DESCARTES AND CIRCULAR INERTIA

EDWARD SLOWIK

Abstract (Word Count: 90)

This paper explores the Cartesian physics of circular motion, in particular, the long-standing puzzle concerning the possible role of a circular inertial concept in Descartes' theories. Although some commentators have claimed that Descartes' famous "rotating sling" examples favor a rotational component of "striving" towards motion, and that this aspect of his project constitutes a form of inertial thinking, it will be argued that a much stronger case for a Cartesian brand of rotational inertial motion can be constructed from a little-known correspondence, the letter to Ciermans, dated 1638.

Notes on contributors:

Edward Slowik is an Assistant Professor in the Department of Philosophy at Winona State University (Winona, MN, 55987-5838). His main research interests are in the history and philosophy of science, particularly the philosophy of space and time, and the physics of the Early Modern natural philosophers. Previous publications on Descartes' physics include: "Perfect Solidity: Natural Laws and the Problem of Matter in Descartes' Universe," in *History of Philosophy Quarterly,* vol. 13, no. 2, April 1996, 187-204; "Huygens' Center-of-Mass Space-Time Reference Frame: Constructing a Cartesian Dynamics in the Wake of Newton's '*De Gravitatione*' Argument," in *Synthese,* 112: 247-269, 1997; and, "Cartesianism and the Kinematics of Mechanisms: Or, How To Find Fixed Reference Frames in a Cartesian Space-Time." in *Noûs* 32:3 (1998) 364-385.

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One of the great triumphs of Cartesian natural philosophy is the prominent role assigned to rectilinear uniform motion in explicating material phenomena. Although this concept of "inertial" motion, as we may anachronistically dub it,[1] is clearly central to Descartes' physics, a careful examination of the details (and elucidating examples) of his natural laws ultimately reveals a much more complex scheme. For instance, in the canonical presentation of the second law of motion, he argues that "bodies which are moving in a circle always tends to move [in a straight-line] away from the center of the circle which they are describing." (Pr II 39)[2] This thesis thereby invokes a tendency towards rectilinear motion within the context of larger, circular, non-inertial motion (i.e., non-inertial, or accelerating, according to the modern interpretation). Not only does this additional insight cast Descartes' mechanics in a different light, but it also greatly complicates any tendency to read Cartesian inertial motion as a straightforward prototype for Newton's system of natural laws. Fanning the flames of this general mystery is Descartes' influential explanation of the "rotating sling", in the *World* and the *Principles of Philosophy* (e.g., AT XI 85-86, Pr III 57-59), which seems to appeal to the rotating rock's "striving" towards circular motion--a concept that several commentators have taken as a latent form of natural-- i.e., inertial--circular motion.

In this essay, we will explore the phenomenon of Cartesian circular motion in order to discern what role, if any, it plays in Descartes' physics. Contrary to those commentators who have pointed to the rotating sling examples as proof of Descartes' unfaithfulness to straight-line inertial motion (mainly, Westfall and Shea), it will be argued that a much more incriminating piece of evidence can be found in a largely-neglected letter from 1638 (to Ciermans, AT II 74). Moreover, after presenting the contrasting approaches to circular inertial motion in Galileo's and Beeckman's work, it will be argued that Descartes' utilization of circular inertia owes more to the latter philosopher's ideas, as opposed to the former's, which is a fact that has also been overlooked by commentators.

1. Circular Motion and Circular Tendencies in Cartesian Natural Philosophy

The concept of circular motion has played a significant role throughout the history of science. Besides its integral importance to ancient astronomy, it figured prominently in the work of many early modern scientists on the inertial motions of both terrestrial and celestial bodies.[3] Principally among these, for our purposes, are Galileo and I. Beeckman, two natural philosophers who had a direct and powerful influence on the development of Descartes' physics.[4] We will examine the views of both of these philosophers before assessing the Cartesian theory, since it will later be argued that recent scholarship has largely overlooked the importance of Beeckman's contribution, possibly as a result of overemphasizing Galileo's influence. As with Descartes, to employ the term "inertial" in this context is rather misleading, but we will retain its use in order to label those aspects of their respective hypotheses which resemble the modern conception.

