On Identifying Background-Structure in Classical Field Theories[†]

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Abstract

I examine a property of theories called 'background-independence' that Einsteinian gravitation is thought to exemplify. This concept has figured in the work of Rovelli (2001; 2004), Smolin (2006), Giulini (2007), and Belot (2011), among others. I propose and evaluate a few candidates for background-independence, and I show that there is something chimaerical about the concept. I argue, however, that there *is* a proposal that clarifies the feature of Einsteinian gravitation that motivates the concept.

1. Introduction

This essay examines the origin and extension of the concept of background-structure in classical field theories. The extension of the concept, before the recent work of Smolin (2006), Belot (2011), and others, was easily circumscribed. The concept denoted what is characteristic of the space-time structures of Newtonian theory and special relativity.

Newton's laws express criteria of causal interaction. They articulate an account in which the physical quantity *force* is the cause of the acceleration of mass. The content of the laws can be summarised as follows: Given a system of particles in motion, there exists a reference frame and a time-scale relative to which every acceleration is proportional to and in the direction of the force applied, and where every such force belongs to an action-reaction pair.[1] Furthermore, given such a reference frame, forces and masses, accelerations and rotations have the same measured values whether that frame is at rest or in uniform translatory motion. In other words, the laws of

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[1]I owe this formulation to Thomson (1884, p. 387) and Muirhead (1887, pp. 479-480).

motion satisfy the Galilei-Newton relativity principle. The equivalence-class structure determined by the invariance of the laws under the Galilean transformations is the structure of Newtonian space-time.

From a retrospective point of view, the structure of the space-times of the Newtonian and special-relativistic frameworks can be equally well discussed in terms of the mathematical structures that their classes of inertial frames presuppose. In the Newtonian framework, those frames presuppose a global affine structure and separate metrical structures for space and time; in the special-relativistic one, they presuppose global affine and conformal structures and also the metrical structure of space-time. In both frameworks, these structures are fixed independently of the theories of special systems, and thus these structures do not evolve along with the special systems. To use a common figure, space and time are the 'stage' on which the 'actors', namely the physical fields, move.

One of the great empirical claims of Einsteinian gravitation is that space-time structure is dynamical, and thus something to be discovered empirically. Einsteinian gravitation comprises affine, conformal, and metrical structures. But, in contradistinction to Newtonian theory and special relativity where those structures are necessary presuppositions of the classes of inertial frames, they are fixed only locally, and their variation over any finite region is determined by the distribution of mass-energy. This is not to say that everything in Einsteinian gravitation is dynamical, but, in this way and others, Einsteinian gravitation motivates the revision of the space-time structures of Newtonian theory and special relativity. Space and time cease to be a fixed stage and become actors.

A number of physicists and philosophers of physics, notably Rovelli (2001; 2004), Smolin (2006), and others pursuing loop quantum gravity, have seen in this empirical claim an insight about nature that ought to be preserved in a future theory. In their interpretation of the claim, they have fashioned a new concept that they call 'background-independence'. This is the concept to be explicated, but, roughly speaking, to say that a physical theory is background-independent means that physical processes do not unfold against a spatio-temporal framework that is presupposed a priori but determine a dynamical framework in their evolution. This new concept figures in a new heuristic principle that they believe to be fruitful for those pursuing a quantum theory of space, time, and gravitation. Smolin states it as a maxim: 'Seek to make progress by identifying the background structure in our theories and removing it, replacing it with relations which evolve subject to dynamical law.' (2006, p. 204). The proper methodological analysis of such a heuristic principle is an outstanding philosophical project, one I hope to pursue in future work.

In this essay, I take up a prerequisite task. I ask: What is this background-structure that Smolin would have us identify and remove? I propose and evaluate four candidates for background-independence, and I show that there is something chimaerical about the sought-after concept. My aim, however, is not solely critical and sceptical. I argue that there *is* a proposal for background-independence—one that stems from the work of Trautman, Anderson, and Friedman—that clarifies the particular feature of Einsteinian gravitation that is the basis for nearly all proposals for background-independence.

