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# Friedman's Thesis

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## Abstract

This essay examines Friedman's recent approach to the analysis of physical theories. Friedman argues against Quine that the identification of certain principles as 'constitutive' is essential to a satisfactory methodological analysis of physics. I explicate Friedman's characterization of a constitutive principle, and I evaluate his account of the constitutive principles that Newtonian and Einsteinian gravitation presuppose for their formulation. I argue that something close to Friedman's thesis is defensible.

## *1. Introduction*

In 'Two Dogmas of Empiricism' (1951), 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 propositions 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 propositions of mathematics are epistemologically distinguished from physical propositions 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.[1]

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[1] Demopoulos (2013) proposes a way of establishing some of the principal conclusions that Carnap based on the analytic-synthetic distinction and that he defended in his long-standing controversy with Quine. It is significant that this proposal does not trade on the notions of truth in virtue of meaning, convention, or stipulation.

This view, while motivated by a particular understanding of the logical empiricists' approach to the analysis of theories, led Quine to the far more general view that no distinctions of kind can be drawn among the propositions comprising our web of belief. There is no distinction of kind between mathematical and physical propositions, and no distinction between these propositions and philosophical propositions. Philosophy is not a form of meta-theoretical, transcendental or critical conceptual analysis, as has long been maintained. Rather, philosophy is itself a part of scientific enquiry. Quine called this view 'naturalism'.

Friedman's view is set against this naturalism. Friedman sees in the conceptual structures of Newtonian and Einsteinian gravitation a clear basis for correcting Quine. He defends the idea that conceptual frameworks in physics are stratified, and he argues that, among the different kinds of principles they comprise, there are certain principles—'constitutive principles'—whose identification is indispensable to a satisfactory methodological analysis. Friedman's proposal culminates in the thesis that I call *Friedman's thesis*: Revolutionary theory change proceeds by deliberate philosophical reflection on constitutive principles.[2] My goal in this essay is to explicate and evaluate Friedman's thesis.

I will begin by presenting Friedman's approach to the methodological analysis of physical theories. I will then examine his characterization of a constitutive principle and his account of the constitutive principles that Newtonian and Einsteinian gravitation presuppose for their formulation. In a final section I will examine Friedman's account of the mechanism of theory change, and I will argue that, while his account of this mechanism represents a significant advance over Kuhn's and Carnap's accounts, it is reminiscent of conventionalism. I hope to show nonetheless that something *close* to Friedman's thesis is defensible and that my criticisms do not undermine his correction of Quine. This analysis builds on work by Robert DiSalle (2002; 2010), William Demopoulos (2013), and others. But I will develop a line of criticism that has not yet been explored.

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[2] The most detailed statements of the thesis in question are found in *Dynamics of Reason* (2001) and 'Synthetic History Reconsidered' (2010a), but it has also been developed in 'Philosophical Naturalism' (1997), 'Transcendental Philosophy and A Priori Knowledge' (2000), 'Carnap and Quine: Twentieth-century echoes of Kant and Hume' (2006), 'Coordination, Constitution, and Convention: The Evolution of the A Priori in Logical Empiricism' (2007), 'Einstein, Kant, and the Relativized A Priori' (2009), 'A Post-Kuhnian Approach to the History and Philosophy of Science' (2010b), and 'Extending the Dynamics of Reason' (2011).

## *2. Friedman on the structure of physical theories*

Friedman defends an account of the structure of theories and theory change in which there are three levels of enquiry. The *first level* is comprised of 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 network of theoretical concepts and their physical interpretations. The *second level* is comprised of empirical hypotheses that are formulable within that framework. The *third level* is comprised of distinctly philosophical or meta-theoretical principles that motivate discussions of the framework-defining principles and the transition from one theory to another.

The first-level principles—those that determine the framework of investigation—Friedman calls 'constitutive principles'.[3] Among them, Friedman calls 'mathematical principles' those that define a space of mathematical possibilities and that allow certain kinds of physical theories to be constructed. 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, among other examples, 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. The mathematical principles are important, but the coordinating principles control the application of the mathematics, something the mathematics by itself does not do.

The notion of coordination peculiar to Friedman's characterization has its origin in Reichenbach (1920/1965, section V; 1924/1969, §2; 1928/1958, §4). Reichenbach proposed an account of the structure of theories in which he defended a special class of physical principles that he called 'coordinative definitions'. These principles interpret theoretical concepts by associating them with something in the world of experience. To take what is perhaps the simplest

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[3] Friedman's account of a constitutive principle has several aspects, and there is no single quotable passage that does it full justice. The following presentation is based on several passages, but especially Friedman (2001, Lecture II).

example, Euclidean geometry becomes a theory of *physical geometry* by means of two coordinative definitions: The principle ‘light rays may be treated as straight lines’ interprets the Euclidean concept of straightness; the principle ‘practically rigid bodies undergo free motions without change of shape or dimension’ interprets the concept of congruence. Since the possibility of carrying out Euclidean constructions implicitly presupposes the concepts of straightness and congruence, these principles control the application of Euclidean geometry. Because of this interpretive function, Reichenbach regarded coordinative definitions as relativized but nonetheless ‘constitutive a priori principles’ that serve to apply an uninterpreted conceptual framework—the ‘categories’—to the world of experience. Coordinative definitions are not true absolutely—they develop along with physical theory, and so are relativized to particular contexts of enquiry. Reichenbach took it as a sort of Kantian principle that coordination is arbitrary, in the sense that no facts can fail to be accommodated within the framework of a priori principles. But experience can nonetheless show certain combinations of individually reasonable coordinations to be inconsistent.

Carnap (1934/1951, p. 78) initially accepted Reichenbach’s notion of a coordinative definition without modification. But, in subsequent work, he came to regard that notion as an oversimplification. Where Reichenbach understood coordinative definitions to give a direct and complete interpretation of theoretical terms in terms of our observational vocabulary, Carnap held that such principles, which he came to call ‘correspondence rules’, interpret them only indirectly, and so partially and incompletely. In a mathematical theory, a theoretical term like ‘number’ can be interpreted completely in logical terms. But this is not possible in the case of modern physical theories. Given a theory of modern physics, in which one takes as primitive those theoretical terms that figure in a few fundamental laws of great generality, the correspondence rules ‘have no direct relation to the primitive terms of the system but refer to terms introduced by long chains of definitions .... For the more abstract terms, the rules determine only an *indirect interpretation*, which is ... incomplete in a certain sense.’ (1939, p. 65) The same view is found in ‘The Methodological Character of Theoretical Concepts’ (1956) and in *Philosophical Foundations of Physics* (1966).

