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Essay review

Understanding space-time

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Understanding space–time: the philosophical development of physics from Newton to Einstein, Robert DiSalle. Cambridge University Press, Cambridge, ISBN 0-521-85790-2, 2006, $75.00, xiii + 173pp.

1. Introduction

Contemporary philosophy of space–time physics took its starting point from the classic papers by Stein (1967) and Earman (1970a, b). Whereas earlier writers, within the logical empiricist tradition, saw Einstein's theories of relativity as predicated on a definitive philosophical rejection of Newtonian absolutism in favor of the relationalist positions of Leibniz and Mach, Stein and Earman argued that the most significant change wrought by Einstein was rather the replacement of Newton's separate three-dimensional space and one-dimensional time by the four-dimensional framework of space–time originally introduced by Minkowski in 1908 and later exploited by the general theory of relativity in 1915–1916. Moreover, it then became possible, as Weyl (1918) and Cartan (1923–1924) soon showed, to reformulate Newtonian physics so that it, too, becomes the theory of a particular four-dimensional space–time structure, and it thereby became clear that none of the space–time theories in question—including general relativity—really implement the thoroughgoing relativity of motion envisioned by Leibniz, Mach, and (at times) Einstein himself. For all these theories essentially involve a privileged state of motion—represented by affine geodesics in a four-dimensional manifold—relative to which deviations caused by physical forces are calculated.

The essential difference between Newtonian physics and general relativity, therefore, is not that the former is absolutist while the latter is relationalist, but that they ascribe different structures to the underlying space–time manifold. Newtonian theory employs a flat four-dimensional affine structure, stratified by a succession of three-dimensional

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instantaneous Euclidean spaces (planes of absolute simultaneity), wherein gravitational forces act immediately (instantaneously) at a distance to produce deviations (accelerations) from the privileged (inertial) state defined by the affine geodesics.[1] General relativity, by contrast, employs a variably curved four-dimensional affine structure, characterized (infinitesimally) by the invariant light cones introduced by Minkowski, wherein (idealized) freely falling particles affected by no other forces except gravitation follow the affine geodesics of a geometry whose curvature is determined by the distribution of mass and energy via Einstein's field equations.[2] Interestingly, however, after this point was assimilated by the philosophy of physics community in the early 1970s, a revised version of the debate between absolutism (or "substantivalism") and relationalism continued anew, now addressed to the ontological and epistemological status of the space–time manifold itself, together with the structures defined upon it. Is this manifold, and are these structures, somehow prior to and independent of the material objects whose motions (trajectories) are described by the various space–time theories, and, if so, how do we justifiably come to know them? The books by Sklar (1974), Friedman (1983), and Earman (1989) initiated and pursued this debate, which culminated in the large literature on Einstein's "hole argument" (concerning the status of the space–time manifold itself) sparked by Earman and Norton (1987).[3]

Robert DiSalle's new book introduces, and beautifully exemplifies, a novel approach to the philosophy of space–time physics. Rather than focussing on ontological and epistemological questions about "postulating" unobservable "theoretical entities"—such as an affine structure defined on a four-dimensional manifold—he focusses instead on the empirical meaning of such structures in the ongoing practice of physics: What do we actually mean, in physics, by the assertion that the empirical phenomena are "represented" by one or another space–time structure? DiSalle argues that the answer to this question (which is prior to the usual ontological and epistemological questions) is by no means obvious and, more importantly, that critical philosophical reflection in pursuit of it has played a central role in the historical development of the various space–time theories. Thus, for example, Newton did not argue that Descartes's relationalist theory of motion made a clear empirical claim which turned out to be false or unjustified, but that it left the concept of motion implicit in the then established laws of motion empirically undefined; similarly, Einstein did not argue that the Newtonian theory of absolute time was merely false or unjustified, but that it, too, failed to give proper empirical meaning to the concept of (absolute) simultaneity implicit in classical mechanics. The philosophical questions on which DiSalle proposes to focus are therefore internal to the physical practice he is describing, and this allows him to look at both the history of space–time physics and the

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[1] From this point of view, the only mistake in Newton's original formulation was using a separate three-dimensional space and one-dimensional time (the four-dimensional structure $E^3 \times T$) instead of the Galilean-invariant structure of what we now call neo-Newtonian or Galilean space–time.

[2] Cartan (1923, 1924) showed that Newtonian gravitation theory could also be reformulated in terms of a variably curved four-dimensional affine geometry (using a generalization of Poisson's equation). From this point of view, the difference between Newtonian theory and general relativity is only that the latter is built (infinitesimally) on the Lorentz-invariant light cone structure while the former still has the Galilean-invariant planes of absolute simultaneity.