2. Background-independence and general covariance

There is a sense in which the earliest discussion of background-structure is found in Newton's criticism of Cartesian physics in *De grav*. But let us begin by getting clear on the kind and degree of background-independence exemplified in Einsteinian gravitation.

Einstein took the first steps towards the account of motion characteristic of his gravitation theory in 'On the Electrodynamics of Moving Bodies' (1905 [1952b]). The Newtonian framework uncritically assumes that we have a way of determining whether spatially separated frames agree on which events are simultaneous. In the 1905 paper, Einstein argued that determining the time of occurrence of spatially separated events depends on a process of signalling. The invariance of the velocity of light—implicit in Maxwell's theory and established empirically by Michelson, Morley, and others—provided such a signal, and Einstein argued that a criterion involving emitted and reflected signals permits the derivation of the Lorentz transformations. This is the basis of Einstein's special theory of relativity. One outcome of Einstein's analysis of simultaneity was the replacement of the nineteenth-century inertial frame concept with the 1905 inertial frame concept: An inertial frame is not merely one in uniform rectilinear motion but also one in which light travels equal distances in equal times in arbitrary directions.

With the special theory of relativity, it was necessary to find a new theory of gravitation that would overcome the contradiction between the invariance of the velocity of light and the instantaneous action at a distance postulated by Newtonian gravitation. In 1907, Einstein had an insight that has been formalised in a principle called the *equivalence principle*.[2] Einstein formulated the principle in a number of ways, but perhaps most perspicuously by way of the thought experiment now known as 'Einstein's elevator'. Suppose you are inside a box from which you cannot see out. You feel a 'gravitational force' towards the floor, just as you would at home. But you have no way of excluding the possibility that the box is in a rocket moving with acceleration g in free space and that the force you feel is an accelerative force. Particles dropped in the box will fall with the same acceleration regardless of their mass or composition. This leads to the following statement of the equivalence principle: It is impossible to distinguish locally between a homogeneous gravitational field and uniform acceleration. But Einstein also ran the thought experiment the other way: Suppose you are inside the box. Only, this time, you feel no gravitational force, just as in free space. But you have no way of excluding the possibility that you are freely falling in a gravitational field. This second aspect of the thought experiment is particularly important: Einstein drew from it that matter obeys the same laws in a locally freely falling frame as it would in an inertial frame. In this way, Einstein began to recognise that freely falling motion and inertial motion are different presentations of the same motion.

But there is a further step in Einstein's argument: Einstein argued from the hypothesis that all bodies fall with the same acceleration in the same gravitational field to the stronger hypothesis that not only matter but light—and moreover, all physical processes—obey the same laws in a freely falling frame as they would in an inertial one. Without this extension, some phenomena, electromagnetic phenomena, e.g., would be a basis for measuring the acceleration of a freely falling particle relative to electromagnetically accelerated trajectories, namely trajectories not determined by gravitation. This would be no different from our ability to measure the

[2]The following is not intended as a careful account of the equivalence principle—it is intended as a *sketch* of the role of the principle in the argument for the 1907 inertial frame concept. For a careful account of the role of the principle in that argument, see Norton (1985).

acceleration of an electron in an electromagnetic field relative to the inertial trajectory of a particle that is not affected by that field. This extension reflects what Will (1993, p. 68) has called the 'universal coupling' of all non-gravitational fields to the gravitational field. If any phenomena failed to couple to gravitation in this way, they would indicate the existence of a 'background-structure' that is distinguishable from the gravitational field. As Will has put it, universal coupling allows us to 'discuss the metric **g** as a property of space-time itself rather than as a field over space-time' (Will, 1993, p. 68).

With his insight of 1907 and the crucial extension to all physical processes, Einstein recognised that freely falling motion and inertial motion are different presentations of the same motion. In this respect, the equivalence principle functions as a criterion for identifying inertial frames and freely falling ones. The equivalence principle fatally undermines the determinateness of the 1905 inertial frame concept. It establishes that the concept is not uniquely determined by its empirical criteria. With this identification, the fundamental distinction between inertial and non-inertial frames was collapsed, and the relevant distinction became one between systems in free-fall and systems in non-free-fall motion.

