On the Cartesian Ontology of General Relativity: Or, Conventionalism in the History of the Substantival/Relational Debate*

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ABSTRACT

Utilizing Einstein's comparison of General Relativity and Descartes' physics, this investigation explores the alleged conventionalism that pervades the ontology of substantival and relationist conceptions of spacetime. Although previously discussed, namely by Rynasiewicz and Hoefer, it will be argued that the close similarities between General Relativity and Cartesian physics have not been adequately treated in the literature—and that the disclosure of these similarities bolsters the case for a conventionalist interpretation of spacetime ontology.

1. Introduction. In a new appendix to the fifteenth edition of his *Relativity: The Special and the General Theory,* Einstein draws a comparison between his General Theory of Relativity (GTR) and Descartes' natural philosophy of space, matter, and motion, concluding that General Relativity "confirms Descartes's conception [of space] in a roundabout way" ([1952] 1961, 136). What is surprising about Einstein's new-born fondness for Descartes' physics is that it occurs relatively late in his career, long after his disenchantment with a Machian interpretation of GTR, which is often classified as relationist. (Machianism in GTR can be characterized as the view that the metric tensor, g, is fully determined by the material contents of spacetime, as represented by T; see Hoefer 1994). Yet, Descartes' physics is often taken as a paradigm instance of relationism, thus making Einstein's endorsement of Cartesianism all the more mysterious. There are a number of these favorable comparisons between GTR and Descartes' physics in Einstein's later essays, moreover; e.g., "I wished to show that space-time is not necessarily something to which one can ascribe a separate existence, independent of the actual objects of physical reality. Physical objects are not *in space,* but these objects are *spatially extended.* In this way the concept of "empty space" loses its meaning" (1961, vi).

Until recently, few commentators have assessed Einstein's analogy, although the alleged similarity of GTR and Cartesian physics did surface in papers by Rynasiewicz and Hoefer on the ontology of spacetime theories: Rynasiewicz (1996) presents Einstein's argument as evidence of the difficulty, if not irrelevance, of applying the traditional "substantival versus relational" dichotomy to modern physics; while Hoefer (1998) disputes this claim by indicating various ways in which Descartes' physics differs from Einstein’s GTR. The point of contention rests on whether GTR does resemble, at least in some respects, Descartes’ supposedly “relationist” physics (as Einstein and Rynasiewicz believe), or is more closely related to substantival conceptions of spacetime (as Hoefer claims). In opposition to Hoefer, it will be demonstrated that a close, and somewhat uncanny, resemblance does indeed exist between Descartes’ relationist physics and GTR, but that this similarity goes beyond the factors cited by both Rynasiewicz and Hoefer (as well as Einstein). This (eccentric) exercise in theory comparison is intended to bring to light an important fact about the content of past spacetime theories, especially relationist theories: namely, that there are few, if any, common features *among* past hypotheses commonly dubbed “relationist” that can be used to differentiate them from substantival/absolute hypotheses, and this realization compromises the claim that there exists a clear, continuous line of conceptual descent from past substantival/relational conceptions of space and time to current debates on the ontology of GTR.

2. “If Descartes’ Physics is good enough for Einstein, it should be good enough for us.” Einstein’s interest in Cartesian physics stems in large part from his conviction that Descartes helped to usher in “the *concept of the field* and its final claim to replace, in principle, the idea of a particle (material points)”(1961, 144). The legacy of Newtonian mechanics, on Einstein’s estimation, led to a conception of “physical reality” comprised of material points whose interactions take place against an independently-existing background spatiotemporal framework (i.e., that can exist in the absence of all material points). Physical fields, on the other hand, do not require an independent background space, for they “only occur within a ponderable mass: they serve only to describe a state of this matter" (145). Einstein thus conceives the metric tensor, g (or g_{ik}), as a physical field akin to the electromagnetic aether; i.e., as a gravitational field, which exists "inside" a physical entity of some sort. We can designate this view "metric field relationism":

