Forthcoming in *Einstein Studies*

Friedman and Some of his Critics on the Foundations of General Relativity

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Abstract

This paper is an examination of Michael Friedman's analysis of the conceptual structure of Einstein's theory of gravitation, with a particular focus on a number of critical reactions to it. Friedman argues that conceptual frameworks in physics are stratified, and that a satisfactory analysis of a framework requires us to recognize the differences in epistemological character of its components. He distinguishes first-level principles that define a framework of empirical investigation from second-level principles that are formulable in that framework. On his account, the theory of Riemannian manifolds and the equivalence principle define the framework of empirical investigation in which Einstein's field equations are an intellectual and empirical possibility. Friedman is a major interpreter of relativity and his view has provoked a number of critical reactions, nearly all of which miss the mark. I aim to free Friedman's analysis of Einsteinian gravitation from a baggage of misconceptions and to defend the notion that physical theories are stratified. But I, too, am a critic and I criticize Friedman's view on several counts, notably his account of a constitutive principle and that of the principle of equivalence.

1. Introduction

There is an approach to the foundations of the exact sciences that is characterized by a certain kind of critical conceptual analysis. This ought not to be confused with the method of analysing notions from ordinary language, of the sort associated with early twentieth-century "linguist philosophy" and found in certain strains of contemporary analytic philosophy. Rather, the kind of analysis in question – one with a long lineage – is the practice of identifying important features of concepts, and by extension conceptual frameworks, by revealing the presuppositions on which their use depends.[1] In the foundations of physics, this analysis is beholden to the body of theory and practice in which concepts are situated and in which they are interconnected with other concepts, both physical and mathematical. A main objective of such an analysis, therefore, is the identification and explication of these connections. While this kind of critical conceptual analysis has several aspects, one of its aims is to reveal what principles are needed for objects of knowledge to be objects of knowledge; in this regard, it is concerned with conditions of possibility, comprehensibility, and meaning.

This kind of analysis was integral to the logical empiricists' approach to the analysis of scientific knowledge. They held that a satisfactory analysis of a theory in the exact sciences should reveal the different methodological character of that theory's components. And in this way they defended the notion that our theoretical knowledge is stratified. The idea of such a stratification was criticized by Quine, who argued that there is no reason of principle for distinguishing between the components of our theories. Michael Friedman's approach to the analysis of physical theories is part of a tradition that aims to rehabilitate this aspect of the logical empiricists' account. He defends the stratification of our theoretical knowledge, arguing that the conceptual structures of Newton's and Einstein's theories of gravitation exhibit just the sort of stratification that Quine rejected. In overview, he draws a distinction between a first level of principles that define a framework of empirical investigation and a second level that are made possible by the former. He argues that the theory of Riemannian manifolds and the equivalence principle constitute the framework of investigation in which Einstein's field equations are an intellectual and empirical possibility.

The view at issue here is not the one Friedman defended in *Foundations of Space-Time Theories* (1983), but the view that is found in several works spanning roughly the past twenty-five years, notably "Philosophical Naturalism," his Presidential Address to the American Philosophical Association (1997), *Dynamics of Reason*, his Kant Lectures at Stanford University (1999), and *Synthetic History Reconsidered* (2010). Friedman's approach is a significant contribution to the foundations of physics and the theory of theories. A number of reactions to it have been gathered in *Discourse on a New Method* (2010) and others can be found. Most of the contributions to this collection pay homage to Friedman. Very little of this work addresses his

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[1] I owe this way of expressing the basic idea of conceptual analysis to Demopoulos (2000, p. 220).

proposal directly. I will consider a number of challenges to Friedman's approach and especially its application to the analysis of Einsteinian gravitation. Some of these challenges have been ruminating in the foundations of physics for years, but have not been properly articulated and defended. Others are implicit in work that is focused on other goals. A few have not been raised at all.

In what follows, I will outline, in §2, Friedman's approach to the analysis of physical theories, followed by its application, in §3, to Einstein's theory of gravitation. In §4, I will develop and reply to several challenges to Friedman's analysis. I will argue that nearly all of these miss the mark. Through the analysis of these challenges, I aim to free Friedman's analysis of Einsteinian gravitation from a baggage of misconceptions. But I, too, am a critic and I criticize Friedman's view on several counts. I challenge his account of a constitutive principle and also that of the principle of equivalence. For all that, I defend the notion that physical theories are stratified, and so defend a position in the vicinity of Friedman's.

2. Friedman's Approach to the Analysis of Theories

It is worth situating Friedman's approach to the analysis of physical theories in a broader tradition in the theory of theories. The theory of theories is that part of the philosophy of science that is concerned with the nature of our theoretical knowledge. It is concerned, in particular, with the epistemic status of the *principles* that empirical theories comprise. It asks the following questions: what is the character of these principles? Are the conceptual frameworks that they generate entirely determined by empirical evidence or do they reflect extra-empirical considerations and stipulations? Do all the principles stand on the same footing or do some have a special status and, if so, what is their status? What is the relation of these conceptual frameworks to the world of experience? These questions arise because we have various empirical theories that are well justified. The theory of theories examines, in short, the *basis* for their justification. Furthermore, by clarifying the structure of theories, the theory of theories aims to improve our understanding of the limits of our knowledge of the world, and we acquire a standpoint from which we can better evaluate claims about reality that are consistent with these theories.

