Spacetime Theory as Physical Geometry

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SPACETIME THEORY AS PHYSICAL GEOMETRY*

ABSTRACT. Discussions of the metaphysical status of spacetime assume that a spacetime theory offers a causal explanation of phenomena of relative motion, and that the fundamental philosophical question is whether the inference to that explanation is warranted. I argue that those assumptions are mistaken, because they ignore the essential character of spacetime theory as a kind of physical geometry. As such, a spacetime theory does not *causally explain* phenomena of motion, but uses them to construct physical *definitions* of basic geometrical structures by coordinating them with dynamical laws. I suggest that this view of spacetime theories leads to a clearer view of the philosophical foundations of general relativity and its place in the historical evolution of spacetime theory. I also argue that this view provides a much clearer and more defensible account of what is entailed by realism concerning spacetime.

The general theory of relativity never quite established two of the philosophical points that Einstein had hoped it would: the claim that motion is now "generally relative" is widely recognized to be mistaken, and the claim that space and time have lost all trace of "physical objectivity" is regarded as debatable at best. Yet Einstein did manage to establish the terms of subsequent philosophical discussions of space and time. Parties to those discussions generally share at least one of Einstein's basic principles: *A spacetime theory postulates the existence of an unobservable object* (spacetime) *in order to explain observable phenomena* (relative motions). The famous philosophical positions ("substantivalism", "absolutism", "relationalism", and associated variations and combinations) differ not on this principle, but on whether and how such a postulate can be motivated and justified.

I will argue, however, that Einstein's principle misconstrues the metaphysical claims and the empirical content of spacetime theory. Spacetime theory is neither causal explanation nor a postulate of a hidden reality behind the phenomena of motion; that the real world actually has a given spacetime structure is therefore not an inference from the observable motions to their unobservable cause. Rather, it is the recognition that the physical laws that govern those motions are, in themselves, aspects of a geometrical structure. Einstein and the philosophers he inspired, especially Reichenbach, recognized a similar connection between physics and geometry with regard to the structure of space, and they developed a sophisticated account of the link between spatial geometry and experience. With regard to spacetime, however, their predisposition to the "relativity of motion", inherited from Mach (1883), convinced them that an epistemologically illegitimate inference was being made, from observable rela-

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tive motions to their unobservable cause – what Einstein called a "factitious cause" (1916, p. 113). And the legitimacy of this causal inference has remained at the center of philosophical debate, for example in recent standard works like Friedman (1983), and Earman (1989).[1] But a better alternative to the causal-explanatory view of spacetime theory can be found in Einstein's own conception of the foundations of physical geometry. By further developing this conception and extending it to spacetime geometry, we can set aside Einstein's objection to a causal inference. Above all, we can arrive at a clearer and more defensible formulation of realism concerning spacetime.

The paper consists of four sections. In Section 1, I consider the epistemological motivation for anti-realism, including the standard forms of relationalism; I show that this motivation makes an epistemological distinction between observable geometrical relations and underlying geometrical structures that is ultimately untenable. In Section 2, I develop the view that spacetime theory, like the theory of spatial relations, is a kind of physical geometry, in which fundamental physical laws are used to give empirical meaning to geometrical structures; I contrast physical geometry with causal-explanatory theories found in other areas of physics, in order to show how a realist view of geometry differs from an inference to a causal explanation. In Section 3, I show that arguments for physical geometry, rather than for causal explanation, have, in fact, motivated the historical development of spacetime theory from Newton to Einstein. Section 4 offers concluding remarks.

1. PROBLEMS WITH THE EPISTEMOLOGICAL OBJECTIONS TO SPACETIME

Einstein's critique of the reality of spacetime started from the claim that the classical distinction between rotation and non-rotation was an "epistemological defect" of classical and special-relativistic physics (Einstein 1916). Einstein therefore expected general relativity to extend the relativity of motion from the Galilean equivalence of uniform motions to the equivalence of all states of motion, including rotation. He also believed (at least at the outset) that general covariance, or equivalence of coordinate descriptions, guaranteed the desired equivalence. As Einstein himself eventually learned, however, any spacetime theory – including the theory of absolute space – could be given a generally-covariant formulation (cf. Friedman 1983). Even those who present general covariance as a decisive argument against "substantival" spacetime, by way of the "hole argument" (Earman and Norton 1987; Earman 1989), admit that, *by itself*, general covariance is no argument against the existence of "absolute" distinctions between states of motion. The persistence of such distinctions – what for Einstein was an epistemological defect – simply does not depend on the truth of the substantivalist interpretation of the spacetime manifold. Rather, it depends on the geometrical features that the manifold is supposed to carry. For example, any relativistic spacetime has a conformal structure, which carries a natural standard of rotation (cf. Malament 1985). Thus, while general covariance has implications for the twentieth-century problem of the ontological status of differentiable manifolds – an important problem for other reasons altogether[2] – it could not solve Einstein's original problem of the relativity of motion. That problem is essentially one of geometrical structure.

How did Einstein come to confuse the problem of manifold substantivalism with the problem of the relativity of motion? Einstein's understanding of the nature of a spacetime theory – as an existence-hypothesis of an unseen "substratum" that causes the observable relations – reflects a traditional epistemological belief that somehow escaped critical scrutiny throughout the history of "relationalism".[3] The belief is that "relations among bodies", and therefore relative motions, are epistemologically immediate: they are observationally *given*, while spacetime structures, like the metric and affine structures, require some further (epistemologically suspect) theoretical claim. At most, spacetime theories are a "best explanation" inferred from the objective relations; at worst, they are superfluous metaphysics that the objective relations can never fully justify. Such a conviction lies behind the arguments of Leibniz (1715–1716, pp. 703–704), Mach (1901, pp. 242–245), and Einstein (1916) about relative motions. It also lies behind Einstein's claims that "point coincidences" are the only objectively observable phenomena.