> If we imagine the gravitational field, *i.e.* the functions g_{ik}, to be removed, there does not remain a space [of the Minkowski type] but absolutely *nothing*. . . . There is no such thing as an empty space, *i.e.* a space without field. Space-time does not claim existence on its own, but only as a structural quality of the field.
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> Thus Descartes was not so far from the truth when he believed he must exclude the existence of an empty space. . . . It requires the idea of the field as the representative of reality, in combination with the general principle of relativity, to show the true kernel of Descartes' idea; there exists no space "empty of field". (155-156)

2.1. (R1) versus (R2) Relationism. Of course, it is possible to interpret Einstein's gravitational field, g_{ik}, as a form of substantival space rather than a material field (see, Hoefer 1998). Nevertheless, if confined to analyzing Einstein's analogy on its *own* grounds, then a likely substantivalist line of attack would be to demonstrate that there does not exist a correlate of Descartes' concept of relationism in GTR—and this naturally leads to the question of the type of relationism purportedly endorsed by both Cartesian physics and GTR. Einstein's discussion clearly places the correspondence between these two theories on their shared rejection of the existence of "substantival" space; i.e., as type of substance that can exist apart from, respectively, matter or g_{ik}. This "weaker" form of relationism, often labeled (R2), is implicitly contained in all relationist theories, but the more important question centers on the "stronger" variety of relationism, (R1), which holds that all motion must be the relative motion of bodies (using the classificational scheme in Earman 1989). Descartes' identification of matter with "extension"(three-dimensional spatiality) leaves no doubt as to his implicit endorsement of (R2),[i] but did he accept (R1) as well?

In Rynasiewicz (2000), the central importance of a strict, (R1) conception of motion to relationism has been challenged on several fronts, the most important (for our purposes) being the commitment to a purely reciprocal view of motion within the more influential historical versions of relationism. As Rynasiewicz points out, the definitions and hypotheses of motion put forward by these theories often do not directly support (R1), and many seem to openly violate it. Besides Leibniz, who held that bodies had determinate states of individual motion (see, e.g., Leibniz [1686] 1989, 51), Descartes's physics also makes an absolute distinction between a body that is, or is not, undergoing a "change of place"(motion); although Rynasiewicz fails to mention that change of place is reciprocal, such that one can assign the motion to either the surrounding bodies or the contained body (that both determine its "place" as a common boundary; Pr II 15, 25).

Although studying the scattered comments and definitions of motion by these relationists can often reveal their anti-(R1) tendencies, Rynasiewicz's argument would have gained more strength if the actual details of these historical relationist theories were examined at greater length. In particular, the relationist analysis of impact, along with their conserved quantities, display a strong predilection for inertial motion and/or individual states of motion. In Descartes' case, the application of his seven collision rules hinges crucially on the individual assignments of bodily motion (Pr II 46-52), such that the very outcome of a given collision (e.g., whether the bodies rebound in opposite directions, or continue in the same direction) depends on the frame-dependent assignment of speed attributed to each colliding bodies. The relationally unpalatable nature of these rules, and the attempt to rectify Descartes' errors, eventually led natural philosophers to the realization of the importance of "privileged perspectives" for viewing collisions and conserving kinematical quantities. In fact, Huygens' discovery that the center-of-gravity (center-of-mass) reference frame could uphold Descartes' "quantity of motion" (size times speed) in each collision has generally not been given the credit that it deserves for ushering in a long tradition that links the success of a relational physics to a set of privileged reference frames, especially the center-of-gravity frame (see, Huygens 1950, vol. 16, 92). After Huygens, Leibniz appealed to such frames in the development of his own theory of impact (which supposedly embodies his relationist doctrine, the "equivalence of hypotheses"), and Mach even provided a formula for determining the center-of-gravity frame as required by his anti-Newtonian relationism.[ii]