For Galileo, the circular motion of, say, a body orbiting the earth is a "neutral" state compounded of a center-seeking vertical motion (or tendency towards motion) and an impressed, usually horizontally-directed motion (or tendency towards motion). In brief, the Galilean analysis of circular motion incorporated hypotheses central to the Scholastic tradition: a quasi-Aristotelean "natural" motion towards the earth's center (which is governed by his "time squared" law for free-fall), and a non-natural (non-vertical) motion closely akin to the earlier "impetus" theories. According to the latter view, an impressed force, or impetus, was believed to be the causal agent responsible for non-natural motions.[5] When transferred to a body, the impetus would "generate" its directed motion until such time as resistance forces dissipated/exhausted the property. Although the details of his theory are somewhat imprecise, Galileo seems to hold that the impressed non-vertical motion not only balances out the vertical natural motion, but also accounts for the circular motion. He is much clearer on one point, however, once the vertical tendency of the body to descend has been held in check, any horizontal motion imparted to the body will result in the observed circular orbit of the body; and this circular motion will be "inertial" in the sense that it will persevere undiminished in the absence of the resistance of a medium. In the his early *Letters on Sunspots* (1613), he states:

> I have observed that physical bodies have an inclination toward some motion, as heavy bodies downward, which motion is exercised by them through an intrinsic property . . . . Finally, to some movements they are indifferent, as are heavy bodies to horizontal motion, to which they have neither inclination or . . . repugnance. And, therefore, all external impediments being removed, a heavy body on a spherical surface concentric with the surface of the earth will be indifferent to rest or to movement toward any part of the horizon. . . . Thus a ship, for instance, having once received some impetus through the tranquil sea, would move continually around our globe without ever stopping; and placed at rest it would perpetually remain at rest, if in the first case all extrinsic impediments could be removed, and in the second case no external cause of motion were added.[6]

As noted above, the precise details of Galileo's theory are much debated by commentators, but his "qualitative" treatment of uniform circular motions (or tendencies towards motion) would find an analogue in Descartes' treatment of the problem (as will be discussed below).

I. Beeckman's approach to circular motion, on the other hand, marked a real advance on the road to the modern conception of inertia, since he reckoned that a uniformly moving body did not require a causal agent, or impetus, to explain its state of motion.

> Once moved objects never come to rest, unless they are impeded. Once an object is put in motion it never comes to rest, except by an external impediment. Furthermore, the weaker the impediment, by this will the object's motion be of greater duration; truly, if it is simultaneously projected high and moved circularly, it is evident to the senses that it does not come to rest before returning to earth; and if it were to come to rest, that it would not result from an equable impediment, but as a result of an

> inequable impediment because many parts of the air touch the moving object in succession.[7]

What is interesting about Beeckman's hypothesis, as can be discerned in this passage, is that inertial motion is not restricted to a linear path: any motion, even circular, qualifies as inertial motion. Only an external impediment can change/alter an internal "state" of motion, which entails that a body circling the earth in the absence of any resistance will never slow down or stop (or change its trajectory). By contrast, Galileo held that it is the imparted (tangentially-directed) impetus which, when accompanied by the center-seeking natural motion, guarantees the uniform circular motion of the body around the earth (also in the absence of resistance forces, of course).

Descartes' analysis of circular motion would seem to owe something to both Galileo and Beeckman, although the specific influences, if any, are not disclosed in his writings. In assessing this theory, we will need to recall Descartes' second law of motion, which states: "all movement is, of itself, along straight lines; and consequently, bodies which are moving in a circle always tends to move away from the center of the circle which they are describing." (Pr II 39) At first glance, it might seem that this law (from the *Principles*) incorporates the modern notion of centrifugal force: i.e., that the centrifugal effects experienced by a body moving in a circular path, such as a stone in a sling, are a normal consequence of the body's tendency to depart the circle along a straight *tangential* path (i.e., the stone, when released, will depart the sling and move along a path perpendicular to the sling's cord at the moment of release) Yet, as stated in his second law, Descartes contends (wrongly) that the body desires to follow a straight line directly away from the center of its circular trajectory. That is, the force exerted by our rotating stone, as manifest by the outward "pull" on the impeding sling, is a result of a striving towards straight line inertial motion directed radially outward from the center of the circle, rather than a striving towards straight line motion aimed along the circle's tangent (see Figure 1).

Descartes does acknowledge the significance of tangential motion in explicating "centrifugal" effects[8], but he relegates this phenomenon to the subordinate status of a composite effect. By his reckoning, the desire to follow a tangential path exhibited by a circling body, such as the flight of our stone upon release from the sling, can be constructed from two more basic or primary inclinations: first, the tendency of the object to continue along its circular path; and second, the desire of the object to travel along the radial line away from the center of rotation. It is the instantaneous composition of both the radial and circular tendencies that results in the ensuing tangential flight of the stone upon release.[9] According to the standard Newtonian explanation, the straight-line inertial tendency of the stone is combined, or balanced, by the person's "centripetal" pull or tug on the line, thereby bringing about the stone's circular motion (when in the sling). Descartes, on the other hand, reverses this explanation by using the combined radially-directed and circularly-directed tendencies towards motion *to be the cause* of the stone's observed tangential flight when released from the sling.