At least part of Einstein's confusion, I suggest, must have arisen from that epistemological viewpoint. Because he believed that relative motions can be known independently of any spacetime theory, he thought (following Mach) that an ontological critique of space and time would leave the relative motions (or at least "point coincidences") in an epistemologically privileged position. One part of Einstein's critique concerned causality: classical physics, he argued, invokes space and time (in particular, inertial frames) as unobservable, "factitious" causes of observable effects, and Einstein insisted that the cause of local inertial effects must be something observable, like "distant masses" (1916, p. 113). The other part of Einstein's critique concerns general covariance: if spatio-temporal coordinates have no real significance, so that the points of spacetime have no objective status, then again the relative motions (or point coincidences) are left as the only physically objective reality (1916, pp. 117–118. An explicit contemporary statement of the same view can be found in Earman and Norton 1987, pp. 515, 521.) I don't pretend to offer a complete account of Einstein's understanding of general covariance. But his belief in the epistemological immediacy of spatio-temporal relations sheds some light on why he thought that his epistemological critique of unobservable entities would solve the classic problem of the relativity of motion.

What the standard epistemological view failed to consider, from Leibniz and Mach through Einstein and his followers, was that the "observable relations" themselves are theoretical objects. Even a purely kinematical description of the relative motions of bodies incorporates theoretical assumptions – all the theoretical assumptions about rigid motion, measurement, and absolute simultaneity that play a part in "instantaneous Euclidean geometry". The "observable relations", in other words, involve theoretical claims about space, time, and motion and the ways in which they are interconnected. Thus the entire classical picture of relations among bodies, because it presupposes absolute simultaneity, is overthrown by special relativity, in which these relations turn out to be observer-dependent projections of the objective *spacetime* relations. One might still say that *spatio-temporal* relations are the observable phenomena, and spacetime the questionable theoretical structure. But the only theory of spatio-temporal relations that we have is relativistic geometry, which determines not only metrical relations among events, but also an affine and a conformal structure – and therefore it determines a "privileged state" of free (geodesic) motion, as well as a distinction between rotation and non-rotation (cf. Malament 1985). Absolute simultaneity enables classical mechanics to separate the kinematics of relative motions (changing instantaneous distances) from the dynamics of rotation and acceleration, but in relativity the kinematical structure and the dynamical structure cannot be separated. This is because the structure that determines a metrical interval between events (unlike the classical measure of relative spatial distance) also determines the spacetime geodesics – the inertial paths – between those events. Observers don't simply observe the objective relations and then hypothesize the existence of spacetime to explain them; they observe relations that depend on their states of motion, and Einstein's theory of spacetime enables them to construct the real relations in accord with the metrical and affine structures of Minkowski spacetime. This is one sense in which relativity makes Newton's distinction between "the real quantities and their sensible measures".

It follows that classical relationalism, usually taken to be an epistemological critique of spacetime theory, is itself a spacetime theory; belief in real spatial relations is a form of realism about spacetime. For, like Newtonian spacetime, relationalism involves metaphysical assumptions about how the history of the world may be decomposed into momentary spaces and about the (Euclidean) geometrical structure of those spaces. In one sense, the relationalist metaphysics is *weaker* than that of Newtonian spacetime, since the former just eliminates the Newtonian affine structure. Because it assumes absolute simultaneity, however, classical relationalism makes *stronger* metaphysical claims than Minkowski spacetime. Evidently these claims – absolute simultaneity and instantaneous Euclidean spatial geometry – were reasonable in the context of classical theoretical assumptions about velocity-addition and rigid bodies; for the very same reason, however, it is equally evident that these claims were not grounded in epistemologically immediate observable relations. It is therefore naive to suppose that, just because it does not countenance absolute rotation or acceleration, relationalism avoids metaphysical claims altogether and keeps to the "observable facts".

Again, we could weaken the relationalist position by regarding point-coincidences as the only objective relations. Even here, however, we are assuming a complicated theoretical structure, namely the differentiable structure of the spacetime manifold. As Einstein pointed out, "all our space-time verifications invariably amount to a determination of space-time coincidences" (1916, p. 117). In that case every observable event must be a point-coincidence (e.g., between some physical system and our measuring instruments). It does not follow, however, that every point-coincidence can be determined by observation. For example, a transit of Venus might appear to be a collision with the sun; we know only on theoretical grounds that Venus remains at a distance from the sun. More immediately, ordinary objects in my visual field might appear to touch one another if they lie in roughly the same direction, while my prior geometrical knowledge informs me that they lie at different distances. We generally consider such knowledge completely reliable, but it certainly lacks the epistemological immediacy that Einstein attributed to "meetings of the material points of our measuring instruments with other material points" (1916, p. 117): that sort of immediacy is necessarily local. In other words, we could strictly separate the observable from the theoretical only by restricting ourselves to coincidences at a point of our own worldline. And if we do draw the line here, the physically interesting large-scale geometry with which general relativity is concerned will fall on the wrong side. Thus an anti-realist view of spacetime structure would undermine not only Newtonian and Minkowski spacetime, but also any form of relationalism except a kind of solipsism.[4]

2. THE PHYSICAL MEANING OF SPACETIME GEOMETRY

In overlooking the theoretical nature of relationalism, for obviously empiricist motives, we have been overlooking a fundamental contribution of the empiricist view of geometry. The forebears of Einstein and Reichenbach in this view were Riemann (1867) and Helmholtz (1870), who pointed out that all geometrical measurements depend ultimately on *physical hypotheses* underlying the method of measurement. For, evidently, any empirical geometry must postulate not only a geometrical structure, but also a geometrical representation of an idealized physical process. Ordinary Euclidean geometry, for example, is based on congruence. Taken as an empirical theory, therefore, it assumes the possibility of comparing ideal rigid bodies, freely movable through space without change of dimension, and it instantiates the concept of length through this physical process. This is precisely what led Helmholtz to assert that any geometry of constant curvature is possible under our basic method of measurement; the particular geometry can be determined empirically as long as the underlying physical principle holds. Riemann considered a much larger class of geometries, and also a much larger set of physical possibilities: idealizations like the rigid body cannot be expected to work under extreme conditions, and the link between geometry and physics will have to be based on more complicated physical objects and processes. In both cases the philosophical point is clear enough. When we attribute real geometrical relations to real objects, we assume some physical principle by which those relations can be determined. Einstein's assimilation of this view (as reflected, e.g., in Einstein 1921) made it possible for him to consider spacetime curvature.