[3] Earman (1989) contains an extensive discussion of this argument and its background in Leibnizean "indistinguishability". For a more recent discussion see, e.g., Stachel (2002), together with the references cited therein.

parallel history of philosophical reflection on this physics from a deeply illuminating new perspective.[4]

2. Critical conceptual analysis and the history of space–time physics

The most familiar example of the kind of critical reflection DiSalle has in mind is Einstein's celebrated analysis of simultaneity at the beginning of his 1905 paper. DiSalle argues, however, that the precise nature of Einstein's analysis has not been properly understood. The logical empiricists, for example, took it as a model for their verificationist theory of meaning, and Bridgman (1927) understood it as a paradigmatic operational definition. For DiSalle, by contrast, the true nature of Einstein's analysis is considerably more subtle. Einstein realized, on the one hand, that the invariance of the velocity of light following from Maxwell's equations and the principle of relativity allowed one to introduce a new concept of simultaneity that dissolved the apparent contradiction between the principle of relativity and the light principle (that light has a constant velocity c independent of its source). But Einstein also realized, on the other hand, that the concept of simultaneity implicit in classical mechanics did not have an empirically well-defined meaning after all. The reason for this, however, was not that the classical concept of simultaneity failed to have a verification procedure or operational definition; rather, the precise way in which it was embedded within the classical mechanical framework involved a tacit presupposition about its empirical meaning which turned out, eventually, to be false.

Newtonian gravitational interaction—operating instantaneously at a distance—gave a clear physical meaning, at least in principle, to the classical relation of absolute simultaneity. Yet there was no direct way to use "gravitational signalling" empirically to determine this relation, and so one relied, instead, on the light signals by which one empirically determined relations of gravitational interaction (as in Newton's analysis of the solar system in Book III of the *Principia*). It was of course known at the time that light travels with finite velocity, but this fact was not yet integrated theoretically with Newtonian mechanics. One simply assumed—tacitly—that light, like all mechanical processes, obeys the classical velocity addition law, and one supposed that its velocity could thereby be successively corrected for so as to approximate, in principle, the instantaneous causal propagation of gravitational interaction. What the Michelson–Morley experiment showed, however, is that this assumption is actually false; and, as Einstein then realized, Maxwell's theory of electromagnetism and optics yields a new concept of simultaneity, internal to electrodynamics, according to which light has the same constant velocity c in every inertial frame. Einstein's analysis does not rest, therefore, on a simple-minded application of verificationism or operationalism, but on what DiSalle calls a critical "dialectical engagement" with both pre-existing physical practice and the unexpected empirical facts which then rendered this practice conceptually problematic.

As already suggested, a second, and less familiar, example of critical conceptual analysis, for DiSalle, is Newton's discussion of space, time, and motion in his famous Scholium to the Definitions of the *Principia*. DiSalle argues that this very discussion shows that Newton, from a philosophical point of view, is following the same critical and empirical

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[4] DiSalle takes himself, in this respect, to be reviving the original point of view of Stein (1967)—which, DiSalle suggests, has not been fully appreciated by the subsequent literature.

method as Einstein, and, accordingly, there is much more continuity between the two than has been traditionally supposed. Newton is reacting, in particular, to Descartes's treatment of motion in the *Principles of Philosophy*, where, on the one side, Descartes articulates a vortex theory of planetary motion (and of light) and, on the other, maintains that the proper "philosophical" definition of motion is change of situation relative to immediately contiguous parts of matter—so that Descartes is then able to say, for example, that the earth is truly at rest because it is not moving relative to the immediately contiguous parts of the vortex carrying around the moon.[5] This definition, Newton realizes, is dynamically incoherent: Descartes needs the concept of true or absolute rotation in his vortex theory—as the source of centrifugal forces—but then has no room for this concept in his "philosophical" definition. Newton's well-known discussion of absolute rotation in the Scholium is then an alternative *definition* of true or absolute motion, precisely in terms of the centrifugal forces thereby resulting. Such forces, in other words, provide us with a well-defined *empirical measure* of the (true) motions in question.[6]