The oversimplification that Carnap identified in Reichenbach's account is avoided by Friedman's characterization of a coordinating principle. But Friedman's notion of a constitutive principle is broader than both Reichenbach's notion of a coordinative definition and Carnap's notion of a correspondence rule—it encompasses principles that have a coordinating function, like Reichenbach's and Carnap's principles, as well as mathematical principles. What is common to Reichenbach, Carnap, and Friedman is the view that frameworks of physical knowledge are *stratified*. Those principles that are constitutive of the objects of scientific knowledge are not of the same kind as properly empirical hypotheses since they make those hypotheses 'possible'.

This account of the structure of theories stands in sharp contrast with Quine's 'naturalism', according to which no elements of the web of belief have any distinguished epistemological status. Quine regarded set theory—and therefore all of mathematics—as continuous with empirical science. Philosophy, as a chapter of psychology, is part of this continuum. With this naturalism, it is precisely the stratification characteristic of the logical empiricists' approach that is lost. For Friedman, Quine's account of the structure of theories is a failure: It does not recognize that distinguishing constitutive principles from empirical hypotheses is essential to a satisfactory methodological analysis of physics, and it fails to appreciate the role played by constitutive principles in the articulation of basic theoretical concepts. This is what is lost with the replacement of *stratification* with the relative *centrality* of certain propositions in our web of belief. This, for Friedman, is the real divergence between Quine and the logical empiricists, Carnap foremost among them.

What is more, Friedman claims that careful attention to the history of physics shows that revolutionary theory change proceeds by deliberate philosophical reflection on constitutive principles. Friedman offers this proposal as an alternative to Kuhn's characterization of revolutionary theory change as the result of a paradigm shift. The proposal is intended to illuminate revolutionary theory change not only in space-time physics, from which Friedman draws his main examples, but in physics in general.

Friedman's work to restore a proper understanding of the stratification of our frameworks of physical knowledge is a significant contribution to methodology. But his characterization of a theory's constitutive component is problematic for its inclusion of the formal apparatus required for formulating the theory. Friedman's inclusion of mathematical principles is motivated by his view that the role of mathematics in physics is distorted when it is regarded as just another element of our web of belief. It is intended to address the Quinean conceit that, in the case of a derivation where the conclusion conflicts with experience, there is nothing to prevent us from holding on the conclusion by revising the mathematical principles that figured in the derivation. Friedman argues against Quine that such a view of the role of mathematics in physics fails to account for the way in which mathematics makes certain kinds of empirical theories intellectual possibilities. Furthermore, it fails to account for the way in which mathematics supplies some of the concepts required for formulating a theory and for deriving predictions.

I agree with Friedman about this, but, in what follows, I will argue that only coordinating principles should be considered constitutive. This restriction marks a difference between the factual and non-factual components of our theories, between principles that are answerable to the world and those that are not. 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 prerequisites to this. To put this another way, coordinating principles and mathematical principles have different criteria of truth. This is not to diminish the importance of the mathematical principles, but to emphasize that only the coordinating principles are constitutive—in the sense that they interpret theoretical concepts by expressing criteria for their application.

### *3. The constitutive basis of Newtonian gravitation*

Friedman brings this approach to the analysis of physical theories to bear on Newtonian and Einsteinian gravitation. Let us begin with Friedman's analysis of Newtonian gravitation.

Friedman distinguishes constitutive principles, both mathematical and physical, and the framework they determine from empirical hypotheses whose formulation that framework permits. He presents Euclidean geometry, the calculus, and the laws of motion as constitutive presuppositions of the law of universal gravitation, which is a genuine empirical hypothesis (2001, Lecture II; 2009, pp. 253-254; 2010a, pp. 696-729; 2011, pp. 433-434).

Friedman asks us to consider the relation between the law of universal gravitation and the laws of motion. The law of universal gravitation asserts that every object in the universe attracts every other object with a force that is directed along the line intersecting the two objects, and that is proportional to the product of their masses and inversely proportional to the square of the distance between them. The concepts of mass and force to which the law refers, however, are constituted by the second law of motion, a law that itself presupposes a state of inertial motion—an ideal force-free trajectory, one from which a particle can be deflected by the action of some force. And that state of motion, in turn, is constituted by all of the laws. Only when they are taken together do the laws of motion constitute the concepts of force, mass, and inertial motion. These concepts have intuitive, pre-systematic meanings that are independent of the laws; for example, one may speak of a push-force or tension-force. But, while such meanings may suffice for everyday purposes, they provide no basis for recognizing an instance of the concept in an unambiguous and intersubjective manner, and, most importantly, they provide no basis for measuring force. It is the laws of motion that constitute the concepts of force, mass, and inertial motion by expressing criteria for their application. The sense of 'constitutive' at issue is not merely that the laws of motion define the concepts to which they refer but that they interpret them. That is to say, they associate theoretical concepts with empirically measurable correlates.

What is more, the laws of motion are constitutive not only of a particular conception of force, mass, and inertial motion but of a particular conception of space, time, and causality.[4] With the development of geometry in the twentieth century, it was shown that the space-time structure determined by the laws can be treated as a particular kind of four-dimensional affine space, with a specific foliation, and with temporal and spatial metrics having certain properties.[5] But this affine space, taken in itself, is just an instance of a pure geometry of the sort made possible by twentieth-century methods. It is the laws of motion that control its application in physical theory.

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[4] It is noteworthy that, for Kant, the employment of our metaphysical concepts of causal interaction, force, motion, space, and time is inseparable from Newton's laws.

[5] The invariance of the velocity of light is another basis on which to treat space-time as a different kind of space; in this case, an affine space supplemented with a conformal structure.

All three laws of motion taken together therefore are constitutive of the framework that the inverse-square law requires for its formulation: They determine and control the application of the framework of empirical investigation—a framework that allows us to pose questions to be answered by the phenomena of motion, including questions about central forces to which the inverse-square law is an answer. Our ability to pose these questions depends foremost on the conception of causal explanation that is expressed in the framework of the laws. The framework identifies the sorts of changes that are objectively measurable and that are indicative of the action of some cause.

Having addressed the relation between the law of universal gravitation and the laws of motion, Friedman asks us to consider next the relation between the laws of motion and the calculus. The concept of acceleration that figures in the second law is a quantity that requires the notion of instantaneous rate of change: Acceleration is the instantaneous rate of change of velocity, which is itself the instantaneous rate of change of position. The calculus makes it possible to give an account of limiting processes and instantaneous rates of change; in short, a mathematical account of continuity. Friedman claims that the calculus, therefore, is a constitutive presupposition of Newtonian dynamics.