This tradition in the theory of theories has its origin in the work of the logical empiricists, and notably in that of Carnap. Carnap took issue with traditional empiricism's claim that *all* knowledge is based on experience. He saw that logic and certain mathematical theories – the latter even in their applications – are not empirically constrained. For example, the statement "2+2 = 4" is not subject to empirical confirmation or infirmation (Carnap, 1973, §10, p. 64).[2] In this way he sought to show that empiricism holds only for empirical principles and not for logical and (certain) mathematical ones.

This view is encapsulated in the thesis that *certain applied mathematical theories are nonfactual*. Demopoulos (2013, Chapter 2) has called it "Carnap's thesis." Carnap's strategy for establishing the thesis rests on his account of analyticity: he held that any statement that is analytic is as nonfactual as a simple tautology.[3] And certainly on one reading of Carnap's account, analyticity can be understood as truth in virtue of meaning, since what is true in virtue of meaning is not informative, that is, is nonfactual.[4]

However we are to establish the thesis that logic and certain mathematical theories are nonfactual, Carnap and the logical empiricists were concerned with the fundamentally epistemological distinction between these parts of our total body of knowledge. These parts of our knowledge have different criteria of truth. Principles tied to the observable, whether directly or indirectly, are "answerable" to experience, in the sense that they are empirically constrained, and the account of their truth, however understood, follows from that. By contrast, the principles of logic and mathematics are not empirically constrained. Their truth rests on different criteria, and, for Carnap at least, this was understood along the lines of Hilbert's proposal that the truth of the axioms of a mathematical theory amounts to nothing more than their consistency.

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[2] Carnap was of course well aware that mathematical theories such as geometrical theories – in their applications – have factual content, whereas arithmetic – in its application – does not. He was not concerned, therefore, to distinguish *pure* from *applied* mathematical theories, but rather *applied arithmetic* from *applied geometry*.

[3] Founding analyticity on tautology is, evidently, a Wittgensteinian move: if a sentence expresses a genuine proposition, i.e., is informative, then it partitions states of affairs into those that obtain and those that fail to obtain. Tautologies and contradictions do not effect such a partition. Therefore, tautologies and contradictions are not genuine propositions.

[4] Other explications of analyticity include truth in virtue of definition or truth in virtue of convention. Carnap himself referenced Wittgenstein's *Tractatus* in his account of analyticity, and for this reason Demopoulos (2013) referred to this strategy for establishing the nonfactuality of certain mathematical theories as the "Tractarian strategy." But Demopoulos proposes another strategy for establishing Carnap's thesis that he calls the "Einsteinian strategy." This strategy has no precedent in Carnap's writing and it turns on Frege's notion of a criterion of identity.

The analytic-synthetic distinction, though originally drawn in general theory of knowledge, as part of a critique of traditional empiricism, was held by Carnap to be indispensable to the analysis of science. He held that the analysis of the language of science should distinguish between the principles comprising an empirical theory according to their criteria of truth, and in the same measure show how they are integrated into a whole.

The analytic-synthetic distinction was criticized by W. V. Quine, notably in "Two Dogmas of Empiricism" (1951) and "Carnap and Logical Truth" (1960). Quine represented scientific knowledge as a web of belief in which no satisfactory analytic-synthetic distinction can be drawn. In the absence of a suitably broad notion of analyticity, no statements deserve to be singled out as being true in virtue of their meanings or as having any other measure of necessity, apriority or epistemic security. Quine acknowledged that certain stipulations like definitions are undoubtedly analytic, but that we can have no assurance that the principles of mathematics are epistemologically distinguished from physical principles just because they have been stipulated to be analytic. The arbitrariness that attaches to any such stipulation led him to reject the analytic-synthetic distinction. For Quine, all that remains of analytic truth is the centrality of certain statements to the web of belief.

This view, while motivated by a particular understanding of Carnap's and the logical empiricists' approaches to the analysis of theories, led Quine to the far more general view that no distinctions of kind can be drawn among the statements comprising our web of belief. There is no distinction of kind between mathematical and physical principles, and no distinction between these principles and philosophical principles. These principles are all just various strands in the web of belief. Quine called this view "naturalism."

From the view that there are no distinctions of kind between the strands of the web of belief, Quine was led to sketch both an alternative theory of knowledge and an alternative account of theories in the final section of "Two Dogmas." This sketch rests on two main ideas. The first is that theories are integrated wholes that are confirmed or infirmed as wholes. This is an appropriation and extension of Duhem's (1962) observation about physical theories. The second is the idea that in the event that the conclusion of a derivation conflicts with experience, there is nothing that prevents us from revising the principles, even the logical and mathematical ones, that figured in the derivation. From this, it follows that all principles in the web of belief have to some extent an empirical aspect.[5] As we will see, Friedman takes a stance with respect to both of these ideas in his analysis of Einsteinian gravitation.

