravitational interaction works long range, and the slightest mass would contradict results concerning the deflection of light.

Weinberg (1995; see also 1979), in his definitive discussion on covariant quantum gravity, showed that, in the vacuum case, one can *derive* the equivalence principle from the Lorentz invariance of the spin-2 quantum field theory of the graviton. Thus, it is sometimes claimed (mostly by string theorists) that the spin-2 theory is equivalent to general relativity and follows from the quantum theory. The upshot of this is that any theory with gravitons is a theory that can accommodate general relativity (in some appropriate limit). This analysis forms the basis of string theory's claim that it is a candidate theory of quantum gravity: since there is a string vibration mode corresponding to a massless spin-2 particle, there is an account of general relativity (see Kiefer 2004: 34).

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[23] For accounts of some of the other lines of research in quantum gravity, see the chapters by Stachel and by Smolin in this volume.

[24] Indeed, so does *any* particle at all. What's more, the background must be flat in order to help oneself to the Poincaré symmetry and thus define a preferred vacuum state, from which one derives the particle content of the theory. Thus, dynamical curved spacetimes are especially problematic from this perspective. See Wald (1994) for the reasons why this is so.

[25] If $\phi \rightarrow e^{ih\theta}$ is a transformation of a plane wave under the the action of a rotation about the direction of propagation, then h is the helicity of the wave.

But this analysis has proceeded from substantive assumptions, that we have available a flat background, and that we proceed using a linear approximation (so that the physical interpretation is one of a few gravitons propagating on Minkowski spacetime). The concept of the graviton, and this way of doing quantum gravity, is an approximation, albeit a pragmatic one that is, perhaps, required to do 'real' physics. Worse, the attempt to use perturbative methods leads to a non-renormalizable theory; any attempt to eradicate the divergences that result from probing the local fields at arbitrarily small distances fails, simply producing yet more divergences. Weinberg knows all of this, of course, but he refrains from ruling out the perturbative approach *tout court*. As we mentioned above, one may view the theory as *effective*; for sufficiently small energies, the theory may still produce testable physical predictions. However, be that as it may, the non-renormalizability of quantum general relativity *is* unequivocal with respect to the 'fundamental' status of the theory: it cannot be fundamental, for this would require consideration of Planckian physics that lies outside of the simple linear approximation. But we should have expected this, says Rovelli, for 'GR has changed the notions of space and time too radically to docilely agree with flat space quantum field theory' (2004: 4).

String theory is, however, one way—by far the most heavily researched—of sticking to the perturbative, covariant, background-dependent methodology of quantum field theory while avoiding the divergences. Another response to the non-renormalizability was to consider 'corrections' to the theory in the form of additional particles with quantum loop amplitudes that serve to cancel out the divergences associated with the gravitons. This is the way of 'supergravity' theories.

As philosophers, what conclusions might we draw from this? The general understanding is that the problems that the old covariant perturbation approaches face stem, at least in large part, from the background dependence that is imposed. The existence of a background, continuous spacetime implies, *ceteris paribus*, that the local fields have no limit of resolution; one can probe them to whatever distances and energies one likes. The metric remains fixed and classical. Divergences follow, as we mentioned above. The answer to the puzzle seems to be that the limitless resolution be limited in some way. One very ingenious way was to add dimensions to the fundamental objects of the theory so that interactions are 'delocalized' away from spacetime points. This is conservative as regards spacetime, since one can retain the fixed, classical background: the revision is applied to the 'material' side of the ontology. This is the way of string theory and M-theory, of course. Alternatively we can delocalize the points themselves, perhaps by making their coordinates 'non-commuting' q-numbers. We might also attempt to make the theory background independent, so that no fixed metric appears in the definitions of the states and observables of the theory; the metric will be a dynamical entity and become an operator in the quantum theory. This way the points, inasmuch as they exist at all, are dynamically individuated by the metric field, and so spacetime geometry itself is quantized—in the loop quantum gravity approach the geometry of space is found to be discrete (in that the geometrical operators on a spatial slice when quantized have discrete spectra).

1.1.6 What's Right about Background-Independent Methods?

Perturbative background-dependent methods attempt to stick as much as possible to the old ways of quantizing fields. Faced with a non-linear field, one treats the non-linearities as perturbations about some linear equation. Likewise, in perturbative quantizations of gravity the trick was to view the variety of curved metrics as perturbations about a fixed background metric. This background supplies all of the machinery of standard quantum field theory, representation theory, and the renormalization techniques. However, it faces a problem: recall from §1.1.3.1 that we should expect quantum gravitational effects to become significant at the Planck scale. Hence, as one approaches higher and higher energies (smaller and smaller length scales) the metrical fluctuations should become ever more non-negligible. It becomes harder and harder to sustain the perturbative idea of treating the various metrics of the various solutions as small perturbations about a flat, fixed background. This idea prompted the search for non-perturbative methods of quantization.

Canonical quantization methods follow this non-perturbative line (quantizing the full metric), and attempt to do physics in a background-independent manner.[26] Originally, the path involved using a configuration space of Riemannan metrics on a three-dimensional hypersurface, so that general relativity was rendered a dynamical theory of the geometry of space—the approach was called 'geometrodynamics' (see Arnowitt et al. 1962). However, that approach faced many problems. A recent modification, ushered in by Ashtekar's change of variables, uses connections on a principle $SL(2, \mathbb{C})$ bundle over a three-dimensional hypersurface—see the articles in this volume by Dorato and Pauri, Rickles, and Smolin for more details on the canonical approach.[27]

Much conceptually interesting material in the canonical approach comes from the way in which the spacetime diffeomorphisms—conceptually interesting in their own right, of course—are implemented by means of constraints. In the quantum theory, these constraints must be enforced too, so that wave functions are invariant under spacetime diffeomorphisms by being annihilated by the constraints. In the 'new

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[26] In this case, non-perturbative methods and background independence seem to be two sides of the same coin. Indeed, in the context of quantum gravity they are often discussed as if they were synonyms (see Smolin, this volume, p. 209). The precise relations that hold between these two concepts, in this restricted context, merit further investigation. As a first step consider the following link between background independence and non-perturbative methods: (1) in non-perturbative methods the full metric is quantized; (2) the metric represents space(time); (3) the metric is dynamical. These three factors seem to give us no choice: quantizing a dynamical metric, without making a perturbative split, *enforces* background independence. String theory might seem like a counter-example to this; however, note that still very little is known about the non-perturbative extension to string theory (viz. M-Theory), and the more that is discovered about it, the more it seems like background independence will be one of its features.