But, contrary to Friedman's view, the calculus should be characterized as part of the formal background or language that makes possible particular applications of Newton's laws and not as part of the theory's constitutive basis.[6] This is not to say that the calculus is not necessary for formulating Newtonian theory. One might say that the account of force in the second law is intelligible without the calculus; for example, one might suggest that force can be understood as the instantaneous result of pulling, pushing or pounding some mass. But it is the calculus that allows us to formulate the notion of a continuously-varying power—to develop the idea, for example, that Keplerian motion might be the manifestation of a yet-undetermined but continuously-varying force.[7] In this respect, the calculus is a necessary presupposition of

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[6] More generally, the calculus is part of the theory's inferential apparatus: It tells us how particular quantities evolve given some initial data.

[7] By way of another example, one could also say that the Galilean composition of motions can be understood without the calculus; for example, the composition of the Earth's annual revolution around the sun and its diurnal rotation. But it is the calculus that allows us to treat arbitrary, continuous orbits as instances of the Galilean composition of motions.

particular applications of the laws of motion, but it is not constitutive. It is part of the non-factual background required for formulating the theory. Further principles are required for its application in physical theory.

For the same reason, Friedman's claim that Euclidean geometry is constitutive should be challenged. For Friedman, as for Kant, Euclidean geometry is a constitutive presupposition of Newtonian gravitation. Newton's own development of his theory presupposes the straightedge-and-compass constructions of Euclidean geometry, which Kant took to reflect our spatio-temporal intuition. But, as I have already noted, the space-time structure of Newton's completed dynamical theory is a particular kind of four-dimensional affine space, with separate spatial and temporal metrics. The laws of motion, therefore, control the application of *this* particular affine space and *not* the framework of Euclidean geometry whose interpretation the laws already take for granted. But, setting this aside, what Friedman's claim most clearly brings to light is the sense of 'constitutive' at issue for him. Here the sense expressed is something like 'condition of the possibility of' or 'condition of our ability to conceive of'. A similar sense of 'constitutive' can also be found in the work of Poincaré (1902/1905), who pointed out that a geometry must be presupposed for the construction of a dynamical theory, but that doing so neither assumes nor precludes the possibility that the completed theory or another theory that is in some sense more fundamental may lead us to revise our presuppositions about geometry. Such a sense may be defensible, but it is different from the one exemplified in the laws of motion.

One result of distinguishing principles that interpret theoretical concepts from mathematical principles or prerequisites is that it defends the idea of a constitutive principle against trivialization. It might be argued that what is constitutive is relative to a theory's particular axiomatization or formalization, and, since what is constitutive in one axiomatization or formalization of a theory is not constitutive in another, the very idea of a constitutive principle is a wash. The limitation I propose permits agreement on the principles that interpret the theoretical concepts of a given theory, even if that theory admits of an alternative axiomatization or formalization. Newtonian theory, for example, admits of various mathematical settings, and those mathematical settings peculiar to analytic mechanics are radically different from Newton's own constructive methods. But, even in the Lagrangian formulation, for example, Newtonian theory still expresses the same fundamental picture of space, time, and causality. However it is developed mathematically, Newtonian theory is the theory whose basic theoretical concepts are constituted by the laws of motion.

Another result of distinguishing coordinating principles from mathematical principles is that a still stronger criticism of Quine's account of the structure of theories can be given. A Quinean might argue that, if mathematical principles are constitutive, they might be said to belong to the theory, which, on Quine's account, is confirmed or infirmed as a whole. It is central to Friedman's argument against Quine that constitutive principles do not face the 'tribunal of experience' on an equal footing with the properly empirical hypotheses whose formulation they permit: They are principles without which the empirical hypotheses in question would make neither mathematical nor empirical sense, and without which no empirical test could be possible. But it might be argued that the principles that truly make Friedman's point are *not* the mathematical principles or prerequisites, which, on their own, are subject to neither empirical confirmation nor disconfirmation, but the *coordinating principles* that interpret theoretical concepts and control the application of the mathematics by the theory. By clearly distinguishing coordinating principles from mathematical principles, a still stronger objection can be levelled against Quine's account of theories.

In spite of these criticisms of Friedman's characterization of the calculus and Euclidean geometry, and so of his characterization of a constitutive principle, his criticism of Quine's naturalism is not undermined. His approach to the analysis of physical theories aims to clarify the relations between the inverse-square law, the laws of motion, the calculus, and Euclidean geometry. And that analysis does succeed in showing that these parts of the total framework of Newtonian gravitation are not of the same kind.

Friedman's analysis goes a long way towards clarifying the structure of Newtonian gravitation, but there is a further sense in which the laws of motion are constitutive, one central to Newton's own understanding of his gravitation theory. One can read Newton's argument from the framework determined by the laws of motion to his gravitation theory as arising from a question about the applicability and adequacy of that framework for giving an account of celestial motion. By pressing the laws of motion as far as they can be pressed, that is, by boldly postulating that *all* bodies influence each other as per the third law of motion, we are driven to the hypothesis that there is an attraction—a 'universal gravitation'—between all bodies that acts instantaneously at a distance. It is only with this empirical hypothesis that an estimate of the masses of the bodies comprising a planetary system becomes possible, that an estimation of the centre of mass of the system is possible, and only with this hypothesis, therefore, that a planetary system can be taken to approximate an inertial frame. The form of the gravitational interaction, however, is not postulated but 'deduced from the phenomena' of planetary motion and gravitational free fall once these phenomena are understood within the necessary and sufficient framework of the laws of motion. Furthermore, not only was universal gravitation an open question but so also was its mode of operation. For example, does gravitation propagate through a medium or immediately at a distance?