Reichenbach (1957), following Schlick (1918), attempted to characterize this view systematically through the notion of "coordinative definition". But he did so in a way that turned empiricism in the direction of conventionalism. In addition to the definitions that relate its concepts to one another, Reichenbach pointed out, a geometry that applies to empirical situations gives definitions that relate fundamental concepts to some empirically given object. "Wherever metrical relations are to be established", he remarks, "the use of coordinative definitions is conspicuous" (1957, p. 14); his emphasis on metrical relations reflects the influence of Helmholtz's view of the role of rigid bodies in Euclidean measurements. But that Reichenbach speaks of definitions, where Helmholtz referred to "the facts underlying geometry", reflects the influence of conventionalism. It cannot be empirically established that a rigid body moves through space without changing its dimensions; in particular, the measuring-body may be subject to distorting forces ("universal forces"). This was the basis for Poincaré's familiar argument (1913, pp. 81–84) that any measurement can agree with any geometry, provided that we account for discrepancies by the hypothesis of a distorting force that affects our measuring instruments. So it is by stipulation that we coordinate spatial distance with rigid rods, and such a stipulation assumes that no "universal forces" are present. Reichenbach neatly captured the sense in which coordinative definitions like this one, unlike definitions that connect concepts to one another, are both empirical and conventional:

> *It is again a matter of fact that our world admits of a simple definition of congruence because of the factual relations holding for the behavior of rigid rods; but this fact does not deprive the simple definition of its definitional* [i.e., stipulative] *character.* (1957, p. 17) [Emphasis in original]

This recalls Schlick's observation (1918, pp. 72–73) that we could arbitrarily coordinate spatial and temporal measurement with any physical object, and be assured of finding some empirical instantiation of our definition; yet empirical facts will determine whether the coordination is unique – that is, whether the same concept will always denote the same object. And empirical facts will decide whether the coordination permits a simple system of natural laws.

Clearly, Reichenbach's immediate inspiration was Einstein: "the philosophical significance of the theory of relativity consists", he wrote, "in the fact that it has demonstrated the necessity for metrical coordinative definitions in several places where empirical relations had previously been assumed" (1957, p. 15). Einstein's definition of simultaneity by means of light rays provided a vivid example. Newtonian physics assumed that simultaneity of distant events is an empirical fact, but Einstein demanded that the concept of simultaneity be coordinated to some physical principle, so that the simultaneity of distant events can actually be determined. He took the speed of light to be invariant, with the well-known result that simultaneity turns out to be relative. Einstein's later methodological remarks on this definition, though less often discussed, are quite revealing. He considers a possible objection to his definition, namely that it assumes that we already know that light takes the same time to travel the same distance in two different directions; the definition is therefore circular, since it already assumes some principle of time-measurement. Einstein replies, however, that the definition is satisfactory because it assumes nothing at all about light: "Only *one* requirement is to be set for the definition of simultaneity: that in every real case it provide an empirical decision about whether the concept to be defined applies or not" (Einstein 1917, p. 15). The invariance of the speed of light is not a physical assumption or hypothesis, but "a stipulation that I can make according to my own free discretion, in order to achieve a definition of simultaneity" (1917, p. 15). Yet the stipulation, though perhaps optional, is not at all arbitrary: it is warranted by Einstein's assumption (1905, p. 35) that the laws of electrodynamics, including light propagation, do not depend on the choice of an inertial frame. (Cf. below, pp. 325f and 331.) Einstein's argument thus illustrates the partly definitional, partly empirical character of coordinative definitions that is fundamental to Reichenbach's view.

This general view of the physical foundations of geometry reveals why the nature of spacetime is a question, not of whether a theoretical entity provides a causal explanation for appearances, but of whether the physical processes of measurement conform to geometrical laws. Reichenbach made this particularly easy to see in the case of Euclidean space. We begin with the coordination of spatial length with the coincidence of rigid bodies, and we stipulate that no "universal forces" distort them, so that one measuring-stick can compare lengths at different places. If our measurements (say, of the internal angles of a triangle formed by light rays) give the results required by Euclidean geometry, we can say that space is Euclidean; if they give other results, we conclude (again, excluding universal forces) that space has some non-Euclidean geometry. Given the initial coordination, the exact structure of space can be determined empirically. In keeping with Einstein's criterion for a satisfactory definition, we have "in every real case" an "empirical decision" about whether lengths are equal.

What if we were now to ask, how do we know whether Euclidean space – something we could never directly observe – is really the cause of these measurement results? Or, how do we know that a measured length represents length relative to Euclidean space? Evidently such questions miss the point. Spatial measurement has been defined by coordination with a basic physical process (motion of rigid bodies). To claim that space is Euclidean *only means* that measurements agree with the Euclidean metric; Euclidean geometry, if true, can't *causally explain* those measurements, because it only expresses the constraints to which those measurements will conform. This clearly does not imply that the content of spatial geometry somehow reduces to measurement operations. For Euclidean geometry systematizes those measurements and exhibits them as aspects of a formal structure, something more abstract and more exact than the appearances could express by themselves. To claim that that formal structure is *really* the structure of actual space is not to posit an underlying cause of the appearances. It is only to claim that, *modulo* the initial coordination, the appearances conform to the laws of that structure. This claim is no less a form of realism than the supposed causal postulate. But it is a form of realism that captures much more clearly the relationship between geometry and experience.