[27] In fact, Smolin was one of the physicists involved in the creation of the approach called 'loop quantum gravity' (arguably the only serious rival to strings). Also, John Baez (likewise a contributor to this volume) has done much to make the mathematical foundations of loop quantum gravity more solid. Carlo Rovelli, the other creator of loop gravity, has written an excellent textbook (Rovelli 2004) on the theory that does much to expose its philosophical implications.

variables' approach, mentioned above, there is an additional constraint that comes from the connection, namely the Gauss law constraint. This expresses invariance under gauge transformations: again the physical wave functions in the quantum theory must be invariant with respect to these too. The Ashtekar variables had the effect of transforming the phase space of general relativity into a copy of the phase space of a Yang–Mills theory.[28] This in turn allowed for the application of mathematical techniques that had proven fruitful in the Yang–Mills context; of particular importance was the loop representation that it afforded. This representation (roughly an infinite Fourier transformation from the connection variables) admits natural solutions to the Gauss-law constraint (i.e. it is gauge invariant), and solutions can be found to the other constraints by considering equivalence classes of loops (under spatial diffeomorphisms), or knots, and intersections of knots. Quantizing the theory led to the application of *spin networks*, introduced in the 1970s by Roger Penrose. In the context of loop quantum gravity it is found that the spin networks form a basis for the quantum states. Penrose's original idea was to dispense with the continuous spacetime manifold, and replace it with a combinatorial structure. He writes, in typically visionary form, that

> A reformulation is suggested in which quantities normally requiring continuous coordinates for their description are eliminated from primary consideration. In particular, space and time have therefore to be eliminated, and what might be called a form of Mach's principle must be invoked: a relationship of an object to some background space should not be considered—only relationships of objects to each other can have significance. (1971: 151)

Following Penrose's line, the claim of many of those working on loop quantum gravity is that spin networks point towards a relational conception of space. Why? The reason, so far as we can see, is connected to the hole argument. The claim is that spin networks represent quantum space (i.e. a quantized version of the spatial part of the gravitational field). However, in order to accomplish this, the states must be diffeomorphism invariant. Yet spin networks are defined on a (compact three-dimensional) manifold, just like the metric was in the classical case. Hitting a spin network with a diffeomorphism shifts it around the manifold. Thus, we need to impose the constraints (i.e. we need to solve the quantum Einstein equations). This is achieved by taking the equivalence class of spin networks under these diffeomorphisms, giving us a diffeomorphism invariant *s-knot* (for 'spin'-knot) or 'abstract' spin network. The idea is that the *s*-knot is 'smeared out' over the manifold; it is not a localized entity—so hitting an *s*-knot with a diffeomorphism does nothing, we simply get the same state back. However, any other fields must then be localized with respect to these *s*-knots; the *s*-knots represent space and define location. Since the *s*-knots are *dynamical* entities—being, roughly, a quantum analogue of the classical metric field—it seems as though localization has been relativized: localization is relational. However, the ontological conclusion regarding the relationalist conception

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[28] There is nonetheless, of course, a crucial difference between the two theories: Yang–Mills theories are formulated with respect to a metric manifold (i.e. they are background dependent) whereas general relativity is not.

of space seems to be drawn from nothing more than the fact that Leibniz equivalence has been imposed—i.e. by solving the diffeomorphism constraint in the move to *s*-knots. Relational localization cannot itself deliver relationalism about space(time), since, on the understanding that the 3-metric and *s*-knot state represent classical and quantum space, the localization is relativized to space! But this then simply begs the question about the ontological nature of space. Thus, this is a non sequitur as has been shown by many substantivalists who also adopt Leibniz equivalence, and as Pooley nicely charts in his contribution to this volume. It is, we say, much better understood as underwriting a structuralist stance. What is objective is the structure that is formed by abstracting the invariant core from the symmetries of the individual localized spin networks. What we get is a delocalized structure which can be understood as encoding relational features; relations between fields.[29]

1.1.7 Background Independence and Structuralism

The chapters that follow this essay are, more or less, united in their focus on background-independent approaches to the problem of quantum gravity. Thus, in general, string theory, and other background-dependent approaches, are mentioned only as examples of how *not* to go about constructing a theory of quantum gravity. One of the main points we wish to make here is that background independence and structuralism are well-matched bedfellows; better matched, in fact, than are the traditional positions of substantivalism and relationalism. Let us spend some time developing this line of thought before turning our attentions to structuralism (and structural realism).

To understand background independence, we need to introduce the notion of *background structure*. This will, no doubt, be already quite familiar to philosophers, though most likely under the somewhat scholastic *sobriquet* of 'absolute object'.[30] The technical use of this term, in the context of spacetime theories and in the sense we intend it here, originated with Anderson (1967), where he used it to refer to those objects that are dynamically decoupled in one direction from the other objects in the theoretical ontology. This means that they can affect the behaviour of other objects—i.e. play a role in determining the kinematical and dynamical properties and relations of a set of fields, for example—without being likewise affected. The idea of absolute object, though intuitively easily graspable, is a notoriously slippery customer. Friedman (1983: 62–70), for example, discerns three distinct senses that can be marshalled under its banner:

- The first arises in the context of the debate about the ontological status of spacetime structures (Friedman 1983: 62–3); that is, the debate between absolute (or, more

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[29] See Rickles (2005a, 2005b) for a detailed philosophical examination of some of these themes.