For DiSalle, therefore, Newton is here executing a critical conceptual analysis of the concept of absolute motion, based on a dialectical engagement with existing mechanical practice and its philosophical interpretation. Existing mechanical practice is founded on the law of inertia, and it is an unavoidable consequence of this law that rotating bodies, in particular, are subject to centrifugal forces arising from the inertial tendency to continue in a straight line tangent to circular motion. Moreover, the well-accepted principle of the conservation of momentum—or, equivalently, the equality of action and reaction—allows us, in turn, empirically to identify states of absolute rotation, because the centrifugal forces in question are not counterbalanced in any action–reaction pair. It is by proceeding in precisely this way, in fact, that Newton is then able fully to resolve the question of the true motions in the solar system in Book III of the *Principia*, where the true center of orbital motion is now identified as its center of mass. Newton's new definitions of space, time, and motion thereby make it possible, for the first time, to turn the question of the true motions in the solar system into an empirically answerable one. Newton is not "postulating" absolute space, time, and motion as unobservable "theoretical entities" in order to *explain* these motions; rather, he is crafting empirically applicable definitions of space, time, and motion (in the Scholium), together with corresponding "interpretive principles" (the Laws of Motion), in order to make it possible to *describe* them.[7]

A third central example, for DiSalle, is Einstein's use of the principle of equivalence in the foundations of general relativity. In particular, Einstein appealed to the well-established equality of gravitational and inertial mass in order to propose a revolutionary new interpretation of the relationship between gravitation and inertia. For it follows from

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[5] As DiSalle points out, that Newton's principal target in the Scholium is Descartes was first made clear in Stein (1967). As DiSalle (and Stein) also point out, this becomes perfectly explicit in Newton's unpublished *De Gravitatione*, now available in a new and improved translation in Janiak (2004).

[6] See also the earlier discussion in DiSalle (2002a), and compare Rynasiewicz (1995).

[7] Newton's conceptual analysis is not fully successful, even on its own terms, because the Laws of Motion only give empirical meaning to the concepts of absolute rotation and acceleration, not the concepts of absolute velocity or rest. It is precisely this defect that is remedied in the twentieth-century conception of neo-Newtonian or Galilean space–time (note footnote 1 above). Indeed, as DiSalle points out, it was already remedied by the concept of an inertial frame of reference developed in the late nineteenth century, and Newton himself comes very close to anticipating this solution in Corollary V to the Laws of Motion. Finally, as we shall see below, there is an analogous—but more subtle—defect in the Newtonian concept of absolute (rectilinear) acceleration as well, as revealed by Corollary VI.

this equality that freely falling frames of reference in a gravitational field are empirically indistinguishable, locally, from inertial frames, and the effects of gravitational forces in inertial frames are similarly indistinguishable, locally, from the effects of so-called inertial forces (e.g., centrifugal and Coriolis forces) in accelerating and rotating frames. Einstein therefore argued for "an extension of the principle of relativity" beyond the classical (and special relativistic) inertial frames, so that a proper relativistic theory of gravitation would somehow implement a thoroughgoing relativity of all motion. Yet we now know, of course, that the finished general theory does not really succeed in this, for there continues to be a privileged state of "natural" or geodesic motion defined by (idealized) freely falling trajectories in a gravitational field, and we now interpret the principle of equivalence as saying precisely this. The principle of equivalence thereby functions as a *definition* of true or absolute motion (true deviation from this privileged state), just as the three Laws of Motion functioned similarly in Newtonian theory.

DiSalle argues that we can find an important strand in Einstein's "jumble of philosophical motivations" for the principle of equivalence, consisting of a critical dialectical engagement with the Newtonian concept of absolute acceleration, which is analogous to Einstein's earlier critique of the Newtonian concept of absolute simultaneity. Consider a privileged center of mass frame arising in Newtonian theory (like the center of mass frame of the solar system described by the law of universal gravitation)—where, in particular, all true accelerations are counterbalanced in action-reaction pairs. By Corollary VI to the Laws of Motion, however, there is no way empirically to determine whether this frame is accelerating in turn, provided that all bodies accelerate at the same rate and in the same direction (compare footnote 7). But gravitational force, as Newton well understood, produces quantitatively identical accelerations in all bodies, and, if the source of this force is sufficiently distant from the bodies in question, the directions of these acceleration are also practically the same. Indeed, Newton appealed to precisely this fact in arguing that the system of Jupiter and its moons, for example, could be treated practically as an inertial frame—that its acceleration towards the sun could be locally ignored.