Now Quine's criticism of the analytic-synthetic distinction was problematic from the start, and many criticisms of it have been raised. There is the classic criticism that Quine's view amounts to scepticism about meaning (Grice and Strawson, 1956). It is also questionable whether Quine ever understood Carnap's thesis, which is concerned with a methodological distinction, as a claim that is detachable from some form of conventionalism (Demopoulos, 2013, p. 32, n. 6). The most significant criticism is that Quine's critique and his sketch of an alternative epistemology fail to draw the factual-nonfactual distinction (Demopoulos, 2013, pp. 43-5). I will elaborate on this further on, and with particular regard to Friedman's account. But whatever one's view of the success of Quine's account, it remains that many, if not most, post-positivist philosophers sided with him.

Friedman's view (e.g., 1997, 2001, 2010) is set against Quine's naturalism and his account of the structure of theories that follows from it. Friedman sees in the conceptual structures of Newtonian and Einsteinian gravitation a clear basis for correcting Quine. These theories show that there are differences between the components of our frameworks of physical knowledge, and furthermore that these components are stratified. To anticipate what is to come, Friedman replaces the analytic-synthetic distinction with a distinction between what he calls "constitutive principles" and "properly empirical claims." I will give a brief overview of this account of theories.

On Friedman's account, the analysis of physical knowledge has three levels of enquiry. The *first level* is comprised of constitutive principles that are epistemologically distinguished by the fact that they define a space of intellectual and empirical possibilities, and so determine a framework of investigation. They articulate a framework of theoretical concepts and their physical interpretations. Of these principles, Friedman calls "mathematical principles" those that define a space of mathematical possibilities and that allow certain kinds of physical theories to be developed. They supply a formal background or language that makes it possible to articulate a theory's basic concepts and that makes particular kinds of applications possible. We find, for

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[5] And, as is well known, Quine held that in theory development we are free to "posit" whatever we will, and that a theory's success will be judged strictly on the basis of its expediency.

example, the calculus, linear algebra, and Riemann's theory of manifolds. But there are other constitutive principles that have a more complex character: these "coordinating principles" interpret the concepts that are necessary for physics as we understand it. They express mathematically formulated criteria by which concepts such as force, mass, motion, electric field, magnetic field, space, and time may be applied. In this way the coordinating principles define and articulate our epistemic relation with the world, they fix an interpretation of the world; the mathematical principles, as part of the formal background or language, are auxiliaries or prerequisites to this.[6] Consider what is perhaps the simplest example of a coordinating principle, namely the principle of free mobility that controls the application of Euclidean geometry. This is the principle according to which rigid body may undergo arbitrary continuous motions without change of shape or dimension. Euclidean geometry, which can of course be understood uniquely as an abstract axiomatic system, becomes a theory of physical geometry when it is supplemented with the principle of free mobility, which underlies our ability to perform the Euclidean constructions.

The *second level* is comprised of empirical hypotheses that are formulable within the framework constituted by the first-level principles. For example, in his analysis of Newtonian gravitation, Friedman identifies Euclidean geometry, the calculus, and the laws of motion as constitutive principles of the framework of empirical investigation in which Newton's deduction of the law of universal gravitation, an empirical hypothesis, from the phenomena is an intellectual and empirical possibility.

Friedman also identifies a *third level* comprised of distinctly philosophical or meta-theoretical principles that underlie and motivate discussions of the framework-defining principles, and so the transition from one theory to another. In fact, we find running through Friedman's work a thesis about the nature of revolutionary theory change that I have called "Friedman's thesis"; see Samaroo (2015) for an examination.

With this account, Friedman's principal goal is to restore a proper understanding of the stratification of our conceptual frameworks in physics. His account stands in sharp contrast with Quine's "naturalism" and his related account of theories, according to which there are no

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[6] See Samaroo (2015, p. 130) for further details on the notion of a coordinating principle, with reference to the contributions of Reichenbach and Carnap.

differences of methodological principle between the strands comprising the web of belief. This, for Friedman, is the true failure of Quine’s account.

3. Friedman’s Analysis of Einsteinian Gravitation

Friedman brings this approach to the analysis of physical theories to bear on Einsteinian gravitation. He regards Riemann’s theory of manifolds and the equivalence principle as constitutive presuppositions of Einstein’s field equations, a properly empirical hypothesis. The former define the framework of empirical investigation in which the latter are an intellectual and empirical possibility. We find this view, for example, in *Dynamics of Reason* (2001):

> [T]he three advances together comprising Einstein’s revolutionary theory should not be viewed as symmetrically functioning elements of a larger conjunction: the first two [Riemann’s theory of manifolds and the equivalence principle] function rather as necessary parts of the language or conceptual framework within which the third [the field equations] makes both mathematical and empirical sense. (Friedman, 2001, p. 39)

To defend these claims, Friedman (2001, 2010) recalls Einstein’s argument from the special theory of relativity to the theory of gravitation, stressing the constitutive function of Riemann’s theory and the equivalence principle. This account is as follows.

Having shown, in 1905, that simultaneity is not absolute but relative, and having derived the Lorentz transformations from a criterion involving emitted and reflected light signals, Einstein realized that his special theory of relativity clashed with Newtonian gravitation: the latter’s hypothesis that there is an instantaneous action-at-a-distance between every body in the universe is incompatible with the postulate that nothing propagates faster than the speed of light. He realized that a new theory of gravitation was needed to remove the conflict.