[30] We should perhaps point out that Smolin, in a relevant early paper, refers to background structures as 'ideal elements' and characterizes them as 'contingent, in the sense that they may be altered without altering the basic character of the theory, play a role in the dynamical equations of the theory, and are not themselves determined by solving any dynamical equations of the theory' (1991: 231). However, he has since converted to the present terminology, and sticks with it for his contribution to this volume.

properly, substantivalist) and relational spacetime. The issue here concerns the *range* of the ontologies employed: the relationalist will wish to reduce spacetime structures to relations between physical objects, so that the ontology is coextensive with the set of physical events (or, if he is a little cleverer, the set of *possible* physical events); the substantivalist, on the other hand, will claim a larger ontological domain containing an independent manifold of possibly unoccupied spacetime points. The distinction between this sense of absolutism and relationalism is just the distinction outlined in Earman's 'R2'; namely, that holding between those views that take spatio-temporal properties and relations to be 'parasitic on relations among a substratum of space points that underlie bodies or space-time points that underlie events' (1989: 12) and those that do not. We are, in effect, back with Sklar's notion of substantivalism; hence, this first sense of absolute has been reassigned to the notion of *substantival* spacetime.

- The second sense concerns the dependence or independence of *quantities* from frames of reference or coordinate systems (Friedman 1983: 63). The absolute objects are taken to be those quantities that are thus independent. An example is simultaneity. In a spacetime with structure $\mathbb{E}^3 \times \mathbb{R}$ the notion of simultaneity can be defined independently of reference frames and coordinate charts; it is, therefore, an absolute quantity. However, shift to a relativistic picture and the notion is relativized to a reference frame. This is, for sure, connected to absolute objects; as Earman (1989: 12) points out in his characterization of 'traditional relationalism': '[R1] All motion is the relative motion of bodies, and consequently, space-time does not have, and cannot have, structures that support absolute quantities of motion.' But although this sense depends upon absolute objects, it does not characterize them. Rather, the absolute quantities are grounded in the absoluteness of the background framework given by the type of spacetime structures employed.
- The third sense is Anderson's, which we mentioned above. It is this sense that we are interested in. Friedman defines an absolute object in this category as a 'geometrical structure … that affects the material contents of space-time (through laws of motion, for example) but is not affected in turn' (Friedman 1983: 64).

However, we don't intend to add anything new to the clarification of the concept of absolute object. We simply wish to line up what physicists call 'background structures' with the third of Friedman's 'senses', and with what Anderson means by absolute object.[31] There is a sense, then, in which the introduction of the background-independent/dependent distinction 'cleanses' the concept of absolute object of one of its ambiguities, but an interpretative problem nonetheless remains: what is the conceptual significance of background independence?

Smolin (1998: 2–3) characterizes background-independence/dependence in the context of quantum gravity as follows:

> The background dependent approaches are those in which the definitions of the states, operators and inner product of the theory require the specification of the classical metric

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[31] For a very careful disentangling of the various senses of 'absolute object', see Rynasiewicz (2000).

> geometry. The quantum theory then describes quanta moving on this background. The theory may allow the description of quanta fluctuating around a large class of backgrounds, but nevertheless, some classical background must be specified before any physical situation can be described or any calculation can be done. All weak coupling perturbative approaches are background dependent, as are a number of non-perturbative developments. … The background independent approaches are those in which no classical metric appears in the definition of the states, operators and inner product of the theory. … [T]he metric and connection enter the theory only as operators, and no classical metric appears in the definition of the state space, dynamics or gauge symmetries.

Now, as we mentioned, the received view amongst physicists is that background independence implies relationalism about space(time). Smolin is quite explicit about this in his contribution, writing

> Thus, we often take background independent and relational as synonymous. The debate between philosophers that used to be phrased in terms of absolute vrs relational theories of space and time is continued in a debate between physicists who argue about background dependent vrs background independent theories. (p. 22)

Rovelli sketches the supposed implication—on the understanding that (active) diffeomorphism invariance implements background independence in general relativity—as follows:

> [Diffeomorphism invariance] implies that spacetime localization is relational, for the following reason. If $(\psi, \mathsf{X}_\mathsf{n})$ is a solution of the equations of motion, then so is $(\phi(\psi), \phi(\mathsf{X}_\mathsf{n}))$ [where ϕ is a diffeomorphism]. But ϕ might be the identity for all coordinate times t before a given t_0 and differ from the identity for some $\mathsf{t} > \mathsf{t}_0$. The value of a field at a given point in $\mathcal{M}$, or the position of a particle in $\mathcal{M}$, changes under the active diffeomorphism ϕ. If they were observable, determinism would be lost, because equal initial data could evolve in physically distinguishable ways respecting the equations of motion. Therefore classical determinism forces us to interpret the invariance under $\mathsf{Diff}_{\mathcal{M}}$ as a gauge invariance: we must assume that diffeomorphic configurations are physically indistinguishable. (1999: 3)

Hence, the ‘physical’ aspects of a system are not given by specifying a single field configuration, but instead by the ‘equivalence class of field configurations … related by diffeomorphisms’ (ibid.). The observables of such a system are then given by diffeomorphism invariant quantities. Such specifications of states and observables are clearly independent of any background metric: only gauge-invariant quantities are to enter into such specification, and any reference to a background metric (via, for example, fixed coordinates or functions on $\mathcal{M}$) yields non-gauge-invariant quantities. Thus, diffeomorphisms change the localization of fields on $\mathcal{M}$; this is represented in the Hamiltonian scenario by the action of the constraints. However, the localization is a gauge freedom, so any states or observables involving localization to points will not be physical. Smolin sees a direct connection between taking the equivalence class of metrics, which pushes towards a relational view of localization, and relationalism about spacetime:

> The basic postulate, which makes GR a relational theory is [that a] physical spacetime is defined to correspond, not to a single (M, g_{ab}, f), but to an equivalence class of manifolds, metrics and fields under all actions of *Diff*(M). (This volume, p. 206)

Rovelli makes the case in more detail as follows:

> [t]he point is that only physically meaningful definition of location within GR is relational. GR describes the world as a set of interacting fields including $g_{\mu\nu}(x)$, and possibly other objects, and motion can be defined only by positions and displacements of these dynamical objects relative to each other. … All this is coded in the active diffeomorphism invariance … of GR. Because active diff invariance is gauge, the physical content of GR is expressed only by those quantities, derived from the basic dynamical variables, which are fully independent from the points of the manifold. … [Diff invariance] gets rid of the manifold. (Rovelli 2001: 108)

What status are we to attribute to the manifold once we remove dependency upon its coordinates, and smear out reference to points with the action of Diff$(\mathcal{M})$? Rovelli suggests that the manifold is an 'auxiliary mathematical device for describing spatiotemporal relations between dynamical objects' (2001: 4). Of course, spacetime coordinates enter into many areas of physics, especially mechanics and field theories, i.e. as positions of objects (particles, strings, etc.) or as the argument of a local field operator. Many physicists believe that general relativity rules out such *absolute* local quantities; there are local degrees of freedom, but the locality is grounded dynamically. This is, again, seen to follow from the practice of taking an equivalence class of manifolds and metrics under diffeomorphisms as the correct description of a spacetime in general relativity. Smolin claims that a consequence of this view is that

> there are no points in a physical spacetime … [since] a point is not a diffeomorphism invariant entity, for diffeomorphisms move the points around. There are hence no observables of the form of the value of some field as a given point of a manifold, x. (2000: 5)

The latter point, that there are no local (i.e. localized to a *particular* spacetime point) observables in general relativity, is perfectly true of course—we think this is the real 'lesson' of the hole argument, as we mentioned above. However, Smolin gets things the wrong way around. It is physical quantities that must be diffeomorphism invariant, and this does indeed supply the result that there are no observables localized to points of the manifold. But it is a big step from here to relationalism and the absence of points.

This 'relationalism from relational localization' move is, then, fairly common,[32] but it is, for the reasons we have given, also a non sequitur: substantivalism is perfectly compatible with the view that observables of general relativity are relational, and it is compatible with the shift to equivalence classes—the sophisticated substantivalists

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[32] The view of the physicists is a far cry from the 'received view' amongst philosophers, which is that general relativity supports spacetime substantivalism. Underlying this belief is the availability of 'empty space' solutions—i.e. those consisting of a differentiable manifold and metric tensor and without any matter fields. But this is as problematic as the move to relationalism: the empty space solutions might just as well be taken to describe a physically real field; as Stachel points out '[a]n empty spacetime could also be called a pure gravitational field, and it seems to me that the gravitational field is just as real as any other' (1993: 144). These features have been used by both sides of the debate to claim victory of the other. The substantivalists have sought to pull the gravitational field to their 'spacetime' side, and the relationalists have sought to pull it to their 'material' side. This tug of war has gone on for some time, and we think that time has come to accept that neither side is given more or less support than the other: we need to look beyond the physics to support these positions, or else look to an alternative view.

have demonstrated this (see Pooley, this volume). Once again (as with the hole argument), we have an interpretative underdetermination: both substantivalists and relationalists can lay claim to this setup. We view this underdetermination as a problem similar to the interpretative underdetermination that plagues quantum statistical mechanics, where there are conceptually incompatible interpretations of quantum particles that are nonetheless both compatible with the quantum formalism.[33] Our response is to evade the underdetermination by adopting a structuralist metaphysics: forget points and forget individual material fields, the structure as characterized by the equivalence class of metrics is where our ontological commitments should lie.

To wrap up this section, we shall indicate how what is called relationalism can be understood as a form of structuralism. Let us begin with a statement of a variety of mathematical structuralism—that of Resnik:

> In mathematics, I claim, we do not have objects with an 'internal' composition arranged in structures, we have only structures. The objects of mathematics, that is, the entities which our mathematical constants and quantifiers denote, are structureless points or positions in structures. As positions in structures, they have no identity outside of a structure. Furthermore, the various results of mathematics which seem to show that mathematical objects such as the numbers do have internal structures, e.g., their identification with sets, are in fact interstructural relationships. (Resnik 1981: 530)

Thus, mathematical objects, for Resnik, have their identities fixed only through their relationships to each other.[34] The overall structure determines the objects' identities. This basic feature—the identities of things being derived from a relational structure—is what characterizes a structuralist position. Now consider the following passage from Smolin:

> Observables associated with classical general relativity with cosmological boundary conditions measure relations between physical fields. Points have no intrinsic meaning and are only identified through the coincidence of field values. The diffeomorphism invariance of the classical theory is thus an expression that that theory is background independent (up to the specification of the topology of the manifold.) (1998: 10)

Recall, as we said above, that the idea that objects are 'identified' and 'have meaning' in virtue of relations to some other things is part and parcel of structuralism. Moreover, the way in which this is cashed out through background independence is firmly within the structuralist camp. There is something akin here—and in the

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[33] See French and Rickles (2003) for a review of the ins and outs of this debate, and a discussion of the connections to the interpretation of spacetime theories vis-à-vis relationalism *vs* substantivalism. Pooley (this volume) strongly disagrees with us that there is an analogy to be had here—we reserve the right to save our response for another occasion!

[34] See Resnik (2000) for a well-developed account of his position. See Parsons (1990) for a critical analysis of this position in which he argues that it cannot in fact be extended to the most elementary objects of mathematics (we'd like to thank one of the referees for pointing this out to us). More recently, Busch (2003) and Psillos (forthcoming) have drawn on the comparison with mathematical structuralism to develop criticisms of the form of (physical) structuralism advocated here. For a response see French (2006).

passages of Smolin and Rovelli given previously—for example, to Mundy's (1992) notion of 'spacetime structuralism', according to which spacetime theories should be recast in non-coordinate geometry terms, using relational predicates, and then shifting to the isomorphism class as the object that encodes the various *equivalent* coordinate spacetimes. Mundy then argues that 'points, like numbers, are structural roles in isomorphism classes of models of certain theories' (p. 523), and with this we are back to Resnik's comments and the central core of structuralism. Baez's discussion of topological quantum field theory (and quantum field theory and general relativity from the point of view of category theory) fits well with this perspective too, since category theory places the weight on morphisms (generalized functions) over objects: the objects are defined by the relations they bear to other objects. In the next section we present some key themes from the history and philosophy of structuralism, so that these connections will be all the more transparent.