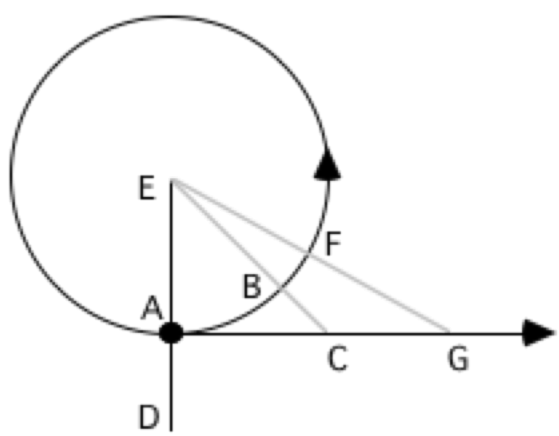

Figure 1. According to Descartes, a body in circular motion around the point E "strives" to move along the circular path to B and along the radial line EAD when at the point A.

For example, in Pr III 57, he insists that "the stone A, when rotated in the sling EA, definitely tends from A towards B (see Figure 1)," but "if instead of considering all the forces of [a body's] motion, we pay attention, to only one part of it, the effect of which is hindered by the sling; . . . ; we shall say that the stone, when at point A, strives only to move towards D, or that it only attempts to recede from the center E along the straight line EAD." By combining these two tendencies, he therefore concludes that if the stone "were to emerge from the sling when it reached the point A, it would go towards C and not towards B; and the sling, though it impedes this effect, does not impede the striving towards C." Thus, Descartes is willing to admit that "there can be strivings toward diverse movements in the same body at the same time," (Pr III 57) a judgment that seems to presuppose the acceptance of some type of "compositional" theory of tendencies[10] analogous to his dissection of "determinations" (see footnote 9). A similar dissection of circular motion is included in his earlier, *The World,* where he asks the reader to imagine the "inclination of the stone to move from A to C as if it was composed of two others, namely, one to move around the circle AB, and the other to move along the straight line [EGH, to match Figure 1] . . . ." (AT XI 85)

2. Critical Assessment of Cartesian Circular Inertia.

In critically analyzing Descartes' explanation of the rotating sling, it is important to bear in mind that he does not ascribe a circular inertial *motion* to the rock. Instead, the "inertial" implications of Descartes' analysis would appear to involve his assignment of a circular component of the body's "striving" towards motion (which, when combined with the radially-directed outward striving, gives rise to the tangentially directed, composite striving). Some commentators have over-looked this circular component of striving, and thereby mistakenly tried to explicate the rock's circular motion by means of the other two tendencies (e.g., Herival[11]).

Another possible source of confusion relates to the, for lack of a better term, "ontological" status of circular tendencies. As is evident above, Descartes' employment of a circular tendency seems to blatantly contradict his repeated claim that bodies only strive to move along straight-line paths. Some commentators have attempted to harmonize these divergent strands in the Cartesian story by relegating circular motion to a secondary, derived status; such that bodies really only strive to move rectilinearly, but that these tendencies are deflected by the intrinsic crowding of the plenum into a circular form. D. Garber appears to offer such a view in the following:

> At any instant, the shove that produces the motion in time can only be a shove in some one determinate direction. A succession of shoves can move the body in a curvilinear path, but any individual shove at a particular moment can push it in only one direction. It is in this sense that only rectilinear motion can be comprised in an instant, and in an instant only that required to produce rectilinear motion can be found. (Garber 1992, 286)

Apparently, Garber envisions Descartes' circular motion as brought about by instantaneous deflections from a rectilinear path. While this might be a successful interpretation of a Cartesian hypothesis of circular motion, it fails to do justice to Descartes' hypothesis of curvilinear *tendencies;* which, it is important to recall, are in effect at an instant (see footnote 9). Descartes specifically refers to the circular "tendency" (*tendere*) at an instant of its motion (i.e., the point A in Figure 1). Overall, it is thus not possible to pass off Cartesian circular tendencies as a species of motion, since motion, in contrast to tendency, is a durational phenomenon that occurs at the level of several instants (and not at an individual instant).