We therefore have a paradoxical situation arising within Newtonian gravitation theory itself: different frames of reference can locally satisfy all the empirical criteria for being an inertial frame, but these same frames can then be accelerating relative to one another. The solution is to accept the principle of equivalence, and to acknowledge that the (classical) inertial frames and (classical) inertial trajectories are not empirically well defined after all. The true privileged trajectories (affine geodesics) are instead freely falling in a gravitational field, and the privileged frames of reference, accordingly, are the local inertial frames corresponding to such freely falling trajectories—each of which represents a partial (and local) perspective on the underlying four-dimensional geometry of variable curvature described by the finished general theory.[8] In this sense, the relationship between the space–time of general relativity and the Newtonian decomposition of orbital motion into inertial and gravitational components is analogous to the relationship between Minkowski space–time and a decomposition, in any inertial frame, into three-dimensional space and one-dimensional time. And in both cases, for DiSalle, we arrive at the appropriate new

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[8] This solution can be implemented equally well in the context of Newtonian gravitation theory, and the result is the variably curved reformulation of that theory first articulated by Cartan (footnote 2). DiSalle is perfectly clear about this, and he suggests (Section 4.5) that the new situation in electrodynamics addressed by special relativity gave this solution, at the time, a particular force and urgency.

space–time structure by critical philosophical analysis of the empirical meanings of the fundamental concepts of earlier theories.[9]

3. Kant, transcendental principles, and Kuhnian revolutions

More than for any other philosopher of the modern period, the Newtonian concepts of space, time, geometry, and motion were central to Kant's philosophical enterprise. DiSalle takes this fact very seriously, and, accordingly, he gives a central place to Kant's philosophical engagement with these concepts in his own philosophical history of space–time physics.[10] Indeed, it was Kant, for DiSalle, who first grasped the properly "transcendental" character of the Newtonian concepts of space, time, and motion—not as mysterious metaphysical postulations but as necessary presuppositions for a mathematically precise and empirically well-defined physics of forces and interactions. Moreover, Kant understood the Newtonian concept of absolute space, in particular, in terms of an empirically well-defined constructive procedure for finding approximations to what we would now call an inertial frame of reference—a center of mass frame defined by the condition that all true accelerations are counterbalanced in action-reaction pairs.[11] Finally, Kant understood mathematical geometry, too, in terms of intuitive constructive procedures—Euclidean constructions with straight-edge and compass—which, in the nineteenth century, were generalized by Helmholtz and Poincaré to non-Euclidean spaces (of constant curvature) via the principle of free mobility. Kant's philosophical analysis of the Euclidean–Newtonian conceptual framework thereby set the stage for further critical reflection throughout the nineteenth century which eventually came to fruition, spectacularly, in Einstein's radical reconfiguration of this framework in the general theory of relativity.

Of course, as DiSalle points out, these later historical developments showed precisely that the principles Kant had taken to be "absolutely" transcendental—as necessary conditions for *any* coherent experience of spatio-temporal causal interaction—were only relatively so, in a particular, contingent context of empirical scientific theorizing.

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[9] DiSalle does not claim that the argument he sketches, in the case of general relativity, was explicitly made by Einstein; rather, he makes a strong case that it can be seen as implicit in Einstein's philosophical motivations by explaining (Section 4.6) how the theory was understood in a manner quite close to this very soon after its first publication—namely, by Weyl (1918) and Eddington (1918, 1920).

[10] In recent discussions emphasizing the debate between absolutism and relationalism, by contrast, Kant's work on the foundations of geometry is hardly mentioned at all—except in so far as Kant's famous example of "incongruent counterparts" is considered as an argument for absolute space: see, e.g., Earman (1989, Chap. 7). Similarly, Kant's discussion of absolute space in Newtonian physics in the *Metaphysical Foundations of Natural Science* (1786) is also almost completely ignored—except in so far as it is summarily dismissed: see again Earman (1989, Section 4.6).

[11] For the nineteenth-century development of the concept of an inertial frame see Torretti (1983), DiSalle (1988, 1991, 2002c). For a discussion of Mach's treatment of absolute space, time, and motion (which, in important respects, is analogous to Kant's) in relation to this development see DiSalle (2002b). DiSalle (Section 3.4 of the present volume) points to the connection between Kant's treatment of absolute space and the concept of an inertial frame, and even suggests a connection between Kant's treatment of absolute space and DiSalle's own analysis of Corollary VI to the Laws of Motion: Kant's constructive procedure proceeds from our parochial perspective here on earth to the center of mass of the solar system, and then to the center of mass of the Milky Way galaxy, the center of mass of a rotating system of such galaxies, and so on ad infinitum; Kant thereby views each temporary approximation to what we would now call an inertial frame as freely falling relative to a more inclusive (and more accurate) such frame.