The new theory had its origin in Einstein’s insight of 1907 into the nature of gravitation. This is the insight, roughly speaking, that bodies in free fall do not “feel” their own weight. Einstein formalized this insight in the principle that we now know as “the equivalence principle.” This principle motivates a critical analysis of the inertial frame concept peculiar to special relativity, which we might call “the 1905 inertial frame concept.” The inertial frame in question is a frame in uniform rectilinear motion (with respect to neighbouring matter) in which the outcomes of all mechanical and electrodynamical experiments are the same.[7]

There are several versions of the equivalence principle. Some are formulated in the context of theory development, others in the context of the completed gravitation theory and exploiting its expressive resources. My focus will be solely on those versions formulated in the context of theory development. Among these, there is a further distinction to be drawn between "gravity-producing" versions of the principle, on the one hand, and "transforming-away" versions, on the other. Both of these can be found in Einstein's own accounts of his theory and its development.[8]

The gravity-producing version is the claim that it is impossible to distinguish between a homogeneous gravitational field and a uniformly accelerated frame. Einstein preferred the gravity-producing version, since true gravitational fields cannot be "transformed away" by free fall. But it is the transforming-away version that is ultimately more important. The transforming-away version, which is an interpretive extrapolation from the principle of the universality of free fall, is the hypothesis that the outcomes of all local non-gravitational experiments are the same as would be obtained in a locally freely falling frame. (Hereafter when I refer to "the equivalence principle" it is to this principle that I am referring.) And what it establishes is that a freely falling frame is locally indistinguishable from a 1905 inertial frame.

We might call the new inertial frame concept that emerges from this analysis "the 1907 inertial frame concept." It is in several respects the cornerstone of Einstein's theory of gravitation. Therefore, the equivalence principle motivates a new inertial frame concept and, with it, a new framework of empirical investigation, one in which the Newtonian and special-relativistic distinction between inertial and non-inertial frames is replaced with a distinction between freely falling and non-freely falling frames. In this framework, Einstein could explore

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[7] As would be discovered later in the twentieth century, this is true not only of mechanical and electrodynamical experiments but of all non-gravitational experiments.

[8] Versions of the gravity-producing principle can be found in Einstein's "On the Relativity Principle and the Conclusions Drawn from It" (1907, p. 454), "On the Influence of Gravitation on the Propagation of Light" (1911, pp. 898-99), and in the review article "The Foundation of the General Theory of Relativity" (1916, pp. 772-3). He expressed it as a transforming-away principle in his Princeton Lectures (1922, pp. 67-8). For further details on Einstein's understanding of the equivalence principle, see Norton (1985).

the significance of freely falling trajectories. For all these reasons, Friedman claims that the equivalence principle is a constitutive principle:

> Einstein's field equations describe the variations in curvature of space-time geometry as a function of the distribution of mass and energy. Such a variably curved space-time structure would have no empirical meaning or application, however, if we had not first singled out some empirically given phenomena as counterparts of its fundamental geometrical notions – here the notion of geodesic or straightest possible path. The principle of equivalence does precisely this, however, and without this principle the intricate space-time geometry described by Einstein's field equations would not even be empirically false, but rather an empty mathematical formalism with no empirical application at all. (Friedman, 2001, pp. 38-9)

With the 1907 inertial frame concept established, it is worth recalling how Einstein interpreted it in such a way as to make it the basis for his geometrical account of gravitation. The special theory presupposes the mathematical framework of an affine space equipped with a Minkowski metric, and the trajectories of inertially moving particles and light rays are geodesics with respect to that metric. In the special-relativistic framework, gravity is a force that pulls bodies off their rectilinear trajectories. But Einstein had the insight that free fall trajectories might be represented by the geodesics of a variably-curved geometry, one determined by the distribution of mass-energy in the universe. This is encapsulated in the geodesic principle, according to which free, massive test-particles traverse time-like geodesics.[9] There were a number of heuristics – all of which falling short of what they needed to establish – that led Einstein to this insight, though Einstein claimed that the "rotating disks" thought experiment was influential.

With the notion that a non-Euclidean and moreover variably-curved geometry might be used to represent the trajectories of freely falling bodies, Einstein turned to his friend Marcel Grossmann for assistance. Grossmann introduced Einstein to Riemann's theory of manifolds, which provided the mathematical framework in which the insight summarized in the geodesic principle might be expressed. For this reason, Friedman claims that Riemann's theory of manifolds is a constitutive presupposition of the metrical conception of gravitation that the equivalence principle motivates:

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[9] It is important to note that in this context – the context of theory development – the "geodesic principle" refers to Einstein's insight that the trajectories of freely-falling particles might be reinterpreted as geodesics in some yet-to-be-developed theory. But, in the context of the completed gravitation theory, there are derivations of the geodesic principle from the field equations.

> Without the Riemannian theory of manifolds … the space-time structure of general relativity is not even logically possible, and so, a fortiori, it is empirically impossible as well. (Friedman, 2001, p. 84)

Together, Friedman claims, Riemann's theory of manifolds and the equivalence principle, are constitutive of the framework of empirical investigation in which Einstein's field equations, a properly empirical hypothesis, are an intellectual and empirical possibility. With these two constitutive principles, we gain a conceptual framework in which it is conceivable that a yet-unknown source-term representing a mass-energy distribution could be related to a yet-unknown geometric object representing chronogeometry.