With the 1907 inertial frame concept, Einstein was faced with the question, how is the concept to be interpreted? Einstein's chain of reasoning towards an answer is the subject of debate, but there is a rational reconstruction of that reasoning that highlights the essential steps. Special relativity presupposes the mathematical structure of an affine space equipped with a Minkowski metric. In the special theory, the trajectories of bodies moving inertially and also those of light rays are interpreted as the straight lines or geodesics with respect to the Minkowski metric while gravitation is a force that pulls bodies off their straight-line trajectories. But Einstein, with much help from Grossmann, saw that Riemann's newly-developed theory of manifolds offered an alternative to such an affine space for interpreting inertial trajectories: The inertial trajectories of freely falling particles can be interpreted as the geodesics with respect to a new metric that is determined by the distribution of mass and energy in the universe. This reinterpretation of free fall is summarised in what has been called the *geodesic principle*: Free massive test particles traverse time-like geodesics.[3] The geodesic principle interprets the 1907 inertial frame concept by expressing a criterion for its application. It provides a framework of investigation in which one can begin to think about how to construct a theory where gravitation is represented as a manifestation of the curvature of space-time structure that is determined by the distribution of mass and energy. In this framework of investigation, Einstein realised that there is no way of smoothly laying down a global coordinate system and that the laws of his gravitation theory required a coordinate-independent expression. He referred to that requirement as the *principle of general covariance*.

With the geodesic principle and the requirement of general covariance with which Einstein connected it, no longer was there an equivalence class of preferred coordinate systems determined by the laws, and no longer were there non-dynamical affine, conformal, and metrical structures. Though Einstein did not use the term 'background-independence', he certainly appealed to the notion in his own characterisations of his gravitation theory. I will call that notion

> *Proposal 1.* A theory is background-independent just in case it satisfies the requirement of general covariance.

But no sooner do we have this proposal in hand than we must respond to an objection: General covariance was trivialised nearly as soon as it was presented. In 'The Foundation of the General Theory of Relativity' (1916 [1952a]), Einstein gave an argument for general covariance that, following Stachel (1980), we now know as 'the point-coincidence argument'. The locution 'point-coincidence' refers to the view that all physical observations consist in the determination of purely topological relations (coincidences) between objects of spatiotemporal perception. The argument runs as follows: (P1) All evidence for or against a physical theory rests on immediately verifiable facts. (P2) Immediately verifiable facts are exhausted by point-coincidences. (C) Thus, physical observations are reducible to point-coincidences. On this argument, any mapping that preserves point-coincidences preserves a theory's physical content, and thus no coordinate system is privileged.

[3]The geodesic principle is stated in terms of test particles because it holds only approximately for extended bodies. The geodesic principle for light rays may be stated: Light rays traverse light-like geodesics.

Kretschmann (1917) brought to light an important physical implication of the point-coincidence argument that he took to trivialise general covariance. He thought that, if indeed a theory's physical content is exhausted by point-coincidences, the equations of any theory can be made generally covariant without a modification of that content. Kretschmann's challenge was taken seriously in the 1960s by Trautman, Anderson, Wheeler, Fock, and others, who learnt to distinguish the requirement of general covariance from the symmetries that equations of motion formulated in the Einsteinian framework admit. Henceforth, we will be discussing those symmetries and not the requirement of general covariance as understood by Einstein.

3. The Anderson-Friedman programme

J L Anderson (1967) challenged the view that general covariance is the characteristic feature of Einsteinian gravitation, pointing out, as Kretschmann did, that any theory can be given a generally covariant formulation. He claimed that the characteristic feature of Einsteinian gravitation is its lack of an 'absolute object'. Anderson's proposal was taken up by Friedman (1983), who sought to give it a more perspicuous formulation, and the following definitions are Friedman's. To state the proposal properly, I will give an abstract sketch of a classical field theory. I will do so only in meanest outline and in a familiar notation. See Pitts (2006) for a technically and historically careful treatment of the Anderson-Friedman programme and the differences between Anderson's and Friedman's definitions.