In short, despite the (R1)-rhetoric, the development of relationist physical theories has relied heavily on the assignment of individual states of bodily motion from the perspective of privileged reference frames—and this procedure can hardly be seen as supporting a robust form of (R1) such that "all motion is the relative motion of bodies". Rather, by linking the success of the physical theory to a subclass of possible frames, the opposite would seem to be the case, since not all assignments of individual states of motion are equal. Put differently, the absolutist/substantivalist can claim that the spacetime required to set up the center-of-mass frames presupposes, or covertly invokes, a form of inertial structure that violates (R1). Since (R1) supposedly implies a spacetime structure, like Leibnizian spacetime, that is restricted to purely relative differences among bodily velocities, accelerations, etc., the center-of-mass procedure violates (R1) relationism by requiring a process or structure that can link the distinct center-of-mass frames located at each point (spatial slice) along a body's trajectory. Yet, any such structure, like the affine connection ∇, violates the prohibition on the purely relative quantities associated with the more sparse Leibnizian spacetime. In response, the relationist can claim that the physical laws can *themselves* pick out the frames that, say, conserve Descartes' quantity of motion, thus avoiding a commitment to ∇ (see, Slowik 1999). Yet, once again, the substantivalist could reply that this strategy simply masks an underlying ∇ structure, or ∇-surrogate; in other words, the conjunction of Descartes' physical laws and the invariants of Leibnizian spacetime constitute a structure similar to ∇, although now limited to linking a select class of center-of-mass frames across time. Additionally, one can state the problem as a species of underdeterminism (in "hole" argument fashion), since the future frames, at t_{n+1}, that conserve quantity of motion cannot be uniquely determined given its conservation from an initial frame at t_n (see, Slowik 2002, chapter 9). Consequently, even if the privileged frames can always be tied to material bodies (which may not be the case for Huygens, who accepted a limited form of vacuum[iii]), the relationist may be restricted to the more modest claim that their theory merely eschews the perspective of substantival space in explaining motion in favor of privileged material reference frames (and possible surrogate ∇); or, more simply, the relational theory accepts just (R2).

Unfortunately, (R2) may not be a sufficient means of differentiating relationism from substantivalism, either. In Stein's famous discussion (1967), for instance, it is argued that Newton's "bucket experiment" (in the scholium on space and time in the *Principia,* Newton [1687] 1999, 408-415) is only intended to make the more limited claim that the absolute motion required to explain the water's rotation cannot be defined, in the Cartesian sense, as a motion relative to the sides of the bucket (see, also, Rynasiewicz 1995). The *Principia* does *not* postulate the existence of space as an "entity" (although his earlier essay, “De gravitatione”, Newton [1666?] 1962, may), so the scholium is itself consistent with (R2) relationism *if* the form of “absolute” space and time sanctioned by Newton is conceived along the lines of a mathematical abstraction or generalization from the relations among bodies (in order to define “absolute” motion, etc.). To take another example, the close similarity between supersubstantivalism (which holds that space is the only predicable substance, as discussed in Sklar 1974, 221-224) and Descartes’ brand of plenum relationism (matter=space) has often prompted the remark that only a conventional (or conceptual) distinction separates the two hypotheses. This last point is nicely demonstrated in Barbour’s relational utilization, or appropriation, of Wheeler’s geometrodynamics (since the latter theory is often identified as supersubstantivalist; see, Barbour 1999, 167; and, Sklar 1974, 221-224). And, indeed, is there really any difference between metric field substantivalism and metric field relationism (but see section 2.3 below)? Accordingly, even if (R2) is a necessary condition for a relational classification, it is not sufficient—and, of course, a “necessary and sufficient” condition is required. Specifically, if the (R2) thesis alone is incapable of settling the ontological dispute in a case as apparently obvious as Newton’s natural philosophy, or supersubstantivalism versus Cartesianism, it would seem even less capable of procuring an answer in the more complex environment of GTR.