The idea that, given the framework of the laws of motion, an account of celestial motion is an open empirical question was central also to Euler's understanding of Newton.[8] Euler (1768-1772/1775), for all his work to turn Newton's theory into what we now recognize as 'Newtonian mechanics', rejected action at a distance. He hoped a viable vortex theory would replace Newton's theory of attraction. But, in spite of that, he recognized the difference between the parts of Newton's theory that *any* theory of motion must constitutively presuppose and hypotheses formulable within that framework:

> Euler saw the difference between the elements of Newton's theory that were, so to speak, idiosyncratically Newtonian—above all the idea that universal gravitation is the sole force at work in the Solar System—and those that represented the common basis of all work in mechanics as then understood, especially the laws of motion and their underlying framework of space and time. Thus he acknowledged the distinction between the physical hypotheses that one might prefer, pursue, and evaluate within the general framework of mechanics, and the conceptual framework without which such hypotheses could not even be intelligible. (DiSalle, 2006a, p. 51)

Euler recognized clearly that the laws of motion constitute a framework of investigation that is independent of hypotheses about what sorts of forces there are. He allowed for the possibility of an alternative to universal gravitation, all the while recognizing that a Cartesian or any other

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[8] See Aiton (1972) and especially Wilson (1992) for discussions of Euler's rejection of action at a distance and for further references.

proponent of a vortex hypothesis must himself presuppose the laws of motion in giving that alternative.[9]

### *4. Friedman's analysis of Einsteinian gravitation*

Let us turn now to Friedman's analysis of Einsteinian gravitation. Friedman regards that framework as the outcome of three revolutionary advances, namely, the development of Riemann's theory of manifolds, Einstein's insight of 1907 that is summarized in the equivalence principle, and Einstein's field equations. All three were brought together to eliminate the contradiction between the instantaneous action at a distance postulated by Newtonian gravitation and the invariance of the velocity of light in special relativity. In keeping with his approach to the analysis of theories, Friedman distinguishes constitutive principles, both mathematical and physical, from properly empirical hypotheses:

> ... the 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 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)

Further on, we find a more detailed account of the constitutive role of Riemann's theory:

> 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)

We also find a sharper statement of Friedman's view that the equivalence principle functions to coordinate Einstein's field equations with experience:

> 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. 38-39)

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[9] It is noteworthy that the laws of motion are implicitly presupposed not only in Cartesian physics but also in the work of Galileo, Huyghens, Wallis, and Wren on projectile motion and elastic collisions. This was Newton's argument for taking them to be axioms.

This is the core of Friedman's analysis of Einsteinian gravitation: Riemann's theory of manifolds and the equivalence principle are constitutive presuppositions of Einstein's field equations. The same claims can be found in more recent work by Friedman (e.g., 2009, pp. 263-264; 2010a, pp. 696-711; 2011, pp. 432-434).[10]

I propose to challenge Friedman's claim that the equivalence principle and Riemann's theory are constitutive presuppositions by rationally reconstructing the argument for curvature and by contrasting that argument with Friedman's account.[11] In my presentation of Einstein's argument I have not hesitated to make use of conceptual and mathematical insights that were gained only later. This departure from the actual history focuses attention on the shape of the argument without getting tangled up in questions about the success of individual steps.

### *4.1. The argument for curvature*

Einstein took the first steps towards the inertial frame concept characteristic of his gravitation theory in 1905. The 1905 inertial frame concept emerged as the result of Einstein's recognition that the nineteenth-century inertial frame concept uncritically assumes that two inertial frames agree on whether spatially separated events happen simultaneously. He showed that determining whether two spatially separated events are simultaneous depends on a process of signalling. The velocity of light—implicit in Maxwell's theory and established experimentally by Michelson, Morley, and others—is the same in all reference frames, and Einstein showed that a criterion involving emitted and reflected light signals permits us to identify the time of occurrence of spatially separated events and to derive the Lorentz transformations. This forms the basis of Einstein's special theory of relativity. With Einstein's analysis of simultaneity, the nineteenth-century concept gave way to the 1905 inertial frame concept: An inertial frame is not merely one

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[10] There is a further aspect of this analysis that I wish to evoke: Friedman claims that the equivalence principle is elevated to the status of a definition in Poincaré's sense: 'In using the principle of equivalence to define a new four-dimensional inertial-kinematical structure, therefore, Einstein has "elevated" this merely empirical fact to the status of a "convention or definition in disguise"' (Friedman, 2009, p. 263). This claim is motivated by the fact that, though both Newton and Einstein were aware that inertial mass and gravitational mass are indistinguishable, only Einstein took that indistinguishability as a basis for reinterpreting the concept of inertial motion. This claim is analogous to Friedman's claim that Einstein elevated the light postulate to the status of a definition: Whereas Lorentz took the invariance of the velocity of light as something to be explained by his theory of the electron, Einstein elevated it to the status of a definition, which he took as a basis for reinterpreting the concept of simultaneity.

[11] I intend 'the argument for curvature' as shorthand for 'the arguments for curvature' or 'Einstein's chain of reasoning'. It is doubtful whether the motivation for curvature can be represented as a single coherent argument.

in uniform rectilinear motion but one, furthermore, in which light travels equal distances in equal times in arbitrary directions.

But no sooner was the 1905 inertial frame concept established than Einstein subjected it to a further critical analysis. In 1907, Einstein had an insight that is summarized in the equivalence principle. It is with this principle that the argument for curvature begins.

Before addressing the 1907 insight, however, it is important to note that by 'the equivalence principle', some will think immediately of the *universality of free fall* that was first established by Galileo: All bodies fall with the same acceleration in the same gravitational field. It may also be stated: The trajectory of a body in a given gravitational field will be independent of its mass and composition. Yet another statement with the same empirical content arises in the framework of Newtonian theory. As is well known, Newtonian theory comprises two different concepts of mass: inertial mass $m$, the quantity that figures in the second law, that is, the measure of a body's resistance to acceleration; and gravitational mass $\mu$, the quantity that figures in the inverse-square law and that is the gravitational analogue of electric charge. It is a well-established experimental fact that the ratio of gravitational mass to inertial mass is the same for all bodies to a high degree of accuracy. And, once we accept that the ratio is a constant, we can choose to use units of measurement that make the two masses for any body equal, so that $\mu/m = 1$. In this way we can ignore the distinction between gravitational mass and inertial mass. This is summarized in what is often called 'the weak equivalence principle': Inertial mass is equivalent to gravitational mass. It is easy to show—though I will not give the argument here—that this statement implies that the acceleration of any body due to a gravitational field is independent of its mass and composition.