With this account, Friedman aims to show that, far from there being no distinctions of kind between the components of a framework, the distinctions are in fact significant. Friedman also aims to show that the Quinean notion that any component of a theoretical framework can be revised is baseless – in the case of Einsteinian gravitation, the theory of Riemannian manifolds and the equivalence principle are conditions without which the field equations are not even conceivable.

4. Challenges and Replies

In what follows, I will develop several challenges to Friedman's program. Some of these have been ruminating in the foundations of physics for years, others are raised implicitly in work with other goals, and some have not been raised at all. None of them have been considered carefully in connection with Friedman's view.

4.1 Many ways to parse a theory

It has been suggested that there are many ways to "parse" a theory, and therefore if what is constitutive is relative to a particular parsing, then Friedman's distinction between first-level and second-level principles is arbitrary. By "parsing," it seems to be meant that there are many ways to formulate a theory or to resolve it into its component parts. This view can be found in the work of Don Howard (2004, 2010).

Howard (2010, p. 349) suggests that we might look to the reconstruction of Einsteinian gravitation due to Ehlers, Pirani, and Schild (1972). On the EPS reconstruction – itself an elaboration of the sketch of Weyl (1918, 1921) – the paths of free particles and light rays are taken as primitive. They define, respectively, projective and conformal structures, and these determine the theory's Lorentzian geometry (up to a scale factor). Howard appeals to the EPS reconstruction to show that there are ways of formulating Einstein's theory that do not appeal to the equivalence principle, and therefore the equivalence principle cannot be said to be constitutive.

While it is true that there are various ways to formulate a theory or resolve it into its component parts, this challenge is based on a misunderstanding of Friedman's view. Friedman aims to identify those principles that make the field equations an intellectual and empirical possibility, and the principles in question reside in the *context of theory development*. He is concerned with the principles that define the framework of empirical investigation in which a relation such as that expressed in the field equations is conceivable. So, to return to Howard's example, the EPS approach does not define the framework of empirical investigation – it resides in the *context of the completed gravitation theory*. It is a reconstruction that is possible only once we have the completed theory in hand. In this respect, therefore, Friedman's distinction between first-level and second-level principles is not arbitrary, though it is problematic in other respects.

4.2 The equivalence principle is unnecessary for developing the field equations

The second set of challenges is intended to show that the equivalence principle is unnecessary for the field equations to be an intellectual and empirical possibility, and therefore that it cannot be regarded as a constitutive principle. The challenges rest on the following counterfactual: if Einstein had not developed his field equations in 1915, particle physicists would have 20 years later and without the help of the equivalence principle.

The conjecture rests on the work of numerous twentieth-century and also contemporary particle physicists, who appeal to the massless spin-2, and to a lesser extent the massive spin-0 and spin-2, theories of gravity.[10] These theories assume the framework of relativistic field theory and a graviton field, and from these and other assumptions versions and relatives of Einstein's field equations can be recovered. Massless spin-2 gravity recovers Einstein's field equations in their source-free linearized form. The equivalence principle is satisfied; it becomes a theorem, a consequence or feature of the field equations, rather than a foundational principle. The theory

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[10] See Pitts (2016a, 2016b, 2018) for a list of the original research papers.

might not be a rival to Einstein's theory itself, but Einstein's theory with some additional assumptions. The massive spin-0 theory gives a single equation which is not part of, or logically compatible, with Einstein's equations. The equivalence principle is violated. Furthermore, the theory does not "bend light," so it has been empirically refuted since 1919. It could not be intended as a rival to Einstein's theory in its own right. The massive spin-2 equations are all different from Einstein's equations, albeit in subtle ways. Here, too, the equivalence principle is violated.[11]

These theories suggest two main challenges to Friedman's analysis. The first and most trenchant is implicit in the particle physics approaches to gravitation theory and in the work of Pitts (2016a, 2016b, 2018). This is the view that the equivalence principle is eliminable, and therefore unnecessary for the development of Einsteinian gravitation.

There are two objections to this "eliminativist" view. First, among the alternative theories, only the massless spin-2 theory recovers precisely Einstein's equations, and then only in their source-free linearized form. Second, the equivalence principle is, so far as tests reveal, exceptionless. Therefore, the massive spin-0 and spin-2 theories must, at a minimum, bring something to our understanding of gravitation that outweighs the cost. It is also worth noting that, although it is true that there are multiple paths to (at most) versions and relatives of Einstein's equations, there is a feature of gravitation – the identity of freely falling frames and Lorentz frames – that the equivalence principle singles out. This feature is integral to our understanding of gravitation and the principle not only singles it out but ties it to a number of other concepts. For these reasons, the alternative theories of gravity can hardly be said to support a successful eliminativist account since none of them allow us to recover the full Einstein field equations, which are founded on the principle.