Thus, to talk of causal explanation is as *in*appropriate, in the case of spatial geometry, as it *is* appropriate in, say, the case of the kinetic theory of gases or the quantum theory of black-body radiation. In those cases we have a phenomenological law – the ideal gas law or the black-body radiation spectrum – and laws at a deeper level, governing processes that are not directly observed, from which the phenomenological law can be derived (or to which the phenomenological law can be reduced). Even without sympathizing with Mach's skepticism about unseen particles, one can at least understand the sense of his question: is it necessary, or justifiable, to hypothesize about such underlying causes if we only experience macroscopic phenomena? Of course there are more than sufficient reasons for a positive answer. But in the case of spatial geometry, the question doesn't even make sense. The theory of Euclidean space is fundamentally phenomenological: it is a formalized way of recognizing one kind of phenomenon (the comparison of freely-movable rigid bodies) as a tool for determining the objective relations among other phenomena (angles and distances between given objects). A particular measurement outcome might demand a deeper explanation – as, for example, the maximum height of a column of water is explained by the theory of atmospheric pressure. But that the height of the column agrees with the Euclidean metric is not causally explained by the theory that space is Euclidean; rather, it is part of the very meaning of the theory. The phenomenon is not reduced to a causal theory at a deeper level, but is simply exhibited – again, through the use of a coordinative definition – as conforming to a phenomenological theory. Indeed, the lack of any such deeper causal theory is precisely why a coordinative definition is required.[5] The result of such a coordination may indeed be regarded as a kind of explanation, in the sense that we achieve some deeper understanding of the phenomena just by recognizing that they conform to the laws of a certain structure. But this is evidently not the sort of explanation that infers an unobservable cause of the phenomena. To see this peculiar characteristic of physical geometry was one of the essential insights of the empiricist tradition in the philosophy of geometry.

In sum, Reichenbach's account of spatial geometry makes it quite obvious that the latter should not be regarded as an explanatory theory of the underlying cause of spatial relations. Why, then, has spacetime geometry come to be regarded that way? That is, why hasn't this insight of geometrical empiricism been considered in the philosophical discussion of spacetime?[6] I believe that this is because Reichenbach's notion of coordinative definition was simply too narrow. And its narrowness is precisely what gives this view its conventionalist and anti-realist overtones. Reichenbach apparently conceived of a coordinative definition as something very much like an operational definition: a coordinative definition relates a concept to some concrete thing that can be used to carry out a measurement – a standard meter, a light-signaling apparatus, a particular clock. Thus the metrical structure of a space has a very concrete significance. Spacetime, on the other hand, involves not only metrical relations but also states of motion. And for Reichenbach, the coordinative definition of a state of motion can only be the arbitrary distinction of a particular coordinate system as being at rest (1957, pp. 219–220). To speak of an "absolute" state of motion is, in Reichenbach's view, just to ignore the need for a coordinative definition.

Einstein's account of physical definitions, however, was considerably broader than Reichenbach's (even if he considered states of motion in the same way), and it captures the sense in which such definitions can be regarded as indicating real features of the physical world. His argument for special relativity illustrates this. If it were merely a question of finding a coordinative definition for simultaneity, then the use of light signals would not necessarily overthrow absolute simultaneity; it might be possible for relatively-moving observers to agree on simultaneity simply by allowing for the travel-time of the signals. This agreement is not possible, however, because of the invariance of the velocity of light. In other words, Einstein is coordinating time not merely to a particular concrete procedure, but to a system of natural laws – the laws of classical electrodynamics – which he regards as fundamental invariants. The coordination is made more vivid in Minkowski's (1908) formulation of the theory, where aspects of spacetime structure are explicitly coordinated with idealized physical processes defined by the most basic physical laws: in particular, paths of free particles are coordinated with timelike geodesics and paths of light rays with null geodesics. These physical coordinations form the basis for identifying the Lorentz transformations with the group of spacetime isometries. Even in the simple case of spatial geometry, the coordination, rightly understood, was never just to concrete objects (rigid bodies) or measurement operations, but also to a physical theory – the theory of free mobility of rigid bodies; only the comparative simplicity of spatial measurement made this circumstance easy to overlook. In the construction of Minkowski spacetime, however, it becomes much more evident that the concrete interpretation is inadequate, for the elements of spacetime geometry are coordinated with fundamental physical laws, and the metrical structure expresses the symmetries of those laws. Indeed, the very idea of spacetime arose out of Minkowski's recognition that the algebraic structure of special relativity defines – more simply, that structure *is* – the structure of a four-dimensional space (Minkowski 1908, pp. 81–83).

Given this broader interpretation of coordinative definitions, we can see that coordinatively defining states of motion is a much subtler process than Reichenbach allowed. It involves, not choosing a rest frame, but establishing laws of motion. While the use of coordinative definitions here may not be so "conspicuous" as in the metrical case considered by Reichenbach, then, it is nonetheless crucial. In fact, laws of motion become, through coordinative definitions, the postulates of spacetime geometry: the law that free particles travel uniformly in straight lines, for example, becomes by coordination the postulate that spacetime has an affine structure. In the case of relativistic spacetime, the coordination of the affine structure with the paths of free particles and the conformal structure with the paths of light rays completely characterizes the spacetime geometry. This gives us another way of looking at Malament's (1985) result: it shows that given the coordination of spacetime conformal structure to paths of light rays, the conformal geometry provides a physical definition of the state of rotation (failure of hypersurface orthogonality for a congruence of worldlines). And it gives us another way to express the fact that, in a relativistic spacetime just as in Newtonian spacetime, rotation and acceleration are "absolute" while velocity and rest are relative. Specifically, the states of rotation and acceleration can be coordinated with invariant dynamical laws, but there is no dynamical law with which rest can be coordinated; only an arbitrary concrete stipulation, as Reichenbach suggested, could define the difference between motion and rest. Where Reichenbach assumed that the need for such an arbitrary stipulation was a basic philosophical principle, we can now see that it is only a contingent aspect of the laws of physics.