In Newtonian theory, the proportionality of inertial mass and gravitational mass is a remarkable fact that lacks an explanation. That explanation is found in Einstein's 1907 insight into the gravitational interaction. The insight is illustrated most clearly with 'Einstein's elevator'.[12] Suppose you stand in 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

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[12] This illustration is found in *The Evolution of Physics* (Einstein and Infeld, 1938, pp. 226-235).

possibility that the box is part of 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. Einstein also runs the thought experiment the other way: You are inside the box. You feel no gravitational force, just as in free space. But you have no way of excluding the possibility that the box is falling freely without rotation in a gravitational field. Though Einstein runs the thought experiment both ways, he recognized that the latter is problematic: True gravitational fields are never 'transformed away' or 'cancelled' by free fall; furthermore, what is transformed away in the thought experiment is only the homogeneous gravitational field. In practice, there *is* a way of distinguishing locally between a freely-falling non-rotating box and a box in free space. For example, an astronaut in a space shuttle that is freely falling without rotation in the gravitational field of the Earth could perform local experiments to determine that a water droplet is not spherical but prolate, that is, to determine that it is subject to a 'tidal effect' and lengthened towards the source of the field.[13] But Einstein was clear about what he took the thought experiment to establish.[14]

Einstein's 1907 insight is that a homogeneous gravitational field and uniform acceleration are identical in their effects. The insight is summarized in the *equivalence principle*: It is impossible to distinguish locally between immersion in a homogeneous gravitational field and uniform acceleration. The field produced by a uniform acceleration is not a mere 'inertial field'; it is not simulated or pseudo gravity, but a genuine homogeneous gravitational field.

In spite of stating the equivalence principle in this particular way, for the reasons outlined above, the 'transforming away' version of Einstein's elevator is a crucial part of the 1907 insight and integral to the argument for curvature. So far as tidal effects can be ignored, matter obeys the same laws in a freely-falling non-rotating frame as it would in an inertial frame. Through this, Einstein began to recognize that inertial motion and freely falling motion are different presentations of the same motion.

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[13] For a good discussion of tidal forces, see Ohanian and Ruffini (1994).

[14] For further details on Einstein's understanding of the equivalence principle, see Norton (1985).

But Einstein's argument does not end here: It is crucial that not only matter but light—and moreover, all physical processes—obey the same laws in a freely-falling non-rotating frame as they would in an inertial frame.[15] Einstein's bold extension is motivated by the observation that there are *no* physical phenomena that are independent of gravitation and that could distinguish a box immersed in a homogeneous gravitational field from a box subject to a uniform acceleration. This is also readily illustrated by Einstein's elevator. Suppose you stand in the box, only this time there is a window. You feel a 'gravitational force' towards the floor, just as you would at home. And, as before, there is no way of excluding the possibility that the box is part of an accelerating rocket in free space and that the force you feel is an accelerative force. But this time a light ray enters the window. Since light carries energy and energy has mass, the light ray, on entering the box, will not travel across the box horizontally to hit a point opposite its point of entry, but will curve downwards towards the floor—in analogy with a ball thrown horizontally in the gravitational field of the Earth. Assuming that the slight curve of its path were measurable, a light ray cannot distinguish the box on Earth from the box that is part of the accelerating rocket.

Einstein's insight of 1907, together with this bold extension, led him to recognize freely falling motion and inertial motion as different presentations of the same motion. In this way, the equivalence principle functions as a criterion for identifying two previously distinct concepts of motion.[16]

To return, for a moment, to the proportionality of inertial and gravitational mass in Newtonian theory, *the equivalence principle establishes that a homogeneous gravitational field*

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[15] This extension of the principle to all physical processes is often referred to as the *universal coupling* of all non-gravitational fields to gravitation.

[16] One could object that Newton had already recognized freely falling motion and inertial motion as different presentations of the same motion; one could suggest that Corollary VI to the laws of motion reflects just this. Corollary VI holds that if bodies moving with respect to one another are influenced by uniform accelerative forces along parallel lines they will move with respect to one another in the same way they would if they were not influenced by those forces. In this way, Corollary VI establishes that matter obeys the same laws in a freely falling frame that it would in an inertial frame. But, for Newton, a 'Corollary VI frame' is only an approximation to an inertial frame determined by the laws of motion; it is a good approximation to an inertial frame in the case where the uniform accelerative forces act along lines that are very nearly parallel. Newton had good reason for thinking that the Corollary VI frame should not be identified with an inertial frame. It was Einstein's insight of 1907, and moreover the extension to all non-gravitational forces, that was the crucial interpretive step, namely, recognizing freely falling motion and inertial motion as different presentations of the same motion.

*and uniform acceleration are identical in their effects*.[17] Since the two concepts of mass figure in the expressions for gravitational force and accelerative force, the principle implies that *inertial and gravitational mass are not merely proportional or equivalent but identical*. In this way the equivalence principle explains the remarkable proportionality of inertial and gravitational mass in Newtonian theory.[18]

Einstein's elevator illuminates the equivalence principle in both its destructive and constructive aspects. The principle is destructive because it fatally undermines the determinateness of the 1905 inertial frame concept. That is to say, the principle establishes that the 1905 inertial frame concept is not uniquely determined by its empirical criteria. It is constructive because it motivates a new concept of inertial motion.

With the recognition of a new concept of inertial motion in 1907, the question arises: How is this concept to be interpreted? Special relativity presupposes the mathematical framework of an affine space equipped with a Minkowski metric. And, in the special theory, the trajectories of bodies moving inertially as well as 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 drew insight from a now well-known thought experiment involving a uniformly rotating frame; this suggested to him that a gravitational field might be represented by a geometry of variable curvature, one furthermore that depends on the distribution of mass-energy.[19] With help from Grossmann, he came to see that Riemann's newly-developed theory of manifolds might be an alternative to the affine space of the special theory and a possible arena in which to construct such a gravitation theory. In this new mathematical framework, no longer would inertial trajectories be geodesics with respect to the Minkowski metric—they would be interpreted as geodesics with respect to a new metric that is determined by the distribution of mass and energy in the universe. Einstein's reinterpretation of free fall is

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[17] Note that the accelerative forces in question here do not include electromagnetic forces or the weak or nuclear forces.

[18] This way of presenting the explanation of the proportionality of inertial and gravitational mass serves to reinforce the importance of prising the universality of free fall from the equivalence principle. Doing so contributes to our understanding of different aspects of the gravitational interaction and to our understanding of the relation between them. But it is essential to note that the so-called equivalence principle is an interpretive extrapolation. The principle that is tested is the universality of free fall.

[19] For details on the 'rotating disks' thought experiment and its heuristic role in the argument for curvature, see Friedman (2001, pp. 62-63 and 112-113) and DiSalle (2006, p. 123).

summarized in what is sometimes referred to as the *geodesic principle*: Free massive test particles traverse time-like geodesics.[20]

This ‘geometrization’ of gravitation is at the heart of Einstein’s proposal for a new gravitation theory. And, with it, Einstein was faced with the problem of constructing a new theory in which a yet-undetermined quantity representing chrono-geometry is coupled to a yet-undetermined source-term representing the local mass-energy distribution.