In another challenge directed explicitly at Friedman's account, Pitts (2018, Section 3) argues that the equivalence principle is not a constitutive principle, in the sense that it is unnecessary for coordinating the empirical content of Einsteinian gravitation with the field equations. He claims that, while the equivalence principle can fulfil this coordinating role, the

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[11] In these theories, immersion in a homogeneous gravitational field and uniform acceleration are not identical in their effects. The difference between gravitational effects and inertial effects is observable only in experiments sensitive to the graviton mass term in the gravitational field equation, that is, only if one looks carefully enough to observe the influence of the mass term on inertial effects. See Pitts (2016b, p. 82) for details.

principle is unnecessarily strong and some weaker coordinating principle suffices. Pitts bases this view about *Einstein's theory* on the fact that a *massive spin-2 theory* is expected to have nearly the same empirical content as Einstein's theory (when the graviton mass term is sufficiently small).

Pitts' reasoning seems to run as follows: since the equivalence principle is false in massive spin-2 theories, it cannot play a coordinating role. What, then, effects the coordination? Pitts (2018, p. 151) writes: "The coordination gets done … not by Friedman's principle of equivalence … Rather, it is done by the field equations …"[12] Pitts holds that the field equations "themselves" effect the coordination and not an "additional principle" (Pitts, 2018, p. 151). From this view of the coordination of a spin-2 theory with its empirical correlates, Pitts concludes that, similarly, the empirical content of Einstein's field equations resides in the equations themselves. Therefore, the equivalence principle is not a (coordinating) constitutive principle.

There are several objections to this line of argument. First, it is an odd to argue that Einstein's theory does not need the equivalence principle as a coordinating principle on the basis of claims about massive spin-2 theories, even if they are found to have nearly the same empirical content in the appropriate limit. The theories in question, though perhaps matching in the appropriate limit, have very different corresponding physical interpretations. Second, even if the geometrical interpretation that we associate with Einstein's theory has no place in a massive spin-2 theory, the latter still needs some principles to coordinate the basic theoretical concepts that figure in the equations with their empirical correlates. Third, as I will argue in further detail below, it is not the equivalence principle at all that coordinates the empirical content of Einstein's theory with its basic geometrical notions: it is the geodesic principle that does that. The equivalence principle and the geodesic principle are separate components of the framework of gravitation theory.

4.3 Only coordinating principles are constitutive

The following challenge is defended in Samaroo (2015). In this and the next section, I develop and refine a few main points.

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[12] In this, he echoes the remarks of Freund, Maheshwari, and Schonberg (1969, p. 861-2) on their massive spin-2 theory.

I have argued that Friedman's account of a constitutive principle is too broad, and that only coordinating principles should be regarded as constitutive. Friedman's inclusion of both mathematical principles and coordinating principles in the category of constitutive principles is intended to counter Quine's contention that the mathematics involved in formulating a theory is just another strand in the web of belief. Friedman argues that this view of the role of mathematics in physics fails to account for the way in which mathematics makes certain kinds of physical theories intellectual possibilities; it also fails to account for the way in which mathematics provides some of the concepts required for formulating a theory and for deriving predictions. I agree with Friedman about this, but there are good reasons for regarding only coordinating principles as constitutive.

The first is that including mathematical principles in a theory's constitutive component opens the notion of a constitutive principle to trivialization. One might argue that what is constitutive is *relative* to some particular formulation of a theory, and since what is constitutive in one formulation is not constitutive in another, the notion of a constitutive principle is undermined. By taking only coordinating principles as constitutive, we can agree about the principles that interpret the basic theoretical concepts of a given theory, even if that theory admits of an alternative formulation. Consider Newtonian mechanics. The theory admits of various formulations, some of which, e.g., those peculiar to analytic mechanics, rest on radically different mathematical frameworks from the one that Newton presupposed. But however the theory is formulated, Newtonian mechanics is the theory whose basic structure is constituted by the laws of motion. (I will consider the situation in Einsteinian gravitation at the end of this section.)

The second reason is that including mathematical principles in a theory's constitutive component lends support to a main feature of Quine's account of theories, namely "confirmational holism." A Quinean might argue that if the mathematics involved in the formulation of a theory is included in its constitutive component, then the mathematics is confirmed or infirmed along with the rest of the theory. Friedman argues against Quine that constitutive principles are not confirmed in the same way as the empirical hypotheses whose formulation they permit: they are principles without which empirical hypotheses would make neither mathematical nor empirical sense, and without which no test would be possible.[13] The principles that truly establish Friedman's argument against Quine, however, are not the mathematical principles, which, on their own, are subject to neither empirical confirmation nor infirmation, but the coordinating principles that interpret theoretical concepts and control the application of the mathematics. Therefore, distinguishing the mathematical principles from the coordinating principles strengthens the case against Quine.