What if we now ask, how do we know that spacetime is the cause of the difference between acceleration and non-acceleration? Or, how do we know that the accelerations that we measure in physical experiments are accelerations relative to spacetime? An "absolutist" or "substantivalist" answers that we infer the spacetime as the best explanation of those phenomena, which relationalism has trouble accounting for; a relationalist answers that assuming the existence of spacetime unnecessarily inflates our ontology relative to the observed phenomena. Once we understand the principle of coordination between spacetime geometry and physical laws, however, we see that these questions make no more sense in the context of spacetime than they did in the context of Euclidean space (cf. p. 324). When we say that a free particle follows, while a particle experiencing a force deviates from, a geodesic of spacetime, we are not explaining the cause of the difference between the two states or explaining "relative to what" such a difference holds. Instead, we are giving the physical definition of a spacetime geodesic. To say that spacetime has the affine structure thus defined is not to postulate some hidden entity to explain the appearances, but rather to say that empirical facts support a system of physical laws that incorporates such a definition. Well before Reichenbach – also perhaps more clearly and perceptively – Frege expressed the sense in which such a dynamical spatio-temporal definition, like the purely spatial definitions considered by Reichenbach, is also partly empirical; in particular, Frege's discussion indicates the sense in which such a definition still expresses a claim about physical reality. The distinction between acceleration and non-acceleration is "real", he noted, "in the same sense in which the constancy of a length is real":

> In both cases we have arbitrary stipulations, which, however, are so closely connected to the lawfulness of nature that they are thereby distinguished from all other stipulations which are mathematically and logically equally possible. If one wants to express this close relationship to the lawfulness of events with the word "real", one must do so in both cases. But perhaps the word "objective" is more suitable. (Frege 1891, p. 157)

In modern terms, that the distinction between acceleration and non-acceleration can be made empirically is precisely what is meant by the claim that spacetime really has an affine structure. The affine structure can't be the cause of that distinction, because it is defined by that distinction – just as Euclidean geometry is empirically defined by the agreement of measurements with the Pythagorean theorem. All we can ask about such a definition is whether it satisfies Einstein's criterion: does it provide an empirical decision, "in every real case", about whether a body is accelerating? Acceleration thus provides all argument against classical relationalism, not because it requires a causal explanation that relationalism can't give, but because it provides an empirically sound physical coordination for a kind of structure that relationalism will not allow.

In sum, then, these coordinative definitions – construed in a considerably more expansive sense than Reichenbach would probably allow – are the key to any connection that spacetime theories can claim to have with observable phenomena. Thus the proper sort of argument for a spacetime theory is not an argument from observable effects to their underlying cause, but, as with any empirical geometry, an argument for the coordination of established physical principles with geometrical structures. So the difference between "relationalist" geometry and "absolutist" geometry lies not in their metaphysical, but in their physical foundations – in the physical processes that they take to be fundamental to measurement. Because we were assuming that the "relationalist" geometry needed no argument at all, and that the "absolutist" theories entailed a radically different metaphysics requiring some extraordinary metaphysical argument, we have not really appreciated the fact that spacetime geometry is, after all, just another kind of physical geometry.

3. GENERAL RELATIVITY IN HISTORICAL AND PHILOSOPHICAL PERSPECTIVE

The foregoing analysis can illuminate the foundations of general relativity, by giving a clearer view of its place in the historical development of spacetime theories generally. General relativity is often presented as the endpoint of a succession of epistemologically-motivated "relativizations" of motion (e.g., Reichenbach 1957; Friedman 1983). I suggest, however, that such a view, while not entirely wrong, fails to explain how the three modern spacetime theories (Newtonian spacetime, Minkowski spacetime, and general relativity) have come to be established – especially in the case of general relativity, whose epistemological motivations turned out to be so misguided. If we ask what sorts of argument and motivation actually placed these theories on solid physical grounds, we see that there is a common element among all three: an argument for the coordination between aspects of spacetime structure and dynamical principles.

The inclusion of Newton sounds surprising at first, because tradition takes Newton's and Einstein's arguments about space and time to be philosophically quite opposite. Newton's arguments, according to tradition, are metaphysical while Einstein's, both for special and for general relativity, are epistemological; Newton offers inductive arguments for a metaphysical conclusion, while Einstein uses epistemological analysis to break down metaphysical notions; Newton infers the existence of a mysterious unobservable cause for observable dynamical effects, while Einstein works to banish the unobservable from physics altogether. A closer look will show, however, that Newton's arguments have the same basic form and purpose as Einstein's arguments for special relativity, and as the *successful* parts of his arguments for general relativity. Newton's thought-experiments concerning the water-bucket and the revolving globes are, in effect, arguments for a way of connecting physical processes with the structures of space and time.