1.2 STRUCTURALISM AND STRUCTURAL REALISM

1.2.1 Motivating Structuralism

Recent years have seen the beginnings of appropriate philosophical investigation of quantum gravity. It is notable—and, to some, surprising—that many physicists have welcomed this interest from philosophers (e.g. Rovelli 1997: 182; Baez 2001: 177—see also Rickles 2005b), and one can find philosophers speaking about quantum gravity at physicists' conferences and publishing in physics journals, and vice versa (cf. Callender and Huggett 2001: 1). Our aim in this chapter has been to indicate how this dialogue might be further pursued from a structural perspective; we now propose to place these developments in their wider historical context.

1.2.2 What is Structuralism?

Defining structuralism is itself a philosophical issue and one of the points we want to press is precisely that it should not be conceived of as a monolithic philosophical position but as a heterogeneous movement composed of a number of intertwined strands. In perhaps its broadest characterization, as already used in this chapter, structuralism can be understood as urging a shift in one's ontology, away from objects, as traditionally conceived, and towards structures, typically conceived of in terms of relations. Crudely put, on the traditional conception, objects ontologically underpin the relevant structures, in the sense that they are the relata for the relations which hold between them. Structuralism shifts the focus onto the relational structures themselves and away from the objects, which must then be reconceived, in some sense, from the structure. The extent of this reconceptualization will then depend on both the form of structuralism adopted and the view of objects from which one begins. A 'weak' form of structuralism might adopt a weak form of reconceptualization and leave the objects as ontologically underpinning the structure, but insist that epistemologically they are 'hidden' in some sense. On this *epistemic* form of structuralism the claim is that we have epistemic access only to the structure, not what might lie behind it; therefore, that is what we should be concerned with in our interpretations of our physical theories. A 'stronger' form of structuralism might urge a more radical reconceptualization of objects, such that they come to be understood as mere 'nodes' or 'intersections' in the structure. More generally, objects might be understood as being *secondary* to the structure; the relations are then to be regarded as having ontological primacy over the objects. Alternatively, one might eschew talk of 'primacy' and adopt a view that is committed to both categories but privileges neither over the other (see e.g. Rickles, this volume).

1.2.3 … and Where Does it Come from?

Of course, how dramatic a shift in focus this amounts to will depend on the view of objects one starts with. Historically, many structuralists took a 'substantivalist' view of objects, in the sense that they were conceived of in terms of some form of Lockean substratum underlying the properties they possess. In these terms, structuralism has been seen as a move towards the 'liberation' of physical ontology from the substance paradigm. This was certainly the stance adopted by Cassirer and Eddington, for example, whose broadly structuralist responses to both General Relativity and Quantum Mechanics have unfortunately been overshadowed by the work of Russell in modern structuralists' own retrospective narratives of the movement's origins.

Both Cassirer and Eddington included a fundamental subjective element in their positions, which perhaps explains their relative neglect in today's more realist context. Cassirer, in particular, was, famously, a neo-Kantian who insisted that, far from being ruled out by the developments of early twentieth-century physics, Kant's philosophy, properly understood, offered the most appropriate framework for accommodating such developments (for an excellent introduction to Cassirer's ideas, see Friedman 2004). The structuralist element of his philosophy was grounded in his reflections on the nature of space and was hugely influenced by Klein's Erlanger programme. This offered a structural conception of geometrical objects which shifts the focus from individual geometrical figures, grasped intuitively, to the relevant geometrical transformations and the associated laws. This shift underpinned Cassirer's insistence on 'the priority of the concept of law over the concept of object'. From this perspective, 'objects' dissolve into a 'web of relations', held together by certain symmetry principles which represent that which is invariant in the web of relations itself.

Cassirer famously applied this structuralist framework to the foundations of relativity theory and argued that the unity of the concept of object, which is apparently lost through the relativistic transformations, is effectively reinstated in structuralist terms via the 'lawful unity' of inertial systems offered by the Lorentz transformations. The shift from a substantivalist conception of objects to a structuralist one is furthered by the General Theory of Relativity and what we are left with is an understanding of the objects of a theory as defined by those transformations which leave the relevant physical magnitudes invariant. General covariance then functions as a principle of objectivity which offers a 'deanthropomorphized' conception of a physical object

(Ryckman 1999). Thus Cassirer saw General Relativity as the natural conclusion of the structuralist tendency:

> With the demand that laws of nature be generally covariant, physics has completed the transposition of the substantial into the functional—it is no longer the existence of particular entities, definite permanencies propagating in space and time, that form 'the ultimate stratum of objectivity' but rather 'the invariance of relations between magnitudes'. (Ibid. 606, citing Cassirer 1957: 467).

When it comes to quantum mechanics, there is a similar shift from things-as-substances to relations as the ground of objectivity in science; or as Cassirer put it, '[w]e are concerned not so much with the existence of things as with the objective validity of relations; and all our knowledge of atoms can be led back to, and depends on, this validity' (Cassirer 1937: 143). In classical mechanics objectivity rests on the spatio-temporal persistence of individual objects and here, ' "[o]bjective" denotes a being which can be recognized as the same in spite of all changes in its individual determinations, and this recognition is possible only if we posit a spatial substratum' (ibid. 177). It is not only the notion of spatio-temporal persistence that quantum mechanics threatens (under the standard interpretation) but the individuality of the particle itself. What is an electron then, Cassirer asks? Not, he answers, an individual object (ibid. 180), as such a conception appears to be undermined by quantum statistics (ibid. 184). At best, quantum particles 'are describable as "points of intersection" of certain relations' (ibid.). From this structuralist perspective, the entity 'constitutes no longer the self-evident starting point but the final goal and end of the considerations: the *terminus a quo* has become a *terminus ad quem*' (ibid. 131).