The third is that including both mathematical principles and coordinating principles in the category a theory's constitutive principles does not draw the distinction that should be drawn between the theory's *factual* and *nonfactual* components, between those components of our theories that are and are not empirically constrained. Taking only coordinating principles to be constitutive allows us to distinguish clearly between those principles that define and articulate our epistemic relation with the world and those that are formal auxiliaries to that. My proposed limitation to the account of a constitutive principle is in no way intended to diminish the role of mathematical principles in the articulation and application of physical theories, nor is it to suggest that they are unnecessary, only to clarify that mathematical and coordinating principles have different criteria of truth. My proposal benefits the account of the stratification of theoretical knowledge and allows for a still stronger criticism of Quine's account to be given.[14]

Now, in reply to these three lines of criticism, one might argue for another account of the stratification of physical theories, for example, Darrigol's "modular" account (2014 and forthcoming). Darrigol develops a new account of the relativized a priori, one founded not on constitutive principles but on "comprehensibility conditions." He claims that this account resolves some of the difficulties with Friedman's account, and that it offers a more natural and nuanced account of the application, development, and comparison of theories in a given domain. Darrigol's modular account is intricate and a proper exposition is beyond the scope of this article; see his (forthcoming) for a detailed presentation and for a comparison with Friedman's account. But Darrigol's account, like Friedman's, restores the idea that our frameworks of

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[13] Schematically, the argument is as follows: if Quine's account of theories is successful, then any component, whether mathematical, coordinating or properly empirical, of our total theory is revisable. Some components of our total theory are not revisable in the way Quine would have it because they have a constitutive function. Therefore, Quine's account of theories is unsuccessful.

[14] In several respects, I am arguing for an account of a constitutive principle that is closer to Reichenbach's (1928) account of a coordinative definition, though without any commitment to his view that coordinative definitions are arbitrary.

physical knowledge are stratified. In this regard, it certainly is a counter to Quine's account of theories, but it also does not, any more than Friedman's, distinguish between a theory's *factual* and *nonfactual* components. Neither nonfactuality nor relative apriority are properties Darrigol aims to distinguish.

4.4 The equivalence principle and Riemann's theory are not constitutive

Having considered the case for regarding only coordinating principles as constitutive, let us turn to Friedman's accounts of the equivalence principle and Riemann's theory of manifolds. Is the equivalence principle a (coordinating) constitutive principle? Is it a necessary condition for the field equations to be an intellectual and empirical possibility? Does it coordinate the theory's basic physical notions with geometric notions? While the equivalence principle expands our space of intellectual and empirical possibilities – it motivates a new concept: the 1907 inertial frame concept – what should be clear from the above account, in Section 3, is that the equivalence principle lacks the *interpretive* function of a coordinating principle. It is an *empirical hypothesis* – at once an inductive generalization from a set of empirical facts and an interpretive extrapolation from them – and it motivates a new constitutive principle: the geodesic principle. The geodesic principle constitutes or interprets the 1907 inertial frame concept by expressing a criterion for its application: if a test-particle falls freely without rotation, then it moves on a geodesic; if not, its motion deviates from a geodesic, in a way that a yet-to-be-developed theory might measure. The principle coordinates a theoretical concept, the 1907 inertial frame, with a geometric notion, a geodesic. The geodesic principle provides a basis for treating the relative accelerations of freely falling particles as a measure of curvature; in this way, it forms the basis for thinking about gravitation as a metrical phenomenon. It defines a new framework of empirical investigation, one that raises the question to which Einstein's field equations are the answer.[15]

It is worth noting that the equivalence principle and the geodesic principle are separate principles. Of course, in the context of the completed theory of gravitation, the principles are closely related. There is a version of the equivalence principle, due to Anderson (1967) and Ehlers (1973), according to which all non-gravitational experiments serve (approximately) to

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[15] The foregoing is a critical analysis of Friedman's account of the equivalence principle. In other work (Samaroo, forthcoming), I have offered a new account of the principle's methodological role. I have argued that it functions as a criterion of identity for freely falling frames and Lorentz frames.

determine the same affine connection in a sufficiently local region of space-time. The affine connection figures in the geodesic equation, and in this way there is an direct relation between the equivalence principle and geodesics. There is also a derivation of the geodesic equation from the equivalence principle; see Weinberg (1972, Chapter 3, Section 2). But Friedman's constitutive principles are found within the context of theory development, so no appeal to these results can yet be made and the equivalence and geodesic principles must be treated as separate parts of the conceptual framework of gravitation theory.

What of Friedman's claim that the theory of Riemannian manifolds is a constitutive presupposition of Einstein's reinterpretation of inertial trajectories as geodesics? The theory of Riemannian spaces is evidently not constitutive in the narrower sense I am defending: it is part of the formal background that made it possible for Einstein to realize his insight that is summarized in the geodesic principle. Some coordinating principle is needed to apply the theory, specifically, the theory of *pseudo*-Riemannian spaces. But is the theory constitutive even on Friedman's account? Friedman emphasizes that a key step in Einstein chain of reasoning was taking spaces of variable curvature to be intellectual and empirical possibilities. But we might distinguish between two things: the transition from the conceptual framework of homogeneous spaces to that of variably-curved spaces; the transition from the conceptual framework of variably-curved spaces to the mathematical framework of pseudo-Riemannian spaces, which can be regarded as a realization of the former.[16] Both transitions are prerequisites for the development of Einsteinian gravitation, but it is the first transition that seems to be constitutive in Friedman's sense.

To my view that the geodesic principle and not the equivalence principle should be regarded as constitutive, some, e.g., Brown (2005, p. 141 and pp. 161-2 and personal communication), have objected that "it is not simply *in the nature* of force-free bodies to move in a fashion consistent with the geodesic principle," and so the geodesic principle has such limited validity that it could hardly fulfil the (coordinating) constitutive function I attribute to it. This claim is based on the fact that tidal forces act on the constituents of freely falling bodies causing them to spin, and so to deviate from geodesic trajectories.