Let me represent the *space-time* of a classical field theory T as an ordered n-tuple of the form $(M, O_1, ..., O_n)$, where M is a smooth manifold and $O_1, ... , O_n$ are *geometric objects* on M. Defining geometric objects is a non-trivial task, but, in general, the objects in question are tensors, tensor fields, and also metric-compatible connections. The *dynamical laws* of T will be built up out of these geometric objects. These laws have the form $f(O_1, ..., O_n) = 0$.

Let me turn now to the notion of an automorphic *mapping* of geometric objects on the manifold. If $(M, \phi_1, ..., \phi_n)$ and $(M, \theta_1, ..., \theta_n)$ are both models for T, then for every point p of M there is a mapping d of a neighbourhood A of p onto a neighbourhood B of p such that $\phi_i = d\ \theta_i$ on $A \cap B$. If that mapping is infinitely differentiable, one-to-one, onto, and has an infinitely differentiable inverse, then the mapping, denoted d, is called a *diffeomorphism*. The arbitrary diffeomorphisms *d* form a group, often denoted *diff(M)* as a reminder that they are automorphisms of *M*. Elements of *diff(M)* act on the geometric objects of the theory in question.

With this framework in hand, let me return to the Anderson-Friedman proposal for characterising Einsteinian gravitation and other classical field theories. A geometric object O_i is an *absolute object* of *T* just in case for any two *T*-models (M, ϕ_1, ..., ϕ_n) and (M, θ_1, ..., θ_n) ϕ_i and θ_i are invariant under *diff(M).* A geometric object that does not satisfy this definition is a *dynamical object*.

Anderson's distinction between absolute and dynamical objects is the basis of his definition of a theory's *symmetry group*, namely the largest subgroup of *diff(M)* that leaves invariant the theory's absolute objects. It is noteworthy that, though Anderson defines a theory's symmetry group in terms of that theory's antecedently defined absolute objects, on an alternative understanding, the lack of absolute objects would be expressed by the lack of non-trivial symmetries.

This definition is significant because it meets Kretschmann's challenge: Theories may be reformulated so that their geometric objects are invariant under the actions of subgroups of *diff(M)* like the Poincaré group or so that they are invariant under *diff(M)* itself, even though, in their standard formulations, they would be invariant only under more limited mapping groups. It is precisely the further requirement expressed in the above definition that is supposed to distinguish a theory's symmetry group from its mapping or covariance group. That requirement distinguishes Einsteinian gravitation, which Anderson claimed lacks an absolute object, from previous theories.

4. Background-structure represented by geometric objects and beyond

I have presented the definition of an absolute object not only to move beyond the trivialisation of general covariance but because Anderson took the presence of absolute objects in a theory's equations to imply that theory's commitment to a certain form of 'background-structure', though he himself did not use that term. Thus, the Anderson-Friedman definition provides us with another strategy for identifying background-independence, which I will call

Proposal 2. A theory is background-independent just in case it has no absolute objects. With this proposal, the notion of background is entirely determined by the geometric objects on a manifold.[4]

As with proposal 1, no sooner do we have this proposal in hand than we must respond to a line of objection, namely that the Anderson-Friedman distinction between absolute and dynamical objects cannot capture the intended and essentially physical distinction. Geroch (reported in Friedman, 1983, p. 59, n. 9) pointed out that there are models for Einsteinian gravitation in which geometric objects like nowhere-vanishing vector fields and symplectic forms count as absolute objects. He made his point with the following example. Suppose we have a cosmological model in which there is omnipresent dust, all particles of which are at rest in some Lorentz frame. Pressure-free dust has the stress-energy tensor $T^{ab} = \rho U^a U^b$, where the density of the dust particles ρ is defined as the number of particles per unit volume in the unique inertial frame in which the particles are at rest and U^a is the four-velocity. In such a universe, the four-velocity would be nowhere-vanishing and would count as an absolute object on Friedman's definition. That is, there would be a background reference frame in the imaginary model, the rest frame of the dust. Torretti (1984, p. 285) offered another counterexample to the Anderson-Friedman distinction. He formulated a theory of modified Newtonian mechanics in which each model has a space of constant non-positive curvature, but different models have different values of curvature. He pointed out that such curvature is undeniably a kind of background-structure, yet escapes the Anderson-Friedman definition of absoluteness. Pitts (2006) presents and challenges these and other counterexamples and he offers a defence of the Anderson-Friedman programme. But he concedes that Einsteinian gravitation may have an absolute object, namely the scalar density obtained by reducing the metric into a conformal metric density and a scalar density.[5]