2.2. Subtle Fluids and Fields. Hoefer’s main criticisms of the Cartesian-GTR analogy is based on a perceived dissimilarity in the function of the metric of GTR and the “subtle fluids” of Cartesian physics. Descartes’ vortex theory had strived to explain the orbits of the planets by situating them (at rest) in large circling bands of minute material particles, which consist of either the atom-sized, globules (secondary matter) or the “indefinitely” small debris (primary matter) left over from impact and fracture of the larger elements (with tertiary matter comprising the largest, macroscopic material element, Pr III 48-54). This three-part division of matter, along with the three laws of nature, are responsible for all cosmological phenomena in Descartes' system. In commenting on the alleged resemblance of this "subtle fluid" to the metric of GTR, Hoefer argues:

> The metric field [of GTR] explains planetary motions, a job that Descartes' vortices tried to do, though obviously not in the same way. In important ways, though, the metric does much more than Descartes's subtle fluids. As Rynasiewicz points out [1996, 283], those fluids did not fill all of space, and so could not play the role that g_{uv} plays of defining all spatial distance relations. The metric also serves to define absolute acceleration and rotation, a function that Descartes's relationism could not allow *any* material thing, no matter how pervasive, to perform. The points of resemblance between the 'ether' or metric field of GTR and Cartesian effluvia are interesting, but by no means do they outweigh the much stronger bond between the metric and Newtonian substantival space. (1998, 460).

In the remainder of this essay, it will be argued that Hoefer's final estimate is incorrect: GTR not only resembles Descartes' theory (contra the reasons cited by Hoefer), but the metric of GTR may, in fact, bare a stronger relationship with Descartes' theory in various respects than with Newton's substantival space.

Overall, Hoefer's (and possibly Rynasiewicz's) analysis of Cartesian physics probably stems from an oversimplified conception of the ontology and function of both matter and force in Descartes' system, in particular, their intertwined roles in explaining all material interactions and motion. In a footnote, Hoefer states: "the fluids of the vortices whose job was to explain the orbits of the planets were *not* like nineteenth-century ethers in that they did not fill space. They were in direct contact with the planets, and perhaps even filled the fine gaps in all ordinary bodies, but that is very different from filling all space uniformly [as does the metric of GTR]" (1998, 460). Although this observation is correct as regards the role of the primary and secondary elements, it is unfortunately irrelevant to the main issue; namely, understanding Descartes' explanation of planetary motion and "gravity". It is not just the primary and secondary elements that account for these phenomena, such that tertiary matter is a *passive* recipient of the forces exerted by the first and second elements—rather, the centrifugal tendencies of *all* Cartesian matter is actively involved in these processes, including the tertiary matter of which the celestial bodies are largely comprised. As described in Pr III 140, a planet or comet comes to rest in a vortex band when its radially-directed, outward tendency to flee the center of rotation (i.e., "centrifugal" force) is balanced by an equal tendency in the primary and secondary elements that comprise that circling vortex ring. If the planet has either a greater or lesser centrifugal tendency than the small elements in a particular vortex, then it will, respectively, either ascend to the next highest vortex (and possibly reach equilibrium with the particles in that band) or be pushed down to the next lowest vortex (which accounts for the phenomenon of gravity, as well). In essence, all Cartesian matter is actively involved in the various hypotheses of celestial and terrestrial motions. Therefore, contra Hoefer, the metric of GTR and Cartesian matter both explain planetary motions, and both "fill" all of space.

Hoefer further contends that the metric of GTR defines absolute acceleration and rotation, whereas Descartes's relationism cannot allow material occupants to perform this function. At face value, this criticism seems to misconstrue Descartes' account of motion, which (as mentioned above) does allow an "absolute" distinction to be made between an object that is, or is not, undergoing a "change of place" (where "place" is *defined* as the common boundary of the contained and containing bodies). Although Descartes does not address the question of accelerations and rotations directly in his definition of motion, it is clear that a similar appeal to his concept of place could likewise determine these types of motions (possibly in conjunction with some of his additional hypotheses, such as the use of the oppositely-directed motions of smaller bodies across the surface of a larger body, Pr II 30, that identify the larger body's transfer).