The preceding account is a rational reconstruction that avoids various pitfalls and distractions raised by the actual history: from the special theory understood in three-plus-one dimensions *not* four, through the equivalence principle, insights from Mach’s principle and Gauss’s treatment of non-Euclidean continua, to the application of Riemann’s theory, disagreement over the notion of geometrization, and the geodesic principle. However the actual argument falls short, it remains that it was sufficient for motivating a new and purely local definition of a geodesic.

### *4.2. The equivalence principle and Riemann’s theory are not constitutive*

With this presentation of the argument for curvature in hand, let us return to Friedman’s claim that the equivalence principle and Riemann’s theory are constitutive.

I have shown that the equivalence principle, together with the claim that all non-gravitational processes couple to gravitation, functions as a criterion for identifying two distinct concepts of motion. This identification is the pivotal step that permits the reinterpretation of free fall as geodesic motion. On my analysis therefore—and in contrast with Friedman’s—the equivalence principle is not a constitutive principle but an empirical hypothesis.[21] Though the principle motivates a new concept of inertial motion, and so expands our space of intellectual and empirical possibilities, it does not constitute that new concept by expressing a criterion for its application. It is the *geodesic principle* that does that: If a body is freely falling without rotation,

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

[21] This point is also made by Howard (2010, p. 349). But Howard does not distinguish the equivalence principle and the geodesic principle as separate components of the conceptual framework of gravitation theory.

it is moving on a geodesic; if not, its motion deviates from a geodesic—in a way that a yet-to-be-constructed theory might measure. The geodesic principle forms the basis for treating the relative accelerations of freely falling particles, which can of course be treated in the Newtonian fashion, as a measure of curvature, expressed as geodesic deviation. In this way the geodesic principle replaces the laws of motion as constitutive presuppositions of the concept of inertial motion. The geodesic principle forms the basis for thinking about gravitation as a metrical phenomenon; in other words, for establishing its geometric character. It determines a new framework of investigation, one that makes it possible to pose a question to which Einstein's equations are an answer.

This account is significant for its clarification of the role of the equivalence principle in the conceptual framework of gravitation theory. It also distinguishes the equivalence principle and the geodesic principle as separate components of that framework. Though the two principles are closely related in Einsteinian gravitation, it is conceivable that future work will reveal that the equivalence principle holds in the face of still more rigorous tests, but that the geodesic principle must be given up: for example, in some new theory of the gravitational interaction.

What of Friedman's claim that Riemann's theory of manifolds is a constitutive presupposition of Einstein's reinterpretation of inertial trajectories as geodesics? Friedman wishes to draw attention to the crucial step of taking spaces of variable curvature to be intellectual and empirical possibilities. The importance of this step to the construction of the gravitation theory cannot be overstated. But I believe one must distinguish between two things. The first is the transition from the *conceptual framework* of homogeneous spaces—those in which the principle of free mobility is satisfied—to the more general framework of variably-curved spaces in which the former is a special case. The second is the transition to the *mathematical framework* of Riemann's theory of spaces of arbitrarily variable curvature that may be regarded as a realization of that conceptual framework. While both transitions are prerequisites for the construction of Einsteinian gravitation, it is the transition to the conceptual framework of variably-curved spaces that seems to capture Friedman's point. That is, it is the conceptual framework of variably-curved spaces and *not* Riemann's theory that is constitutive in Friedman's sense. But, setting this aside, Riemann's theory is not constitutive in the narrower sense I have defended. It is, rather, part of the formal background that makes the construction of Einsteinian gravitation possible—in the same sense as the calculus and Euclidean geometry in the case of Newtonian theory. We need some physical principle that expresses a criterion for the application of Riemann's theory.

Friedman's inclusion of Euclidean geometry, Riemann's theory, and the calculus in the category of constitutive principles widens that category in the direction of taking everything involved in the formulation of a theory to be constitutive and in some sense part of the theory—with the implications considered above. The principles that are truly constitutive are not those that supply the formal background or language but those that interpret theoretical concepts by expressing criteria for their application; those same principles control the application of mathematical theories such as Euclidean geometry, affine space, Riemann's theory, and others.

As with my criticism of Friedman's characterization of the constitutive basis of Newtonian gravitation, this account of the constitutive basis of Einsteinian gravitation in no way undermines Friedman's criticism of Quine's naturalism. I am arguing only for a different account of that basis and a stronger response to Quine. Friedman's account of the structure of physical theories aims to distinguish a theory's constitutive principles from the properly empirical hypotheses whose formulation they permit; it aims, in this way, to vindicate something close to the analytic-synthetic distinction rejected by Quine. But Friedman's characterization of both mathematical principles and coordinating principles as constitutive principles does not mark the distinction that should be drawn between the factual and non-factual components of our theories—a distinction that, I have argued, benefits the account of the stratification of our frameworks of physical knowledge.[22]

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[22] It may be useful to return now to Friedman's claim, mentioned in fn. 9, that Einstein 'elevated' the equivalence principle to the status of a definition. From my presentation of the argument for a new concept of inertia, it should be clear that the idea of such an elevation is based on a mischaracterization of Einstein's 1907 insight that is summarized in the equivalence principle. The 1907 insight has nothing to do with an elevation to a definition, but consists in the recognition that inertial motion and freely falling motion are different presentations of the same motion. While the recognition of their identity was the first step in Einstein's argument for a new inertial structure, it seems odd to characterize the principle that brought it about as based on a stipulation ('elevated to a definition'). Provided that one accepts a straightforward fact-convention or fact-definition distinction, the equivalence principle falls clearly on the side of the factual: The universality of free fall is an inductive generalization from a set of empirical facts, and the equivalence principle is an interpretive extrapolation from the universality of free fall. If any principle were to be elevated, in Friedman's sense, that principle would be the geodesic principle and not the equivalence principle.

### *4.3. An objection to taking the geodesic principle to be constitutive*

There is a possible line of objection to the idea that the geodesic principle is a constitutive principle. It might be pointed out that spinning bodies do not move according to the geodesic principle:

> It has long been recognized that spinning bodies for which tidal gravitational forces act on its elementary pieces deviate from geodesic behaviour. What this fact should clarify, if indeed clarification is needed, is that it is not simply *in the nature* of force-free bodies to move in a fashion consistent with the geodesic principle. (Brown, 2005, p. 141)

But the fact that the geodesic principle is an idealization—it is strictly satisfied only in the case of zero tidal forces—does not undermine the characterization of the principle as a constitutive principle. In fact, the idealization is essential. It is precisely this idealized conception of motion that is the basis for measuring geodesic deviation, which, in Einstein's theory, can be understood in terms of components of rotation, expansion, and shear, given some congruence of geodesics.