[4]There is a discussion that I would like to acknowledge, if only briefly. Though Anderson did not introduce absolute and dynamical objects with reference to action principles, he certainly regarded dynamical objects as variational, while absolute objects are not (1967, pp. 88-89). Some (e.g., Hiskes, 1984) have seen in this another way of drawing the absolute-dynamical distinction: No object that is varied in a theory's action principle should be considered absolute. But others (e.g., Rosen, 1966; Sorkin, 2002) have argued that a flat metric can be derived from an action principle by introducing geometric objects that vary in the required way. It is significant that Anderson himself (1967, p. 83) headed off this line of objection by proscribing what he called 'irrelevant variables'. Anderson was concerned with the essentially physical distinction between space-time structure in Newtonian theory and special relativity, on the one hand, and Einsteinian gravitation, on the other. For him, that distinction was never a merely formal one and he was at pains to defend it from those who would undermine it with formal 'tricks'.

[5]See Pitts (2006, pp. 366-367) for details.

Some may consider these counterexamples to be reason enough for giving up proposal 2. But Trautman (1966; 1973) hints at another way of thinking about physical theories, one that Pitts does not consider in his defence.[6] This work suggests that the space-times of Newtonian theory and special relativity are *characterised* by absolute objects; the space-time of Einsteinian gravitation is *characterised* by dynamical ones.[7] That is to say, theories of special systems formulated in the Newtonian or special-relativistic frameworks presuppose geometric objects that determine a fixed metric affine geometry; those of systems formulated in the framework of Einsteinian gravitation depend on geometric objects that determine a dynamical one. On this interpretation, there is no suggestion that Einsteinian gravitation lacks an absolute object. The distinction between Anderson's and Friedman's accounts, on the one hand, and Trautman's, on the other, is not merely verbal. The claim that the metric affine geometry of Einsteinian gravitation is characterised by dynamical objects is importantly different from the claim that Einsteinian gravitation has no absolute objects. In this way, the line of objection motivated by the counterexamples and a debate over the viability of the Anderson-Friedman programme is better avoided. This way of characterising physical theories can also be used to motivate another proposal for background-independence; we might call it

> *Proposal 2a*. A theory is background-independent just in case its metric affine geometry is characterised by dynamical objects.

This proposal helps preserve something of the intended and essentially physical distinction that motivated the distinction between absolute and dynamical objects.

Nonetheless, there is a line of objection that undermines both proposals 2 and 2a in a different way. These proposals commit us to the view that whether a theory is background-independent depends on its geometric objects. But Belot (2011, pp. 12-20) has recently pointed out that the concept of background-independence admits of degrees. He considers, among other examples, the vacuum solutions to Einstein's field equations that give rise to de Sitter, anti-de

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[6]In fact, the notions of absolute and dynamical objects are due to Trautman. But it was Anderson and Friedman who gave them a perspicuous formulation. For this reason, Anderson and Friedman are more readily associated with them than Trautman.

[7]Passages supportive of this reading can be found in Trautman (1973), though the claim that Einsteinian gravitation has no absolute object can also be found in Trautman (1966). In any case, I will attribute this reading to Trautman.

Sitter, and Minkowski space-times. These and other solutions have the asymptotic behaviour of one of the spaces of constant curvature.

To take another family of examples in Einsteinian gravitation, suppose one attaches a boundary to a four-dimensional manifold.[8] Suppose, further, that one builds into the kinematically possible configurations of a theory's geometric objects not only such requirements as smoothness and global hyperbolicity but also the requirement that space-time is approximately Minkowskian as one approaches the boundary.[9] Such a theory will have no geometric objects that determine a background, but such a theory will admit *diff(M)* only locally, not generally; at the boundary, the theory will admit only a subgroup of *diff(M)*. The theory will lie between paradigmatically background-dependent theories in which geometric objects propagate in Minkowski space-time and paradigmatically background-independent theories such as spatially compact Einsteinian gravitation. So, even though the theory has no geometric objects that determine a background-structure, the boundary conditions ensure that any solution has the structure of a Minkowskian background at spatial infinity.