Yet, a more intriguing resemblance between GTR and Cartesianism can be drawn if one investigates the apparent interrelationship between Descartes' hypotheses of motion and individual material "body", bearing in mind their additional connection to the universally conserved "quantity of motion" (size times speed). On Descartes' cosmology, all of matter (space) was originally homogenous and divided into equal parts before God imparted an invariant amount of quantity of motion to the universe (Pr III 46). This conserved motion, which can be likened to a universally conserved "force", ultimately resulted in the division of the homogenous matter into the three different material elements that comprise the current cosmological picture. Now, the Cartesian correlate of the metric of GTR would, presumably, consist of the surfaces, shapes, volumes of all material bodies, given the identification of spatial extension with matter; whereas the Cartesian version of the stress-energy content of space, T, would be represented by either the same material field (since space=matter) or by the conserved quantity of motion, as a universal "force" or "energy". Consequently, much like in GTR, a direct interrelationship is manifest between the content of the spacetime (either matter or quantity of motion) and the metric (i.e., the division of three-dimensional extension into particular volumes and surface areas, or bodies, which thus includes the distances between bodies). Put differently, the relationship between the geometric content and the material content of the

Cartesian theory is quite radical, and it goes beyond the mere identification of spatial extension with matter. The very concept of place—a metrical notion—cannot be isolated from the relative positions and motions of *bodies*—and hence, matter and quantity of motion. This direct interrelationship is revealed in Descartes definitions of both motion and body (and thus place), an explanation that no doubt verges on circularity, but which is best viewed as revealing their essentially *interrelated* content, such that both motion and body are "on a par" ontologically: [motion] is *the transference of one part of matter or of one body, from the vicinity of those bodies immediately contiguous to it and considered at rest, into the vicinity of [some] others.* By *one body,* or *one part of matter,* I here understand everything which is simultaneously transported. . ." (Pr II 25; original emphasis). In short, if a philosopher is seeking an Early Modern theory of physics that exhibits the type of interconnection between the material and metrical aspects as found in GTR, then Descartes' theory is the natural choice, since the independent and "immutable" nature of Newton's absolute space rules out any form of *reciprocal* interrelationship with the material content of the spacetime.

2.3. The Vacuum Solutions Problem. A substantivalist might respond to these alleged similarities by citing the well-known existence of vacuum solutions to GTR, i.e., where the metric can take any number of determinate forms although $T = 0$. In Descartes' theory, as presented above, the spatial and material aspects cannot be separated, which thus raises serious obstacles for our proposed Cartesian-GTR analogy.

While the vacuum solutions remain a challenge for Machian interpretations of GTR, it is unclear that they pose a serious problem for "metric field" relationism.[iv] As a "physical" field (gravitational energy), g would still exist in the $T = 0$ models, although there would be no matter (stress-energy) to “interact” with this field. If, in addition, gravity waves are present, then one could follow the suggestion by Earman and Norton (1987) that identifies these gravitational waves (and thus the metric field that carries them) with a type of physical content of the matter-less spacetime, since “in principle [the wave’s] energy could be collected and converted into other types of energy, such as heat or light energy or even massive particles” (1987, 519). Hoefer (2000) tries to block this maneuver by showing that it depends on a well-defined notion of the stress-energy carried by the gravitational field, which, he concludes, is not actually sanctioned by GTR. Specifically, the problem arises because the term that represents the stress-energy of the gravitational field, t^{ab}, is a pseudo-tensor, where “its non-tensorial nature means that there is no well-defined, intrinsic ‘amount of stuff’ present at any given point” (2000, 193). Yet, Hoefer’s response is not without its own set of problems, for it seems to entail that the energy lost by a gravity wave source is a *real* loss, such that the energy is not simply somewhere else in space. Likewise, the energy gained by a gravity wave detector is a real gain (in apparent *ex nihilo* fashion). As Hoefer himself admits, “such a perspective seems to strain our general cause-effect intuitions by positing a cause-effect relationship without an intermediary carrier” (196).