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[16] What is at issue here is the conceptual framework of homogeneous spaces that is picked out by the principle of free mobility. This framework for thinking about physical space was a stumbling block to Poincaré, who, it is conjectured, might otherwise have taken some of the same steps as Einstein towards the gravitation theory.

The geodesic behaviour of free particles is evidently an ideal. But this does not mean that, in the limit in which tidal forces are zero, free test-particles do not exhibit geodesic behaviour. The geodesic principle expresses this ideal which in fact is essential: it is the basis for measuring geodesic deviation (in terms of components of expansion, rotation, and shear), and through this, the basis for learning about the sources of the gravitational field. In Einstein's theory this can be measured.

To my view that only coordinating principles should be regarded as constitutive, one might also object that there is no *unique* way of identifying a given theory's coordinating principles. That is, there is no canonical set. And, if this is so, then one might say that constitutive principles lack a measure of necessity that one would want to attribute to them. The principles do not succeed as conditions of the possibility of the empirical meaning of the field equations.[17]

It is certainly true that there are differences in the accounts of the principles that coordinate the Lorentzian metric to physical events and processes. For example, Malament (2012, pp. 120-1) presents a set of three coordinating principles, which he supplements further on with another involving clocks, and still further on with others involving generic matter fields; Schutz (1985, pp. 182-4) presents another set. Malament's minimal set makes use of only point-particles and light rays; Schutz's employs rods and clocks.

The fact that there are various possible coordinations of the basic physical and geometrical notions should not surprise us, but for this reason it might be said that there is no unique set of coordinating principles. But this would be to overlook what is common to the various coordinations found in relativity texts, namely the geodesic principles for point-particles and light rays. Whatever the differences we find between coordinations, these principles at least are necessary for giving empirical significance to the Lorentzian metric. In this way, therefore, we find something close to the desired uniqueness claim.

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[17] I thank two audience members in Bern for raising this objection.

5. Significance

Where does the foregoing leave us? Quine reduced analyticity and apriority to the centrality of certain statements to the web of belief. Friedman dispenses with analyticity and retains the a priori in a relativized form: constitutive principles are relativized to particular contexts of enquiry, e.g., the Newtonian and Einsteinian ones, but they determine frameworks of empirical investigation and are in this sense "prior" to the empirical hypotheses whose formulation they permit. But in spite of Friedman's work to restore the idea that conceptual frameworks of physics are stratified, his inclusion of mathematical principles in the category of constitutive principles is a step in the direction of Quine's centrality – it undermines the application of the factual-nonfactual distinction to different components of our conceptual frameworks.

I have argued that those principles that define and interpret basic theoretical concepts should be distinguished from the formal prerequisites or auxiliaries that the principles presuppose, and all of these principles and prerequisites, which together constitute frameworks of empirical investigation, should be distinguished from the empirical hypotheses whose formulation they permit. This allows us to better recognize the salient differences in methodological character. In particular, separating mathematical auxiliaries, on the one hand, from coordinating principles and empirical hypotheses, on the other, allows us to distinguish the *factual* from the *nonfactual* components of our theoretical frameworks.[18]

Setting aside these challenges to Friedman's approach to the analysis of theories, my analysis also clarifies several things specifically related to the foundations of Einsteinian gravitation. For one thing, the role of the equivalence principle has been examined. Although there are approaches to relatives and variants of Einstein's field equations that do not appeal to the equivalence principle, the "eliminativist" view, implicit in the work of the particle physics tradition and in the work of Pitts, does not succeed. Furthermore, Pitts' (2018) suggestion that the equivalence principle is not a constitutive principle – in the sense that it is unnecessary for coordinating geometric notions with their empirical correlates – is problematic in several respects. In a final line of argument, I presented and developed the view originally defended in

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[18] For an altogether different account of the factual-nonfactual distinction that is independent of the notion of centrality, and also of the notion of a constitutive principle, see Demopoulos (2013, Chapter 2) and Samaroo (forthcoming). This account turns on the notion of a criterion of identity and considers its employment in the foundations of space-time theories.

Samaroo (2015). I argued that while the equivalence principle motivates the 1907 inertial frame concept, it is the geodesic principle that constitutes this concept by expressing a criterion for its application. This is the principle that allows us to conceive of gravitation as geometrical phenomenon, and that defines the framework of empirical investigation that permits the formulation of Einstein's field equations.

Far from offering an unqualified defence of Friedman's program or his analysis of Einsteinian gravitation, I have argued that we should critically engage Friedman, but carefully and with criticisms that attain the mark. What my view unequivocally shares with Friedman's is its defence of a stratification of our conceptual framework in physics. Like Friedman, I have defended the importance of identifying the epistemological distinctions between parts of our conceptual frameworks and clarifying their criteria of truth and their functions. And though I can envisage further disagreement about my particular approach to stratification and my replies to the challenges, I hope at least to have freed Friedman's analysis from some of the misconceptions that beset it, and in this way to have strengthened the case against Quine.

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