Eddington's importance in the history of General Relativity is well known, of course and in both his 'popular' and 'professional' works he presented structuralism as offering the most appropriate way of understanding the foundations of the theory:

> The investigation of the external world in physics is a quest for structure rather than substance. A structure can best be represented as a complex of relations and relata; and in conformity with this we endeavour to reduce the phenomena to their expressions in terms of the relations which we call intervals and the relata which we call events. (Eddington 1923: 41).

Beginning with point events, the aggregate of which constitute 'the World' and which is postulated to be four-dimensional, the interval can then be defined, as a quantitative relation, and the operation of comparing intervals eventually yields—via a fair bit of jiggery-pokery—the field equations. Eddington insisted that these should be read from left to right, not as laws of the World relating the continuum of points events and matter, but as mathematical identifications denoting 'definite and absolute' conditions of the world (Kilmister 1994: 44–6). Hence, 'Matter does not cause an unevenness in the gravitational field; the unevenness is matter' (Eddington 1923: 152). By matter here, Eddington means matter as substance and thus this construction is seen as eliminating substance from our ontology in favour of relational structures, which were taken to be of a kind defined and investigated by group theory (see Eddington 1936: ch. XII and 1939: , ch. IX).

From this perspective, substantivalist and relationist metaphysics, as traditionally conceived, are nothing more than embellishments to the 'bare structural description' which the structuralist focuses on. Thus, taking the example of uniform spherical space, all that we know about such a space, Eddington argued, is that it has the structure of the rotation group. 'When we introduce spherical space into physics we refer to something—we know not what—which has this structure' (1939: 146). Similarly, Euclidean space and Riemannian space are referred to as something with a specifiable group structure. The usual attempts to describe space in terms of more or less familiar metaphysical categories are an 'unauthorized addition' to physical knowledge. Here again the structuralism is underpinned by a shift away from entities, in this case spacetime points and Eddington insisted that 'Space is not a lot of points close together; it is a lot of distances interlocked' (1923: 10).

Furthermore, as in the case of Cassirer, Eddington took the implications of quantum statistics for particle individuality as opening the door to a structuralist accommodation of quantum physics. And again, it is a substantival conception of object that must be abandoned, in favour of a group-theoretic understanding (for more on Eddington's structuralist conception of quantum particles, see French 2003). What we obtain, then, is a structuralist view of all of science:

> Physical science consists of purely structural knowledge, so that we know only the structure of the universe which it describes. This is not a conjecture as to the nature of physical knowledge; it is precisely what physical knowledge as formulated in present-day theory states itself to be. In fundamental investigations the conception of group-structure appears quite explicitly as the starting point; and nowhere in the subsequent development do we admit material not derived from group-structure. (Eddington 1939: 142–3).

Eddington's later work, particularly as presented in his *Fundamental Theory*, represents an attempt to articulate a unified theory of physics—that is, in part, a theory of Quantum Gravity—within such a structuralist perspective. That it remains barely comprehensible, if at all, should not detract from the heroic effort involved![35]

Of course, to modern eyes, the concern with substance might seem somewhat idiosyncratic. And if one were to initially regard an object, not as a substance possessing properties, but as nothing more than a bundle of such properties and relations (perhaps united by some kind of primitive 'compresence' relation) to begin with, then the structuralist shift may not seem quite so radical after all.[36] Furthermore, it has come to be appreciated that one can in fact maintain a view of objects as individuals in the context of quantum statistics, where this individuality can be understood as grounded in either some form of substantival metaphysics, or a broadly Scholastic notion of haecceity or 'primitive thisness' (French 1989; French and Krause 2006). However, the bundle theory, just mentioned, appears not to fare that well, since it requires the acceptance of some form of Leibniz's Principle of the Identity of Indiscernibles—so that no two 'bundles' can be exactly alike—and this appears to be ruled out by quantum mechanics (French and Redhead 1988). Nevertheless, Saunders has recently elaborated a kind of 'modernized' form

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[35] For an almost equally heroic effort to render it comprehensible and relate it to modern concerns, see Durham (2005).

[36] This point is made in French (2001) and also in Pooley's contribution to this volume.

of the Principle which is compatible with quantum theory (Saunders 2003; for comments, see French and Rickles 2003). Interestingly, this form grants relations an individuating role and it can thus be regarded as yielding a form of structuralism, in that the very individuality of the object is grounded in the latter's relations with other objects. Similarly, but less plausibly, perhaps, Stachel suggests, in his contribution to this collection, that haecceity or 'primitive thisness' can have a relational basis too; one might wonder how the haecceity can still be regarded as 'primitive' under such a conception.

It can also be argued that even if one were to accept the traditional implication of quantum statistics with regard to individuality, one does not have to give up a metaphysics of objects entirely since the supposed non-individuality can be captured via some non-standard formal framework which accommodates a conception of objects still, albeit of a strange kind (see Krause 1992; French and Krause 2006). Nevertheless, that both these metaphysical packages—'quantum objects-as-non-individuals' and 'quantum objects-as-individuals'—are effectively supported by the physics provides an alternative motivation for structuralism. Put simply the idea is that what we have here is a form of 'metaphysical underdetermination' in which the metaphysical interpretation—in this case of quantum objects as either individuals or non-individuals—is underdetermined by the physics itself. This can be taken to raise a fundamental problem, in that we can no longer ascertain which metaphysics of objects—at the most basic level of their individuality—is implied by the physics. This problem can then be resolved, or 'sidestepped', by reconceptualizing the notion of object in structuralist terms, for it only afflicts object-based ontologies (be they individuals based or non-individuals based). Pooley (this volume) has questioned the strength of this motivation, on the grounds that the underdetermination only exists in 'logical space'. Here he seems to be following Redhead and Teller, who have argued that the non-individuals package meshes better with quantum field theory and hence we have grounds for choosing that horn of the apparent dilemma, so the underdetermination evaporates.[37]