Moreover, if we explicitly identify the gravity wave carrying “capacity” of g with Cartesian quantity of motion (which is admissible since matter=space), then the ill-defined nature and function of Descartes’ conservation law can be seen to resemble the equally uncertain conservation of stress-momentum in GTR. After demonstrating (incorrectly) how quantity of motion is conserved in the locally-defined collisions of two bodies, Descartes infers that quantity of motion is conserved globally—from the primary elements that fill the wake of moving bodies to the large-scale motions of vortices—yet, he never explains how these diverse phenomena actually conserve quantity of motion (see, Slowik 2002, chapter 5). Accordingly, there is a "holistic", and thus (quasi-)non-linear, character to Descartes' quantity of motion that mirrors the non-linear aspect of GTR's field equations. Quantity of motion is likewise equally non-tensorial: although specific coordinate systems can conserve quantity of motion, most do not (even among inertial systems). Furthermore, it is not clear that a relational interpretation of the relevant conserved quantity requires a tensor formulation: as long as there exists at least one reference frame that measures a non-zero quantity of motion or t^{ab}, that may be sufficient (albeit awkward) for the relationist.

Finally, the vacuum solutions to GTR that do not contain gravity waves also find a natural analogue in Descartes' system. As noted above, God divided extension into equal parts prior to the introduction of a conserved quantity of motion (Pr III 46). Hence, since motion and body are inter-defined, God's ability to make different geometric distinctions in extension *before* material bodies and their motions are formed is comparable to the choice of metric in the vacuum models of GTR without gravity waves. These God-induced partitions of extension are quite different from motion's normal role in bodily division, needless to say; but they do suggest that there are unusual circumstances wherein it makes sense to entertain metric differences in Cartesian extension (i.e., shape, volume, etc.) without quantity of motion (much like the equally atypical vacuum models of GTR).

3. Conclusion. Admittedly, our investigation into the correspondence between GTR and Descartes' physics has been somewhat whimsical; yet it does have a serious purpose. If, as Einstein believed, GTR can be successfully compared to Cartesian physics, then the simplified historical surveys of the "substantival versus relationist" debate often encountered in modern philosophy texts are seriously misleading. This does not necessarily mean that an investigation into the ontology of modern spacetime theories is irrelevant, of course: it only means that the attempts by present-day philosophers to draw a continuous line of development from past theories dubbed "substantival" or "relational" to contemporary theories using the same dichotomous ontological classification is an exercise fraught with limitations and arbitrary choices (as Rynasiewicz suggests). At most, what the examination of non-contemporary physical theories of space and motion might reveal is that certain *aspects* or *portions* of these past theories may resemble contemporary ones: for instance, the vacuum solutions of GTR are arguably closer in spirit to Newton's conception than Descartes'; but, on the other hand, the interrelationship between space and matter in Descartes' physics (as revealed above) obviously bears a much closer resemblance to GTR than Newton's immutable, absolute space. Consequently, if only distinct components of past theories can be compared and contrasted with contemporary theories, then Rynasiewicz's claims about the continuing relevance of the substantival/relational debate would seem to be vindicated at least in part (since the choice of which of the numerous components of a past theory resembles which of the equally diverse portions of a contemporary theory is thus largely a conventional choice).

More critically, a key factor in the failure to categorize theories along clear substantival/relational lines probably resides in a general uncertainty concerning what constitutes a “relational” theory: e.g., Are they (R1) or (R2)?, Are they based on actual or modal relationships?, etc. If one were to propose a “Kuhnian” analysis of these difficulties, one might claim that relationism does not constitute a full-fledged “paradigm”, since there is no agreement on the minimal content of relationism (except for possibly (R2), although even this criterion is not sufficient; see section 2.1). Nevertheless, given the lack of consensus on the fundamental issue of what theoretical content would classify a spacetime theory’s ontology as either a substance, property, or relation, a better Kuhnian correlate might regard the entire substantival/relational *ontological* dispute as inherently pre-paradigmatic.

REFERENCES

Barbour, J. (1999), *The End of Time.* Oxford: Oxford University Press.

Descartes, R. (1983), *Principles of Philosophy.* Translated by V. R. Miller and R. P. Miller. Dordrecht: Kluwer.