Given what we know about Newton's theological convictions, especially his belief in God's place in space and time, it is tempting to interpret his Scholium on space and time as arguing for his fundamental ontological commitments. But if we look closely at what he says, we see clearly that the Scholium doesn't directly address those convictions. Instead it directly addresses two rather narrowly-defined questions: what conceptions of space, time, and motion are necessary to the project of the *Principia*, and what arguments are needed to make those conceptions plausible? The first indication of this fact is the place of these arguments in the book: they are in a scholium *to the definitions*. Having defined technical terms like mass, "*vis inertiae*", and "accelerative quantity of a centripetal force", he declines to define space, time, place, and motion because they are too familiar: he asserts, however, that "it will be convenient to distinguish them" into absolute and relative, etc. (Newton 1729, p. 17), according to their "properties, causes, and effects" (1729, p. 19). The important fact to note is that he does *not* say that space and time *are* absolute rather than relative. Nor does he claim, much less try to prove through dynamical examples, that absolute space and time *exist*. Whatever his deepest convictions about space and time might have been, all that Newton actually claims to do in the Scholium is to introduce some "convenient" technical distinctions and to show how they can be applied. When we read that "Absolute time flows equably without regard to anything external", or that "Absolute space remains similar and immovable" (1729, p. 17), we are accustomed to asking – whether we are "absolutists" or "relationalists" – what could possibly justify such strong metaphysical claims. What this question overlooks is the fact that for Newton, these are just the *definitions* of absolute space and time.

We also debate whether the water-bucket experiment really proves that absolute rotation, rather than relative rotation, is the cause of centrifugal forces. Here again we overlook the fact that Newton is trying to define something, namely absolute rotation. The experiment is described in a paragraph on "the effects which distinguish absolute from relative motion"; Newton points out that the spinning water in the bucket endeavours to recede from the axis of motion, and states that "the true and absolute circular motion of the water, which is here directly contrary to the relative, becomes known, *and may be measured by this endeavor*" (1729, p. 21; emphasis added). Surely Newton speaks plainly enough: centrifugal force is the criterion and the measure of absolute rotation. So it doesn't make sense to ask whether he has *established* that absolute rotation is responsible for the effect. He is *defining* absolute rotation as that which produces such an effect.[7] At the same time he is criticizing Descartes's definition of "motion in the philosophical sense" as motion of a body relative to contiguous bodies;[8] the bucket experiment shows that the water can be rotating in the Cartesian sense with or without any dynamical effect, since the dynamical effect is independent of the relative motion of the water and the bucket (1729, p. 21). The effect itself, meanwhile, does provide a consistent physical measure of the rate of rotation. Newton closes by showing that since it depends on identifiable physical forces, his definition can be consistently applied even in the absence of observable reference bodies. For if two globes joined by a cord are alone in an otherwise empty universe, the tension on the cord still provides a criterion and a measure of the amount of true circular motion (1720, p. 22).

We know that since his definition depends on physical forces, it is only as good – as consistently applicable – as the laws of motion that those forces obey. But if the laws do hold, then Newton's criterion can be applied. And even Newton's most "relativistic" critics (Leibniz and Huygens) believed in those laws. Relative to the laws of classical physics, Newton's definitions of absolute velocity and rest are flawed, because the laws respect Galilean relativity. This is why Newton has no coordinative definition for absolute rest, but only a definition of the concept by other concepts (1729, p. 19). But as long as Newton's laws hold, his definitions of absolute rotation, absolute acceleration, and absolute time all satisfy Einstein's criterion: they can always provide an empirical decision about whether a body is rotating, whether a particle is accelerating, and whether two time-intervals are equal.

I emphasize the role of dynamical laws in order to make it clear that, in asserting that Newton was proposing definitions required by his theory, I do not imply that he was an instrumentalist or conventionalist about space and time, or that there is something arbitrary about such definitions. Again, we can define a physical concept by any criterion we wish. But it is an empirical question whether the regularities of the universe are such that our criterion can be consistently applied; Newton's empirical comparison of his definition of rotation with Descartes's makes precisely this point. The distinction between rotation and non-rotation is presented as a definition, but that the distinction can be made is an empirical claim that rests on the viability of Newtonian mechanics. And it makes no sense to say that Newtonian spacetime is the unobservable cause of that distinction; rather, the existence of such a distinction is part of what is intended by the claim that the world has the structure of Newtonian spacetime. We now say that that structure contains superfluous ontology (e.g., absolute simultaneity), but we can do so only because we have adopted physical laws that require a different geometrical structure.

The foregoing analysis suggests that the fundamental question of Newton's scholium was not whether space and time are absolute, or whether absolute space and time really exist. Instead, the question was how the geometrical distinctions implicit in the structure of absolute space could be coordinated with the dynamical distinctions implicit in the accepted laws of dynamics. In any case, the crucial importance of this question for contemporary philosophy does not depend on whether my analysis turns out to be historically correct. The analysis also suggests what kind of philosophical argument enabled Einstein to overthrow Newton's basic principles and replace them with new ones. What Einstein presented in 1905 actually turns out to be analogous to Newton's water-bucket argument against Descartes. Einstein asserts, as Newton did, that a familiar conception (that of simultaneity) cannot be consistently coordinated to or measured by a lawlike physical process; he then proposes a new definition founded in well-established dynamical laws (the laws of electrodynamics, especially the constant velocity of light propagation). So much emphasis has been placed on the *destructive* aspect of Einstein's arguments – the critique of absolute time – that philosophers have often missed the significance of this *constructive* proposal for a new coordination between geometry and physics. In particular, the traditional epistemological view of geometrical relations has led us to overlook the fact that the new geometrical structure is coordinated to a physical theory, and therefore that the relativistic account of "relations among bodies" is also founded on that theory – not on some purported reduction of theory to what is immediately observable. In short, Einstein's 1905 argument is not for an epistemological reduction, any more than Newton's was for a causal-explanatory hypothesis; both present essentially the same kind of argument for a new coordination between geometry and physics.