Of course, these alternative metaphysical packages were articulated in the context of 'first quantized' quantum mechanics and it should, perhaps, come as no surprise that the force of an apparent underdetermination weakens once one broadens the theoretical context. But note, it would be a mistake to view the move to quantum field-theory as truly *resolving* the underdetermination since in the field-theoretic context we do not, strictly speaking, have objects at all but only field excitations. It is rather a case of a particular underdetermination which exists in one theoretical context, not featuring in another, and this should not be unexpected. Nevertheless, new forms of underdetermination might arise in these new contexts and indeed, in the field-theoretic context, Redhead has located the structuralist stance as laying between the two questions 'what is a field?' and 'what are the equations which govern its behaviour?' (Redhead 1995: 18). The standard answers to the first—that a field is some kind of substance or merely a set of properties instantiated at spacetime

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[37] For discussion of this line of argument, see French and Krause (2006).

points or regions—are not exhausted by the answer to the second. Harking back to the history again, Cassirer, for example, rejected the substantival account for philosophical reasons and insisted that a field is not a 'thing' but rather a 'system of effects' (1937: 178). Those who prefer their structuralism less in thrall to an already given philosophical position might want to articulate another form of metaphysical underdetermination—this time between fields as substances and fields as instantiated properties. Even if one were to follow Cassirer and choose the latter horn of the underdetermination, this would still leave the nature of spacetime as a potentially non-structural element of one's ontology.

Whether similar motivations can be articulated in the context of the foundations of spacetime theory is a further, interesting question. Certainly it is debatable whether the traditional dichotomy between substantival and relationalist views of spacetime can be understood as a form of metaphysical underdetermination in the above sense (Pooley, this volume, argues not). Recent interest in 'spacetime structuralism' has been motivated, in large measure, by the hole argument, which, as we have seen, presents an apparent dilemma of either giving up manifold substantivalism or accepting a form of indeterminism. In an attempt to avoid having to succumb to a relationalist position, various structuralist alternatives have been articulated—though, as we mentioned previously, these positions often parade under a label other than structuralism (Dorato 2000 is an exception). Still, concerns over the individuation of spacetime points may still drive one to a form of spacetime structuralism (see, for example, Stein 1967). We recall Eddington's understanding of space as 'not a lot of points close together; it is a lot of distances interlocked' (1923: 10) and more recently, Dorato has asserted that 'To say that spacetime exists just means that the physical world exemplifies, or instantiates, a web of spatiotemporal relations that are described mathematically' (2000: 7).

This suggests that spacetime has an objective existence that is not grounded in some form of substantivalism, but then Dorato appears to agree with Cao (1997) that the existence of spatio-temporal relations must be underpinned by the existence of the gravitational field, understood as a 'concrete' and hence, presumably, substantive, entity. As far as Cao is concerned a field is a 'hypothetical entity', employed as the basis for generating the field equations which describe the structural aspects of these entities and from which particles emerge as 'observable manifestations' (2003). But this just pushes the question back: what is this hypothetical entity, metaphysically speaking? The structuralist's answer is that the field is just the structure, the whole structure, and nothing but the structure (French and Ladyman 2003).

1.2.4 Structural Realism

Interest in the structuralist programme has recently been reawakened in the context of the realism–antirealism debate in the philosophy of science. Psillos's characterization of different forms of structuralism in terms of the 'upwards' and 'downwards' epistemic paths represents a useful way of framing the recent discussions in a way which connects current positions to their predecessors (2001). Broadly speaking, when we follow the 'upwards' path we begin with supposedly secure knowledge and then infer what we can know on that basis. Thus Russell, for example, began with 'percepts', which represent our experiences and which we know via direct acquaintance, and then used his causal theory of perception to infer that all that we can know of the external world on that basis is its structure (Russell 1927). Thus he writes,

> When we are dealing with inferred entities, as to which we know nothing beyond structure, we may be said to know the equations, but not what they mean: so long as they lead to the same results as regards percepts, all interpretations are equally legitimate. (p. 287)

Now this view famously came under attack from the mathematician Newman (1928), who argued that if we know only the structure of the world, then we actually know very little indeed. The argument is apparently straightforward: given any 'aggregate' of relata A, a system of relations can be found having any assigned structure compatible with the cardinality of A; hence, the statement 'there exists a system of relations, defined over A, which has the assigned structure' yields information only about the *cardinality* of A. In other words, to say we know the structure of the world is to say nothing more than that we know the cardinality of the world. Russell himself appears to have been convinced by Newman's conclusion and in the context of our history above, it is worth noting that Braithwaite also deployed it against Eddington (Braithwaite 1940), writing that

> his [Newman's] strictures are applicable to Eddington's group-structure. If Newman's conclusive criticism had received proper attention from philosophers, less nonsense would have been written during the last twelve years on the epistemological virtue of pure structure. (Braithwaite 1940: 463)

Unlike Russell, however, Eddington was less impressed, arguing that Newman's conclusion depends on a mathematical distinction between *elements* of a set and the relevant *relations*, but that from the group-theoretical perspective on which his form of structuralism is founded, no such distinction is possible: 'The element is what it is because of its *relation* to the group structure' (Eddington 1941: 269; his emphasis). In particular, he contrasts Russell's 'vague' conception of structure as a pattern of entities—or, perhaps, a pattern of relations—with his group-theoretic understanding of structure as a pattern of 'interweaving', or a 'pattern of interrelatedness of relations'. As an example, he presents the algebra of operators representing rotations acting on elements, for which the 'pattern of interrelatedness' is manifested in the associated multiplication table and, he insists, the information encoded in such a table is by no means trivial in the way Newman indicated (for further discussion, see French 2003).