With these sorts of situations in mind, Belot proposes an elegant scheme for fixing the extension of background-structure.[10] No longer is background-independence an all or nothing affair: Theories are shown to have degrees of background-independence. To make precise various degrees of background-(in)dependence, Belot introduces a distinction between a theory's geometrical and physical degrees of freedom. The *geometrical degrees of freedom* are represented by the geometric objects, figuring in the dynamical laws of a theory, that parametrise the equivalence classes of space-time geometries. The *physical degrees of freedom* are represented by the geometric objects that parametrise the quotient-space obtained by identifying gauge-equivalent solutions. A theory is then said to be *fully background-dependent* just in case it has no geometrical degrees of freedom, and *fully background-independent* just in case its geometrical and physical degrees of freedom match. Of greater moment, however, is the possibility of characterising theories of ambiguous background-structure. A theory is said to be *nearly background-dependent* if it has only finitely many geometrical degrees of freedom and

[8]For details on attaching various kinds of boundaries, see, e.g., Hawking and Ellis (1973).
[9]I owe this family of examples to Belot (2011).
[10]The following is only a sketch of Belot's proposal; see Belot (2011) for details.

nearly background-independent if it has a finite number of non-geometrical degrees of freedom. In this way, proposals 2 and 2a are recovered and situated in a larger space of possibilities in which their uniqueness is undermined.[11]

Belot's proposal is a significant contribution. But, as much as it clarifies the idea that there are various degrees of background-independence, it also sharpens the ambiguity of the concept. Provided that a theory has no absolute objects, does background-independence require (i) that a theory *presuppose* nothing about global structure or (ii) that a theory *preclude* the possibility of such structure? For Einsteinian gravitation could be said to satisfy neither (i) nor (ii) since the theory holds that geometry is everywhere locally Lorentzian, making Belot's proposal trivially true, or Einsteinian gravitation could be said to satisfy only (i) in that geometry is dependent on the distribution of mass and energy. Though I leave aside the question of the methodological status of a principle like Smolin's for future work, this particular ambiguity already suggests a reason to avoid asserting a meta-principle about eliminating background-structure.

Belot's proposal also provides an opportunity to comment on the distinction between local and global structure in Einsteinian gravitation. Einsteinian gravitation departs from Newtonian theory and special relativity in that it places weaker a priori restrictions on global structure. (To put the point in Carnapian terms, global structure is relegated to the *P*-rules of the framework.) But that departure, though radical, does not stem from a philosophical or methodological motivation to construct a theory with that characteristic but from the fact that the equivalence principle motivates a purely local definition of a geodesic.

5. Further beyond geometric objects

To this point, I have only considered some of the strongest mathematical structures that may be imposed on a manifold, namely metrics and other geometric objects both absolute and dynamical. I have considered certain solutions to the field equations and also the imposition of asymptotic boundary conditions from which background-structure may arise. In contrast, Trautman (1973),

[11] Belot's proposal represents a significant advance over the work of Trautman, Anderson, and Friedman, but it is noteworthy that the idea that geometric objects parametrise a theory's degrees of freedom is already there in Trautman (1966, p. 322).

Thorne, Lee, and Lightman (1973), Smolin (2006), and others have pointed out that one may count dimension, topological and differential structure, temporal orientation, and even the metric signature as background-structures, though they leave it as an open question whether these lower levels of background-structure are essential to all physical theories or whether they may be replaced by a future theory. In this vein, one might ask, why use the real numbers as opposed to some other field? And, taking this still further, one might well ask whether all the mathematical structures a theory 'quantifies over' are to be considered background-structures. Though I take the suggestion of Trautman and others seriously, it reinforces that there is something chimaerical about background-independence: No sooner have we cut off one head than two more spring up to take its place; no sooner do we seem to be getting a hold of the concept when it slips away again. In any case, it is noteworthy that Einsteinian gravitation presupposes these lower-level features, yet allows for scenarios in which certain of these features are violated by (e.g.) singularities.