Earman, J. (1989), *World Enough and Space-Time.* Cambridge, MA: MIT Press.

Einstein, A. (1961), “Relativity and the Problem of Space”, in *Relativity: The Special and the General Theory.* New York: Crown.

Hoefer, C. (1996), “The Metaphysics of Space-Time Substantivalism”, *Journal of Philosophy* XCIII, 5-27.

Hoefer, C. (1998), “Absolute versus Relational Spacetime: For Better or Worse, the Debate Goes On”, *British Journal for the Philosophy of Science* 49, 451-467.

Hoefer, C. (2000), “Energy Conservation in GTR”, *Studies in History and Philosophy of Modern Physics* 31, 187-199.

Huygens, C. (1950), *Oeuvres Complètes.* La Haye: Société Hollandaise des Sciences.

Leibniz, G. W. (1962), *Leibnizens Mathematische Schriften.* Edited by C. I. Gerhardt. Hildesheim: Olms.

Leibniz, G. W. (1989), *Leibniz: Philosophical Essays.* Translated and edited by Ariew, R. and D. Garber. Indianapolis: Hackett.

Mach. E. (1942,) *The Science of Mechanics,* 9th edition. London: Open Court.

Maudlin, T. (1993), “Buckets of Water and Waves of Space: Why Spacetime is Probably a Substance”, *Philosophy of Science* 60, 183-203.

Newton, I. (1962), *De gravitatione et aequipondio fluidorum,* in *Unpublished Scientific Papers of Isaac Newton.* Translated and edited by A. R. Hall and M. B. Hall. Cambridge: Cambridge University Press.

Newton, I. (1999), *The Principia: Mathematical Principles of Natural Philosophy.* Translated by I. B. Cohen and A. Whitman. Berkelely: University of California Press.

Rynasiewicz, R. (1995), "By Their properties, Causes, and Effects: Newton's Scholium on Time, Space, Place, and Motion", *Studies in History and Philosophy of Science* 25, Part I; 26, Part II.

Rynasiewicz, R. (1996), "Absolute Versus Relational Space-Time: An Outmoded Debate?", *Journal of Philosophy* XCIII, 279-306.

Rynasiewicz, R. (2000), "On the Distinction Between Absolute and Relative Motion", *Philosophy of Science* 67, 70-93.

Sklar, L. (1974), *Space, Time, and Spacetime.* Berkeley: University of California Press.

Slowik, E. (1999), "Descartes, Space-Time, and Relational Motion", *Philosophy of Science* 66, 117-139.

Slowik, E. (2002), *Cartesian Spacetime.* Dordrecht: Kluwer.

Snelders, H. A. M. (1980), "Christiaan Huygens and the Concepts of Matter", in *Studies on Christiaan Huygens.* Edited by H. J. M. Bos et al. Linse: Swetz & Zeitlinger, 104-125.

Stein, H. (1967), "Newtonian Space-Time", *Texas Quarterly* 10, 174-200.

FOOTNOTES

[i] See, Pr II 4. References to Descartes are from the *Principles of Philosophy* (Descartes [1644-47] 1983), with part and section numbers following "Pr".

[ii] Leibniz invoked the center-of-gravity frames in his *Dynamica* (Leibniz [1690] 1962, vol. 6, 226), as did Mach in *The Science of Mechanics* ([1883] 1942), 271-297. Mach's account of rotation is much closer to (R1) relationism, however, although it is separate from his exploration of the center-of-mass frames (see, Earman 1989, 81-84).

[iii] On Huygens' departures from orthodox Cartesianism (if there did indeed exist such a notion), see, e.g., Snelders (1980).

[iv] Einstein's own view is unclear, since he does not address the matter-less solutions in these later essays. In personal correspondence, Rob Rynasiewicz and John Norton have suggested that Einstein hoped that a unified field theory would ultimately secure a link with the metric at a level more fundamental than T, and this would presumably eliminate the worries over the $T = 0$ cases.