Nevertheless, the Newman argument continues to be presented by critics of structuralism,[38] possibly because these critics see structuralism as following the 'upwards' path in general and as beholden to Russell in particular. However, Russell's account emerged at a specific time, historically (1926–7) and although it contains

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[38] See, for example, Demopoulos and Friedman (1995); Psillos (1999); Ketland (2004); for a response, see Melia and Saatsi (forthcoming).

a good representation of the then current understanding of spacetime theory, the implications of the new quantum mechanics were only dimly appreciated. Indeed, given Cassirer's and Eddington's concern to develop a form of structuralism that could accommodate these implications, one might suggest that it is to these authors, rather than Russell (and Newman) that both structuralists and their critics should look.

In its modern form, a structuralist accommodation of modern physics can be characterized in terms of what Psillos calls the 'downward path'. Here one begins with the full, theoretical edifice, as it were, and then undertakes a strategic, epistemic retreat according to what one learns from reflection on both the progress of science and its metaphysical implications (or lack thereof). Thus Worrall has famously presented a form of structuralism as a response to Laudan's 'Pessimistic Meta-Induction' (Worrall 1996). Put rather crudely this asserts that the history of science is, to a significant extent, a history of changing ontologies—as one moves from the particle theory of light to the wave theory to Maxwell's theory and so on, to take one example—and given this, one has good reason not to be a realist with regard to the ontology of our current best theories. Worrall's response, again put rather simply, is to note that the same history suggests that important structural elements of theories are preserved through these changes. By 'ontology' here is meant the theoretical representation of scientific entities, such as light, electrons, etc. The relevant structures, on the other hand, are represented for Worrall by the appropriate mathematical equations—Snell's Laws are incorporated into Maxwell's Equations and so on. Thus, whereas the ontological component of a theory may be subjected to a pessimistic meta-induction, as far as the structural component is concerned things look quite optimistic.

This gives rise to a form of 'Structural Realism' (SR) which holds that one can, and should, adopt a realist attitude towards the well-confirmed structural aspects of theories (see also Redhead 1995). As Ladyman has pointed out (1998), this should be regarded as an epistemic form of SR since it holds that all that we know are the structures, while the objects themselves remain epistemologically inaccessible. Again there is a historical aspect to these developments, since in defending this position Worrall draws on those famous passages from *Science and Hypothesis* where Poincaré writes that theoretical terms 'are merely names of the images we substituted for the real objects which Nature will hide forever from our eyes. The true relations between these real objects are the only reality we can ever obtain' (1905: 162).[39]

Setting aside these historical issues again, Worrall noted that this form of structuralism might be capable of accommodating quantum physics, although he did not develop this aspect of his account. However, in retaining the idea of epistemologically inaccessible objects, hidden behind the structures as it were, Worrall appears to run up against the very implications that Cassirer and Eddington took to underpin their

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[39] Elsewhere Poincaré presents group theory as the most appropriate representation of these 'true relations' and displays certain Kantian inclinations which hardly commend him to the realist. Such inclinations appear again and again through the history of structuralism and the issue arises as to whether, in drawing on this history for her understanding of 'structure', the structural realist can neatly peel them off from the rest of structuralist programme.

forms of structuralism, namely that quantum particles are not individuals in some sense. Here, in the context of defending realism, the above underdetermination between objects-as-individuals and objects-as-non-individuals has a particular bite: van Fraassen has argued that realism should be understood as requiring a commitment to a metaphysical interpretation, at this most basic level (van Fraassen 1991). However, this underdetermination indicates that no such interpretation can be given founded on the physics itself. The realist is thus faced with a problem.

Ladyman's 'ontic' form of SR (Ladyman 1998) can be seen as responding to this concern (as well as to the pessimistic meta-induction) by effectively eliminating the objects completely, leaving only the structures. Again, put simply, the idea is that it is not just that all that we know are the structures but that all that there *is* are the structures. It is important to emphasize (because some critics appear incapable of grasping this) that although Ladyman's view bears some resemblance to earlier forms of structuralism—in taking the ontology of the world to be structural most crucially—the underlying argument is quite different (it is not that quantum mechanics implies that quantum objects are in some sense non-individuals but that on the basis of the physics alone we cannot say whether the particles are individuals or not and hence if we want a realism compatible with our current best theories, we had better adopt a different ontology). The elaboration and development of this position has raised a number of interesting issues, to do with the representation and metaphysics of structure, the conceivability of structures without any underlying objects, the identity conditions for such structures, and so on, some of which, at least, have been addressed elsewhere (Ladyman 1998; French 2001; French and Ladyman 2003). It is important to realize that in eliminating objects from the realist's ontology, the structuralist is not advocating the view that physicists cannot talk, whether theoretically or informally or whatever, of 'electrons', 'quarks', etc., but rather is insisting that from a metaphysical perspective these entities must be reconceptualized in structural terms. Furthermore, this form of 'ontic structuralism' can be extended to quantum field theory along the lines already sketched above (French and Ladyman 2003).

Of course we are not suggesting that to understand the foundations of quantum gravity one must be a structural *realist*. One could be a structural empiricist and adopt van Fraassen's modal stance towards interpretations of theory and insist that what these interpretations tell us is how the world could be (see Bueno 2000, for steps leading in this direction). In the case of structuralism, what we are asserting, according to this empiricist stance, is that the world could be, metaphysically, structural. In either case—that of the structural realist or that of the empiricist—what is important for our purposes is that we are provided with the resources for giving an ontological account of the foundations of quantum gravity. These resources will include the representational, whether they be group theoretic, as Eddington advocated, or category theoretic, as Baez and others have suggested, and the metaphysical, as in the claim, defended, again, by Eddington and, more recently, Rickles, that relations and the objects which act as their relata come together in a structuralist package, as it were; or the view, proposed, in various forms, by Saunders, Stachel, and others, that it is relations 'all the way down', even to the level of the individuality of the objects, so the latter emerge as mere 'nodes' in the structure, or intersections of relations, as Cassirer thought. And of course there is still a great deal of work to be done in articulating those resources fully and properly and there are a number of criticisms that must be faced (see, most notably, Chakravartty 1998 and Psillos, forthcoming) but we hope, at the very least, that the essays contained in this collection will lead to a greater appreciation of both the virtues of this approach and the obstacles still to be overcome.

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