Nevertheless, DiSalle argues, it remains true that the spatio-temporal principles in question (the principles of geometry and mechanics) do have a properly transcendental function, as necessary conditions for a mathematically precise and empirically well-defined science of motion at a *given* stage of physical theorizing.[12] What Kant did not see, however, is that such principles have tacit empirical presuppositions which may, unexpectedly, turn out to be false—thereby precipitating a radical conceptual revolution affecting even our most fundamental concepts of space and time. In this sense, Kuhn is correct that conceptual "incommensurability" is indeed characteristic of the transition from Newton to Einstein; but his account of critical conceptual analysis then provides DiSalle with a response to Kuhn. Einstein's arguments for the new conceptual framework (like Newton's original arguments for his framework) are in no way objectionably circular; rather, they involve a dialectical engagement with the old framework that begins with its *internal* conceptual problems (in a given empirical setting) and results in new definitions of the fundamental spatio-temporal concepts in which these problems are resolved.

DiSalle's novel approach to the philosophy of space–time physics—emphasizing the empirical meaning of spatio-temporal concepts rather than the ontological or epistemological status of "postulated" spatio-temporal structures—is extraordinarily rich and illuminating. Not only does it bring a fresh perspective to the familiar historical development from Newton to Einstein, it integrates this development with the parallel history of philosophy of space, time, and geometry from Kant through Helmholtz and Poincaré, and it suggests a powerful response, as well, to the Kuhnian problem of conceptual incommensurability. DiSalle's book, despite its relatively modest length, is a magnificent achievement in the history and philosophy of space–time physics, which no one seriously interested in the topic can now afford to ignore.

I cannot conclude this review, however, without briefly commenting on the relationship between DiSalle's response to Kuhn and my own, which I have recently developed—with reference to the same revolutionary transition between Newtonian and Einsteinian conceptual frameworks—in Friedman (2001).[13]

Consider, for example, our differing treatments of Einstein's philosophical motivations for general relativity in connection with the principle of equivalence. My account emphasizes Einstein's example of the rigidly rotating disk—which Stachel (1980/1989) has called the "missing link" in the history of general relativity—and connects this example with the debate between Helmholtz and Poincaré on the empirical foundations of geometry. As Norton (1985/1989) has shown, Einstein began to explore the principle of equivalence in the years 1907–1912 by attempting to construct relativistic models of the gravitational field via the inertial forces arising in accelerating and rotating frames of reference within the framework of special relativity. Einstein first investigated homogeneous (what we now call static) gravitational fields corresponding to uniformly

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[12] This kind of generalization (and relativization) of Kantian transcendental principles was suggested in Reichenbach (1920)—which I have discussed, and further developed, in a number of recent writings: e.g., Friedman (1999, Chap. 3; 2001) (both of which are cited by DiSalle). What is distinctive of DiSalle's approach, however, is the idea that such "interpretive principles" function basically as a *theory of measurement* for the fundamental spatio-temporal quantities (Section 5.2) and the claim that conceptual transformations between different sets of "interpretive principles" are mediated by critical analyses of the relevant fundamental concepts.

[13] DiSalle generously remarks, in the Preface, that his work has deep roots in a philosophical engagement with mine; I should add that Friedman (2001) has equally deep roots in a philosophical engagement with his—especially with DiSalle (1991, 1995).

accelerating systems, and he then turned to the more general case (what we now call stationary gravitational fields) corresponding to uniformly accelerating or rotating systems. It was precisely here, as Stachel has shown, that Einstein first encountered a non-Euclidean *spatial* geometry corresponding to the gravitational field in 1912, and it was at precisely this point that Einstein was then able to generalize his approach to the variably curved *space– time* geometry of what we now call general relativity. I claim that it was only in this way, in particular, that the idea of a four-dimensional space–time geometry acquired real physical meaning in the first place.[14]

For DiSalle, by contrast, Einstein's use of the rigidly rotating disk is at best heuristic, for it cannot actually warrant the four-dimensional geometrical structure employed in the finished theory.[15] This is perfectly correct—and, indeed, from the point of view of the finished theory, the rotating disk reveals no true space–time curvature in any case, for it arises in precisely the context of a *flat* Minkowskian space–time.[16] Yet what DiSalle's account does not quite satisfactorily explain, in my view, is how the idea of four-dimensional space–time geometry became a real physical possibility in the first place, and, more generally, it seems to me that DiSalle does not fully convey how difficult it actually was to arrive at this idea. The question whether a genuinely physical use of four-dimensional space–time geometry is even possible is prior, in my view, to the question of its warranted correctness, and I claim that it was Einstein's use of the rigidly rotating disk, in particular, which first made such a four-dimensional geometry physically possible. So it is no accident, on this view, that the now accepted interpretation of the principle of equivalence in terms of four-dimensional affine curvature was only properly understood soon after Einstein's formulation of the final theory (footnote 9), and its application to Newtonian gravitation theory then followed several years later (footnotes 2 and 8).