This last point becomes clearer if we note that Einstein's argument linking the classical concepts of length and time with absolute simultaneity, and absolute simultaneity with the possibility of infinite signal velocities, had been presented two decades earlier in Thomson (1884). At that time, Thomson's argument did not initiate any great conceptual change. Nor should it have done: those concepts of length, time, and simultaneity were presuppositions of the classical laws and represented invariants of Galilean relativity. The classical structure of inertial frames (also introduced in Thomson 1884) was conceived as a representation of those invariants, and no reason was offered at the time to abandon those laws, or to coordinate spatio-temporal structure with some other laws. So there was no compelling reason, at the time, to elevate the practical impossibility of determining absolute simultaneity to a problem of principle. Providing such a reason was the unique contribution of Einstein (1905): he argues that the established physical principle of the invariance of the velocity of light yields a consistent definition of simultaneity – and, ultimately, a new invariance group. And just as Newton was able to show that his coordinating principles led to a solution of an outstanding scientific problem of his time – determining the structure of the planetary system – Einstein could show that by coordinating spatio-temporal concepts with the theory of light propagation, instead of classical mechanical laws, he could resolve questions about the "asymmetries" of Maxwell's equations (cf. Einstein 1905, p. 35) and the significance of the Lorentz contraction. Thomson's epistemological arguments were merely intriguing; Einstein's proposal for a new coordinating principle turned out to be revolutionary.

Against the background of these analyses of Newton's scholium and Einstein's argument for special relativity, we can examine Einstein's philosophical case for general relativity in a new light. He thought that extending the relativity postulate involved an epistemological critique of Newtonian and special-relativistic spacetime theories, but, as we have seen, this is precisely the part of his case that does not succeed. But if Einstein's philosophical motivations in developing general relativity were so confused, we might wonder how they could have led to such a successful theory – especially a theory whose persuasiveness has always been thought to derive more from its philosophical soundness than from its empirical confirmation. The successful part, we can now see, is precisely that argument which follows the pattern of Newton's discussion of rotation and Einstein's own critique of simultaneity.

The essential coordinating principle is the equivalence principle. First it leads to a destructive argument analogous to Newton's argument against Descartes. That argument is not that all reference frames are equivalent, but that the classical coordination of uniform motion in a straight line with the paths of force-free particles cannot be carried out unambiguously or consistently. In a universe where the gravitational field is ubiquitous, the classical theory carries out its coordination of geometry and physics by requiring that every gravitational motion be decomposable into a uniform motion and (any number of components of) a gravitational acceleration toward some source (or sources) of the field. But the equivalence principle assures us that this decomposition can never be unique, because free fall is not locally distinguishable from uniform motion. In fact such a decomposition implies a violation of general covariance, for it amounts to an arbitrary choice of a coordinate system (Einstein 1916, p. 114). We can choose any coordinate system and identify its straight lines as geodesic worldlines; then we can construct the gravitational field just as is required in order to make up the difference between these geodesics and the actual motions. (This is essentially the form in which Einstein actually represented gravitational curvature, for his notation required him to pick a "flat" derivative operator from some coordinate system, and then to represent the curvature in the Cristoffel symbols. Cf. 1916, p. 132.)

The constructive argument then shows that the arbitrariness of the old coordination leads to a new one (cf. Einstein, 1916, pp. 142–143). That is, the covariant essence of the gravitational field is the sum of the spatio-temporal and gravitational parts (as it is the sum of the coordinate-dependent "flat" derivative operator and the corresponding Cristoffel symbol), rather than any particular way of decomposing the sum. Therefore that sum, the actual path of a freely-falling particle, offers an unambiguous, coordinate-independent physical process with which to coordinate the geodesic structure of spacetime.

We now see more clearly the special philosophical significance of general covariance in the context of general relativity: its role in establishing this new coordinative definition – the coordination of spacetime geodesics with free fall – is precisely the physical role that general covariance plays in general relativity and does *not* play in flat spacetime theories. Moreover, we can see that the existence of a privileged state of free fall is not causally *explained* by the existence of curved spacetime. Rather, the existence of such a unique state, together with the fact that non-gravitational forces can be measured with respect to that state, is part of what is meant by the claim that spacetime is curved in the presence of mass-energy. In the end, general relativity succeeded in spite of its original epistemological motivations, because it provided such an empirically solid coordination between a geometrical structure (the curved affine structure) and a physical principle (the equivalence principle).

4. CONCLUSION: THE METAPHYSICAL CONTENT OF SPACETIME THEORIES

Placing the foundations of general relativity in proper perspective means recognizing its essential similarity with Newton's theory of space and time and with special relativity. Beyond merely acknowledging the formal similarity of all three as spacetime theories (cf. Friedman 1983), we must appreciate the similarity of their philosophical foundations and of the metaphysical claims they make. Spacetime theories are not the sort of theory that Einstein thought they were, because they don't really make the sort of metaphysical claim that he thought they make – in particular, spacetime theories do not claim that some unobservable thing is the cause of observable effects. Instead they make a more restricted, but perhaps more profound and certainly more useful claim: that particular physical processes, governed by established physical laws, can be represented by aspects of geometrical structure in the universe. And this claim provides the only physically meaningful sense in which the universe can be said to *have* a geometrical structure. More precisely, a claim such as Minkowski's (1908), that the structure determined by a particular set of physical laws is the structure of a particular four-dimensional space, expresses the only physically meaningful sense in which the universe can be said to have a spacetime structure. To characterize the sense in which spacetime structures are real was also the aim of substantivalism. If it hasn't completely succeeded in this attempt, I suggest that this is because substantivalism has conceded relationalism's misconception of its task, as one of justifying the inference from geometrical phenomena to their unobservable cause.