How, then, are we to fix the extension of background-independence so as to include those kinds of background-structures that escape a proposal such as Belot's? There is an intuition that seems to underlie the views of Smolin (2006), Giulini (2007), Belot (2011), and others. And, though I do not do full justice to their views, I will summarise it in what I call

> *Proposal 3.* A theory is background-independent just in case it has no fixed 'stage' that shapes the evolution of the fields without itself being shaped by them.

This proposal is very nearly the so-called action-reaction principle: For something to be physical it cannot act without being acted upon.[12] For Einstein, something like this principle is satisfied by his gravitation theory and not by Newtonian theory or special relativity. And the idea certainly lies behind Anderson's definition of an absolute object. I will not address here Einstein's view that space-time should not act without being acted upon. Nor will I address the bearing of the action-reaction principle on discussions of background-independence. But it is important to note that the action-reaction principle seems to loom behind nearly all proposals for fixing the extension of background-independence.

[12]So far as I know, 'action-reaction principle' nowhere appears in Einstein's writings, though the idea is certainly there. See, e.g., Brown (1996; 2005), where the principle is formulated explicitly.

A metaphor by Novalis—'Theories are nets: only he who casts will catch'—is particularly apt for the evaluation of proposal 3. The main objection to proposal 3 is that it is a step too far: It is a catch-all for virtually any kind of mathematics used in the formulation of a theory. All of the above proposals are subsumed, but room is left for other conceptions of background-structure. It may be that some still finer-grained classification is possible, but I will not attempt that here. I only want to point out that, by catching everything, proposal 3 blurs even the line between the *language* required for saying anything at all and *interpreted mathematical theories*. Where that line is drawn varies from theory to theory, and it is not drawn a priori or by some philosophical or methodological demand such as (e.g.) the demand that a theory be background-independent. Rather, it is a set of empirical criteria—the laws of motion, a criterion for identifying time of occurrence, the geodesic principle—that controls the application of some or another body of mathematical theory. In Einsteinian gravitation, for instance, one needs an empirical reason to consider certain solutions to the field equations as physical possibilities or to impose asymptotic boundary conditions, and, in view of that, one might not want to formulate the theory or a meta-theoretical principle about the theory so that certain solutions or the imposition of boundary conditions is precluded a priori. At the very least, an important strength of proposals 2 and 2a over proposal 3—or any proposal motivated by the action-reaction principle or something like it—is that it does not dissolve the important differentiation of background-structures into a 'night in which all cows are black'.

If proposal 3 is a step too far, what, if anything, remains to be said about proposals 2 and 2a? I have presented the case against these proposals: I have charged them with failing to account for kinds of background-structures that are not determined by the geometric objects on a manifold. To be sure, the analysis of the concept of background-structure cannot end with proposals 2 and 2a. But the net cast by Trautman, Anderson, and Friedman was a good one. It is a virtue of proposal 2a that it illuminates a central feature of Einsteinian gravitation: The Einsteinian framework does not presuppose certain global structures, though it does not preclude them. It does not preclude, for example, that we might want to study bounded systems like stars, and so investigate space-times that are asymptotically flat. That one can formulate and study scenarios such as those identified by Geroch and Belot does not diminish that proposal's isolation of the difference between theories formulated in a Newtonian or special-relativistic framework, on the one hand, and certain theories formulated in the framework of Einsteinian gravitation, on the other. In this way, that proposal sharpens—and does not blur—the feature of Einsteinian gravitation that is the basis for nearly all proposals for background-independence.

With a clearer understanding of the empirical motivation for a dynamical geometry, we might attempt to express Smolin's methodological principle more reasonably. We might formulate it: 'Find out whether there are background-structures that cannot be empirically motivated and eliminate them.' But this principle, too, reflects no philosophical insight peculiar to Einsteinian gravitation. In the absence of some particular empirical motivation for applying or eliminating a given mathematical structure, it reflects only the standard empiricist's application of Ockham's razor—and it could apply not only to background-structures, understood in terms of absolute objects, but also to dynamical objects if they have no empirical motivation. By criticising Smolin's principle, I do not mean to suggest that no meta-principles play or have played a heuristic role in theory construction. But what is revealed in Einstein's own construction of his theories, and in his provision of empirical criteria that articulate theoretical concepts, is that *methodological analysis* promises a clearer understanding than *meta-principles* of what constraints are imposed by our present understanding of gravitation on future theories.