It is important to note that an idealized conception of geodesic motion is equally essential to Newtonian theory. The third law of motion ensures that the bodies comprising an isolated system—as well as the particles comprising a single body—will interact with each other so that the forces between them are balanced. In such a state of equilibrium, the centre of mass of the system will follow an approximately geodesic trajectory. The geodesic motion of the centre of mass of an isolated or 'near enough' isolated system is not a precise relativistic notion, but it is crucial to Newtonian reasoning: This state of motion is the basis from which perturbations can be measured.

Newton's method consists in beginning with idealized simple cases and moving to increasingly more complicated ones. In the case of bodies subject to inverse-square centripetal forces, Newton considers in Book I of *Principia*: one-body problems; two-body problems, subject to the third law of motion; and problems of three or more interacting bodies, for which Newton obtains only limited, qualitative results. A distinctive feature of this kind of reasoning is its focus on systematic deviations from Kepler's laws. Smith writes:

> Newton is putting himself in a position to address the complexity of real orbital motion in a sequence of successive approximations, with each approximation an idealized motion

> and systematic deviations from it providing evidence for the next stage in the sequence. (Smith, 2002, p. 155)

What the work of Smith and others clarifies is that the framework of the laws is the basis for a *perturbative analysis* of planetary systems. That is, the laws are not only a basis for determining the centre of mass of a quasi-isolated system but for reasoning from such a system to a larger system in which the quasi-isolated system is contained and in which systematic deviations from its ideal state of motion can be detected and measured. In both Newtonian and Einsteinian gravitation, therefore, the idealized conceptions of geodesic motion are the basis for the empirical measurability of the gravitational field. In the Newtonian picture, ideal geodesic motion is the basis for learning about the sources of the gravitational field; in the Einsteinian one, it is the basis for learning about curvature from the relative accelerations of geodesic trajectories.

## *5. The Kuhnian and Carnapian aspects of Friedman's thesis*

In this final section I wish to consider a further implication of Friedman's view. While Friedman's thesis is primarily motivated as an alternative to Quine's naturalism, it is also a corrective to Kuhn's account of the transition from Newtonian to Einsteinian gravitation. The transition from Newtonian to Einsteinian gravitation is the main example considered by Kuhn in Chapter IX of *The Structure of Scientific Revolutions* (1962/1970), and Friedman sees in the logical empiricists' approach to the analysis of physical theories a basis for correcting Kuhn.

In *The Structure of Scientific Revolutions* (1962/1970), Kuhn introduced the idea of a scientific 'paradigm', which he understood not merely as a set of theoretical principles but as an entire world-view consisting of metaphysical views, methodological rules, a conception of what constitutes a legitimate scientific question and what does not, and an understanding of what constitutes a scientific fact. Kuhn called the science pursued within a paradigm 'normal science'. Normal science proceeds without any questioning of basic principles, and consists of puzzle solving, that is, answering questions set by the paradigm with standard methods. Periods of normal science are broken by periods of 'revolutionary science', which are marked by an accumulation of unsolved puzzles, decreasing confidence in the reigning paradigm, and the appearance of alternative paradigms. Kuhn claimed that science progresses not cumulatively but by a succession of revolutions called 'paradigm shifts'. The main problem posed by this characterization is this: How can one argue for and commit oneself to a new paradigm if, in periods of revolutionary science, the very criteria of factuality and scientific rationality are being challenged? Kuhn's answer is that the argument for a new paradigm is necessarily circular: 'Each group uses its own paradigm to argue in that paradigm's defense.' (Kuhn, 1962/1970, p. 94) Paradigm shifts cannot therefore be the result of a rational process—a paradigm shift is ultimately a social or psychological phenomenon. Supposing that one accepts the problem and the response, Kuhn's view can be understood to support relativism, though Kuhn himself did not endorse that consequence.

Friedman's thesis provides an alternative to Kuhn's characterization of revolutionary theory change. It is distinguished from Kuhn's characterization in two important respects: its transcendental character, and its replacement of a paradigm shift with a rational process of revision. By its transcendental character, I mean its employment of a method of analysis whose aim is to reveal the principles that determine the framework of investigation. It is the revision of *these* principles especially—principles that make possible properly empirical hypotheses, with their associated ontological pictures, methodological rules, puzzles, standards of solution, and modes of community life—that represent revolutionary theory change. Friedman is concerned with the conceptual prerequisites for a theory capable of supporting a tradition of normal science. It would be a mistake therefore to regard the replacement of a set of constitutive principles as an explication of a paradigm shift, even though Kuhn (2000, pp. 104) regarded his account as 'Kantianism with movable categories'. The replacement of such a set completely replaces the notion of a paradigm shift in an altogether different account of our knowledge and its revision.

The second respect in which Friedman's proposal differs from Kuhn's is the account of the mechanism of theory change. This part of Friedman's thesis faces the same problems as conventionalism. Friedman's view has a broadly Carnapian aspect, and it inherits something of Carnap's account of theory change, according to which we adopt a new framework because it is expedient to do so. Carnap's account is problematic—it presupposes that the new framework is already on the table. It cannot explain what motivates the transition in periods of revolutionary science in which the new framework is not yet constructed. DiSalle (2006b, p. 208) has observed that the question 'do freely falling bodies follow space-time geodesics?' is either an internal question about how geodesics are interpreted in Newtonian theory, in which case it is answered by a mathematical investigation, or an external question about the expediency of adopting a framework in which the trajectories of freely falling bodies are interpreted as geodesics. But, in the context of theory construction, there is no theory in which the trajectories of freely falling bodies are interpreted as geodesics. There is at most the framework of empirical investigation constituted by the geodesic principle—a framework that has yet to lead to the field equations, which, in turn, are a long way from being confirmed. That framework provides us, nonetheless, with a picture of motion, one in which we may ask, for example: What conditions are required for constructing a theory in which free fall trajectories are geodesics? What assumptions must be made about the form of such a theory for Newtonian gravitation to be recoverable in a certain regime? But, with only the external question of whether to adopt Newtonian or Einsteinian gravitation, no such considerations enter into the account of theory change. As DiSalle has put it, 'Carnap's distinction ... does not comprehend the possibility of a conceptual analysis that discovers, within a given framework, the principle on which a radically new framework can be constructed.' (DiSalle, 2006b, p. 208) In the absence of such a possibility, the mechanism of theory change lies in the decision to adopt a framework on the basis of expediency.