Obviously, realism about spacetime faces the same philosophical challenges as realism about any other aspect of physics. It does not face a special challenge of the sort posed by Einstein, however, once we understand spacetime theory as a form of physical geometry. Like all physical geometry, spacetime theory explains phenomena of motion just to the extent that it exhibits the structural constraints to which the phenomena conform; this is why claims about the structure of spacetime have clear empirical content and have always been open to empirical revision. Thus the very empirical modesty of its claims – in contrast to those of causal-explanatory hypotheses – ought to protect spacetime theory from the sort of epistemological criticism it has traditionally encountered.

Incidentally, my analysis also suggests what it would take to realize the strong version of "Mach's principle" as an empirical theory. General relativity recognizes that "distant masses" influence the inertial behavior of bodies by influencing the curvature of spacetime, but it has made no progress on incorporating the most radical "Machian" claim, that the inertia of a body is *entirely determined* by the distribution of masses and must vanish when no other masses are present. The closest Einstein ever came to this goal was to insist that the universe is finite and closed – thus eliminating *by fiat* the possibility that a single body has inertia in the absence of other masses. At least a plausible explanation for this failure is that this proposal for a Machian theory lacks any coordinating principle. Because it has no way of singling out the state of zero inertia, it has no criterion or measure of other bodies' contributions to the inertia of a particular body, except relative to the body's initially-given mass. The theory of curved spacetime is an empirical theory in virtue of its coordinative definition, that is, insofar as it defines physical criteria for the state of geodesic motion. The strong version of Mach's principle, in the continuing absence of such a definition, is sheer physical speculation. For while the distant masses themselves may be observable, their determination of the inertia of nearby bodies is not. It is therefore not general relativity, but this extreme Machian theory that, despite its empiricist motivations, actually postulates an unobservable, unmeasurable cause for observable effects.

The same analysis offers a philosophical perspective on possible alternative theories to general relativity. The Brans–Dicke theory, for example, often considered the most convincing of the recent alternatives, postulates a long-range scalar interaction in addition to the spacetime metric; the purpose of this field is to realize a version of Mach's principle, in which the scalar field would carry the influence of distant bodies on each other's mass. To make this theory empirically plausible, on my view, would require finding a physical process to which the measurement of this scalar field could be coordinated. In fact such a process has been defined: violations of the "strong equivalence principle" (cf. Will 1993) can be represented as measures of the strength of the Brans–Dicke field. While no experiment has so far unambiguously detected such a violation, at least it is clear how the presence of the scalar field has become open to empirical investigation. Another general type of alternative is the theory of gravity as a quantum field in flat spacetime. What philosophical advantage does general relativity have against such a theory? Only that general relativity has an established coordinative definition for its spacetime structure; if such a flat-spacetime theory is to succeed – as many physicists suppose it must – it will have to provide a way to measure the acceleration of freely-falling frames relative to the Lorentz frames of the flat spacetime. In other words, it will have to show that there is, after all, a physical process to which to coordinate the structure of flat spacetime. The philosophical virtues of a spacetime theory depend on the physical coordinations that make them into empirical virtues.

NOTES

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[1] Friedman (1983), for example, introduces methodological considerations, such as unity, simplicity, and explanatory power, to justify belief in spacetime as the causal explanation of relative motions; he explicitly compares this to the use of the kinetic theory to explain the behavior of gases. Earman (1989) uses a combination of mathematical and epistemological arguments against Friedman's position, evidently sharing Friedman's view of the fundamental issue. The original and most influential statement of this view, of course, is Einstein's (1916) critique of absolute rotation. He imagines two bodies (S_1 and S_2) in uniform rotation relative to one another, one of which is a sphere and the other an ellipsoid of revolution, and he asks, "What is the reason for this difference in the two bodies?" Newtonian mechanics, he continues, invokes the "privileged space" R_1 in which S_1 is at rest. "It is therefore clear that Newton's mechanics does not really satisfy the requirement of causality . . . since it makes the factitious cause R_1 responsible for the observable difference in the bodies S_1 and S_2" (1916, pp. 112–113). For further discussion see DiSalle (1992).

[2] See, for example, Earman (1989, Chap. 9); and Maudlin (1993).

[3] It has been occasionally criticized, however; see, for example, Weyl (1918, 1949) and Reichenbach (1957). Both pointed out that even relative motions can only be determined under the assumption of a fixed structure within which relative distances can be determined; they also pointed out that according to general relativity, spacetime cannot be expected to have such a structure. Reichenbach referred to this situation as the "relativity of relative motion" (1957, p. 220). See also DiSalle (1994).

[4] A similar remark is made by Reichenbach (1957). See also DiSalle (1994, p. 282).

[5] This is not to say that there could not be a deeper causal theory that might explain the structure of space or of spacetime. The strong interpretation of Mach's principle, in which the inertial structure of spacetime is explained as the effect of a long-range interaction, might yield an instance of such a theory if it could be brought to fruition. (Cf. below, p. 334.) My point is only that the geometrical theories that have actually prevailed in physics (and that have been the focus of philosophical discussions) have not been causal-explanatory theories, and that a spacetime theory that did provide a causal account (like certain Machian theories) would be an altogether different sort of theory from what we currently use.

[6] It has been considered quite seriously in the physics literature: most systematically by Weyl (1923), and more recently by Ehlers et al. (1972).

[7] This fact has already been pointed out by Stein (1967) and Schlick (1920, p. 40). Interestingly, Schlick accepted Einstein's views on the relativity of motion, but recognized that even if Einstein's physics (as he thought) no longer required absolute rotation, classical physics nonetheless had provided a perfectly good coordinative definition of it. He concluded that the concept of absolute rotation was not "epistemologically defective", but merely based in an outmoded physics.

[8] This is also pointed out by Stein (1967), Laymon (1976), and DiSalle (1992). They agree also that Newton is not here trying to prove the existence of absolute space, though they do not consider Newton's definitions from the geometrical point of view developed in this paper.

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