DiSalle acknowledges that (p. 129) "it was probably impossible to express this connection between gravitation and inertia [on his account] until it could be represented in the framework of space–time". In his view, however, Minkowski had already executed a critical conceptual analysis of special relativity in 1908, from which it follows, in particular, that (p. 115) "[t]he physically objective quantities must be expressed as the invariants of a four-dimensional structure," and "Einstein's 1905 paper only states the true spatio-temporal relations in a form bound by the limits of spatial intuition." It is noteworthy, then, that Einstein himself at first dismissed Minkowki's formulation as a mere mathematical trick, and he did not begin to appreciate its value until his own work on the principle of equivalence led him to a four-dimensional space–time geometry in 1912.[17]

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[14] For details see Friedman (2001, 2002). Einstein encountered a non-Euclidean spatial geometry in the case of the rotating disk via the Lorentz contraction experienced by idealized rigid rods laid off along any circular circumference centered on the axis of rotation, and he therefore had to take Helmholtz's side, against Poincaré, on the direct geometrical significance of "practically rigid bodies."

[15] See DiSalle's discussion in Sections 4.4–5, and compare his earlier treatment in DiSalle (2002b, pp. 186–188). In particular, DiSalle's own analysis of the principle of equivalence leads to a definite construction (Section 4.5) of variably curved four-dimensional affine geometry in terms of "geodesic deviation."

[16] Einstein, in the period 1907–1912, was, in effect, using the non-vanishing components of the affine connection in certain non-inertial coordinate systems to represent the gravitational field; intrinsic space–time curvature, however, is indicated by the non-vanishing of these components in *every* coordinate system.

[17] See Pais (1982, p. 152): Einstein first dismissed Minkowski's formulation as "überflüssige Gelehrsamkeit" (a superfluous show of learning); he then began to use four-dimensional geometrical methods in 1912 and explicitly recognized the importance of Minkowski's work in facilitating the transition from special to general relativity in 1916.

I believe that Einstein was basically correct that the real physical meaning of four-dimensional space–time geometry emerged only with his own work on the principle of equivalence in the years 1907–1912; and I do not see, in particular, why it follows from Minkowski's work that the physically objective quantities *must* be expressed as four-dimensional invariants. To be sure, once the four-dimensional framework is already accepted, we can see that there is no separate three-dimensional space left invariant by the Lorentz group—the only geometrical invariant is the four-dimensional Minkowski metric itself.[18] But I see absolutely nothing defective, at this stage, in Einstein's original three-plus-one-dimensional formulation, where the Lorentz group transforms inertial frames onto one another, and each such frame has its own decomposition into three-dimensional (Euclidean) space and one-dimensional time. What does become clearly problematic in the traditional conception of spatial geometry even in 1905, however, is the idea of rigid motion underlying the principle of free mobility in Helmholtz and Poincaré (footnote 14); and it was Einstein—and Einstein alone—who then saw how delicately to exploit this situation, with precisely the example of the rigidly rotating disk, in order to turn *space–time* geometry into a real piece of physics for the very first time.[19]

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[18] Compare DiSalle (p. 115): "By recognizing the relativity of time, Einstein had raised the *spatio-temporal* displacements, the Lorentz transformations, to a privileged status that the spatial displacements could no longer legitimately claim—because, unlike the Galilean transformations, the Lorentz transformations implied that spatial geometry was no longer a fundamental invariant."

[19] Thus, even though the three-dimensional geometry in any inertial frame remains Euclidean, the Lorentz contraction precludes the possibility of isometrically moving putatively rigid bodies. And it is this fact, as Einstein showed, which then leads to a non-Euclidean geometry in certain non-inertial frames—where inertial forces, according to the principle of equivalence, are equivalent to a gravitational field. Of course this is not quite the same thing as a true gravitational field according to the finished theory (footnote 16); but, in my view, we need to go through an intermediate stage that is not yet fully coherent from the later point of view in order to explain how the finished theory first came to be recognized as a genuinely live physical possibility.

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