Where Carnap's account fails, Friedman's account of the role of distinctly philosophical analysis at a meta-framework level is meant to be a solution. Friedman argues that this distinctly philosophical analysis in periods of fundamental conceptual revolution, in periods when the usual criteria of scientific rationality break down, involves another kind of rationality altogether. This 'communicative rationality' is characterized, roughly speaking, by a process of argument that appeals to patterns of argument acceptable to all participants, with a view to achieving agreement on what the constitutive principles of some domain are. It is opposed to 'instrumental rationality', which is characterized as an individual process of deliberation in view of achieving some goal. Friedman argues that it is the recognition of only this instrumental rationality in both normal and revolutionary science that accounts for Kuhn's failure to find permanent criteria and values across the development of science that enable paradigm shifts to be the result of a rational process. Friedman claims that it is the exercise of communicative rationality that permits agreement on a new framework when framework-dependent criteria of rationality are no longer of service. This is what effects theory change on Friedman's account.

Friedman's account of the mechanism of theory change is a significant improvement over Kuhn's and Carnap's. It restores the idea that revolutionary theory change is the result of a rational process, and it dispenses with mere expediency. But his account of the transition from the constitutive basis of Newtonian gravitation to that of Einsteinian gravitation is still reminiscent of conventionalism. His account of a 'change of constitutive principles' seems close at times to a 'change of conventions', even if the transition is achieved by the exercise of communicative rationality. To be sure, Einsteinian gravitation is not adopted merely because it is expedient to do so. Friedman clearly acknowledges Einstein's argument that leads to the reinterpretation of free fall. But there are passages (e.g., Friedman, 2001, pp. 62-63; Friedman, 2009, pp. 260-266) in which he seems more concerned with the external question about the adoption of a new framework than with Einstein's insight within the old framework—and it is this insight that actually motivates the revision.

In contrast with Kuhn, Carnap, and Friedman, a better and still more strictly empiricist account of revolutionary theory change is possible. The proper development and defence of this account is beyond the scope of this essay; see DiSalle (2002; 2006a; 2010) and Demopoulos (2010; 2013) as exemplars of this account. But such a development and defence must relocate the role of distinctly philosophical or critical conceptual analysis: This kind of analysis ought not to be understood as floating above the existing framework and a candidate-framework, which somehow or other have come to be, but as situated in the existing framework, where its objects are those concepts whose interpretations are at issue. To return to the example of the transition from Newtonian to Einsteinian gravitation, the equivalence principle does not merely suggest that the 1905 inertial frame concept may not be the whole story—it undermines the determinateness of the concept definitively and irrevocably. And the consequent reinterpretation of inertial motion as movement along a geodesic that is summarized in the geodesic principle is not a side-effect or by-product of theory change but is itself constitutive of a new framework of investigation. On this understanding, the transition from Newtonian to Einsteinian gravitation is the outcome of a *dialectical* process that begins within the old framework and, through a rational process involving scientific and philosophical considerations, results in a new constitutive principle.

Where Carnap's account cannot comprehend the possibility of an argument for a new framework that has its origin in the old one, this account begins squarely within the old framework. And, by beginning within the old framework, Kuhn's claim that defenders of different paradigms live in different worlds and so cannot argue with each other is undermined.

## *6. Conclusion*

I began by formulating a proposal that runs through Friedman's recent work on the analysis of physical theories. I called this proposal 'Friedman's thesis', and I set out to explicate and evaluate it. I considered Friedman's characterization of a constitutive principle as well as its antecedents in the work of Reichenbach and Carnap. I proposed that a constitutive principle be characterized as a principle that interprets a theoretical concept by expressing a criterion for its application. And, with this proposal, I argued that the scope of Friedman's characterization should be narrowed, and that only those principles that have this function should be considered constitutive. This separates the factual from the non-factual components of our frameworks, the principles that articulate and interpret theoretical concepts from the principles that are formal prerequisites to this. I argued that this narrowing avoids the objection to the notion of a constitutive principle arising from the observation that our space-time theories admit of various mathematical settings, and so might be said to have correspondingly many sets of constitutive principles—an objection that would trivialize the notion of a constitutive principle. This narrowing also allows a stronger criticism of Quine's account of theories to be given.

Having considered Friedman's account of a constitutive principle, I turned to evaluate his analyses of Newtonian and Einsteinian gravitation. My main focus was his analysis of Einsteinian gravitation, especially his claim that the equivalence principle is a constitutive principle. I argued that the equivalence principle is not a constitutive principle but an empirical hypothesis that motivates a new constitutive principle, namely, the geodesic principle. Then I addressed the possible challenge that since free particles follow geodesics only approximately the idea that we should regard the geodesic principle as constitutive is undermined.

In a final section I considered Friedman's correction of Kuhn. Though, for Friedman, revolutionary theory change is the result of a process of rational revision and not a paradigm shift, I suggested that his account of theory change is still reminiscent of conventionalism. It is more concerned with the external question of adopting a new framework—a question answered at the meta-framework level through the exercise of ‘communicative rationality’—than with the insight within the old framework that motivates the revision. I proposed that the role of distinctly philosophical analysis be relocated: It should be situated within the old framework, where the argument for a new constitutive principle begins.

In spite of these criticisms, I hope to have shown that Friedman’s thesis—at least so far as the methodological analysis of space-time theories is concerned—is eminently defensible. More generally, I aimed to clarify the sense in which Friedman’s thesis embraces the transcendental method of analysis without being committed to rescuing Kant’s philosophy. Essential to this method of analysis is the recognition that there is a stratification of our knowledge. The idea of a set of constitutive principles stands at some remove from Kant’s absolute ‘necessities of thought’, but it is concerned nonetheless with the identification of those principles that secure our basic physical knowledge, that make it possible for objects of knowledge to be objects of knowledge. These principles do not have the same status as empirical hypotheses. They are prior to them in that they determine the framework of empirical investigation, and so make genuine empirical hypotheses possible. This is the aspect of the logical-empiricist approach to the analysis of theories that Friedman seeks to rehabilitate, and that he urges against Quinean and post-Quinean thought.

Looking towards future work, Friedman’s thesis is intended to illuminate our analysis of revolutionary theory change not only in space-time physics but in physics and in the other exact sciences. Whether and to what extent this is possible is an open question, as Friedman himself (2001, pp. 117-129) acknowledges. This question is important not only for the further evaluation of Friedman’s thesis but, more importantly, for the continuing articulation and evaluation of the idea that Kant’s transcendental method is a ‘model of fruitful philosophical engagement with the sciences’ (Friedman, 1992, p. xii).

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