6. Conclusions and a further consideration

With each of my proposals, I have tried to identify a genuine candidate for background-independence. There is a sense in which the requirement of general covariance is a candidate for background-independence. But Kretschmann showed that theories that are not generally covariant in their standard formulations may be reformulated, a point that the Anderson-Friedman programme masterfully addressed. I argued next that there is an important sense in which a theory that has no absolute objects—or whose metric affine geometry is characterised by a dynamical object—is a candidate for background-independence. But the challenges to proposals 2 and 2a, from several directions, seemed to suggest that this strategy could not capture important conceptions of background-structure. This motivated proposal 3. That proposal captures too much, and I suggested that one might want to distinguish between different kinds of background-structures, namely those arising from certain solutions to Einstein's field equations, from the imposition of boundary conditions, and from lower levels of background-structure. In this regard, Belot's proposal is significant for its clarification of the sense in which even a theory whose metric affine geometry is characterised by a dynamical object can still have various degrees of background-independence. But Belot's proposal also draws attention to the more basic question of what is demanded by the concept of background-independence. I have suggested that, though Belot's analysis provides an important explication, it says nothing about whether the concept requires that a theory *presuppose* nothing about global structure or that a theory *preclude* the possibility of such structure. The empirical interest of studying certain isolated systems in Einsteinian gravitation, e.g., would appear to be a good reason not to preclude the possibility of such structure a priori. We are left, then, with only the weaker demand that a theory presuppose nothing about global structure—at least so far as we set aside questions about lower-level background-structures like topological and differential structures, the metric signature, and others. *This* is the sense that the programme of Trautman, Anderson, and Friedman succeeds in capturing. So, while there is something chimaerical about background-independence, there is also a sense in which the feature of Einsteinian gravitation that motivated all of the proposals is aptly captured by that programme.

There is a further consideration with which I would like to conclude. I set out by recalling the fundamental insight into the nature of the gravitational interaction that is summarised in the equivalence principle. I recalled that the equivalence principle motivated a new inertial frame concept and that the geodesic principle expresses a criterion for the application of that concept.

The equivalence principle that I have discussed has been called 'Einstein's equivalence principle', which is itself an interpretive extrapolation from the universality of free fall. Einsteinian gravitation is not the only theory that satisfies this equivalence principle: Newtonian theory satisfies it too. Anderson (1967), Ehlers (1973), and others have shown that Einsteinian gravitation also satisfies another principle. This has been called 'the principle of minimal coupling', according to which no terms of the special-relativistic equations of motion contain the Riemann curvature tensor. In this way, minimal coupling ensures that special relativity is a local approximation so long as tidal gravitational effects can be ignored. Not only does Einsteinian gravitation satisfy this stronger demand—it is essential for ensuring the local validity of special relativity. The conjunction of Einstein's equivalence principle and minimal coupling amounts to what has been called 'the strong equivalence principle'.[13] The strong principle implies that no more than the dynamical metric g_{ab} is needed to account for gravitation.

This stronger principle bears directly on the question of background-independence because a modification of Einsteinian gravitation like the Brans-Dicke theory, which comprises absolute and dynamical objects, fails to satisfy it. The exclusion of the Brans-Dicke theory and others by the strong equivalence principle serves to isolate, in yet another way, what is distinctive about Einsteinian gravitation. Here the strong equivalence principle is playing the same role as proposal 2 in excluding those theories that comprise absolute objects. In this way, the strong equivalence principle further clarifies the sense in which Einsteinian gravitation is background-independent, whether or not the concept is of any service as a heuristic.

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[13]Note that the strong equivalence principle is more commonly presented as the conjuction of the principle of the universality of free fall, which grounds Einstein's equivalence principle and is in this sense more fundamental, and the principle of minimal coupling. (See, for example, Anderson (1967), Ehlers (1973), and Will (1993).) I have discussed Einstein's equivalence principle throughout because its role in the argument for the 1907 inertial frame concept is more immediate.

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