A devoted Cartesian could nevertheless invoke a variation on Garber's argument to overcome this difficulty. Rather than propose rotational motion as the derived phenomenon, a more successful strategy might simply allot this role to rotational tendencies. Accordingly, while moving bodies only *really* possess radially-directed tendencies, the ubiquitous plenum crowding induces a secondary, or derived, circular tendency (as required to form Descartes' large circling material bands). Freed from the confines of a plenum, bodies would never exhibit these additional, secondary tendencies; which thereby explains Descartes' repeated claim that bodies only tend to move along radial lines. This strategy, while resourceful, is unfortunately not supported by any textual evidence in the Cartesian cannon; but it is consistent with Descartes (apparently inconsistent) further claim that bodies have multiple tendencies towards motion (as above, Pr III 57). Therefore, unless more textual evidence were forthcoming, this proposed solution to the problem of circular motion must remain merely an intriguing possibility.

A basic question needs to be addressed at this point in our critical examination of Descartes' theory: Even if we do acknowledge an irreducible tendency towards circular motion in Cartesian bodies, in what sense does this constitute a form of circular inertia (as, for instance, endorsed by Beeckman's natural philosophy)? According to some commentators, the incriminating factor in Descartes' account of the rotating sling is his claim that the sling does not impede or affect the circular striving of the rock. R. Westfall, for instance, argues that "when he referred to the circular component as that part of the body's tendency 'the effect which is not impeded,' he returned unconsciously virtually to embrace the idea of a natural circular motion." (Westfall 1971, 81-82) A similar allegation is put forth by W. Shea: "the circular component of the motion of the stone is 'in no way impeded,' hence inertial."[12] In other words, if the body is not pressing (or being pressed by) the sides of the sling, then the body must be naturally "inclined" to move in a circle, thereby manifesting a form of circular inertia.

Yet, there is a general problem with this line of argument, for it ignores Descartes' additional hypotheses on the necessity of circular motion in a plenum setting (i.e., matter-filled universe). In Pr II 33, he states: "It has been shown . . . that all places are full of bodies . . . . From this it follows that no body can move except in a complete circle of matter or ring of bodies which all move at the same time." Descartes mandates these large-scale circular motions because there exist no empty spaces for a moving object to occupy. If the motion were not circular, the movement of a single body in his "indefinitely" large universe could produce a vacuum, or an indefinite material displacement that threatens the Cartesian conservation law. More importantly, for our purposes, is his stipulation that the circular motion of the bodies occurs synchronously "in such a way that [a body] drives another body out of the place which it enters, and that this body takes the place of yet another, and so on until the last, which enters the place left by the first one at the moment at which the first one leaves it." (Pr II 33) In the light of this additional hypothesis, the failure of the rotating rock to resist the sling does not thus constitute sufficient evidence for an instance of circular inertia in Descartes' plenum: since both the rock and sling partake in a large circular motion that occurs simultaneously, the rock *can not* impede the sling. In short, there can be no resistance among bodies that move synchronously in the same direction. The instantaneous striving of the rock towards circular motion is matched by an identical striving of the sling, thereby accounting for the failure of the latter to impede the former. But, there exists no circular motion, and thus no instantaneous synchronized strivings, with respect to that portion of the sling contiguous with the outward radial direction of the rock's rotation. In that direction, the rock's striving is clearly impeded by a vast number of (relatively) stationary bodies (i.e., the bodies contiguous with the outer portion of the sling do not strive to move along the radial direction, so that the sling must "force" them into a large-scale circular motion of their own). Consequently, the appeal by both Westfall and Shea to the lack of circular impedance, as exhibited by the sling, does not of itself warrant an accusation of circular inertia in Descartes' natural philosophy.

There remains a problem with the Westfall/Shea critique, however, which apparently stems from an ambiguity intrinsic to Descartes' explanation of the rotating stone; namely, the fact that the philosophical implications of his theory (as regards circular inertia) lie somewhere in between both Galileo's and Beeckman's account of the phenomenon. Descartes appears to invoke, in a Beeckman-ian fashion, a form of circular inertia in utilizing an unimpeded circular tendency; yet, in a Galilean manner, he presents the circular motion of the body as a composite, non-natural (non-inertial) state. Westfall refers to this sort of vague explanatory duality in the qualification that proceeds his claim that "[Descartes] returned unconsciously virtually to embrace the idea of a natural circular motion."

> I say 'virtually to embrace', for the conception of circular motion implicit in the analysis was closer to that held by Galileo, a conception in which circular motion appeared as a state of equilibrium between whatever constraint exists to turn bodies into a circular path and the force bodies exert against it. (Westfall 1971, 81-82)

If one is willing to admit this point, however (i.e., that Descartes' analysis is closer to Galileo's), in what sense can a charge of "circular inertia" be pinned on Cartesian natural philosophy? A mere tendency towards circular motion hardly counts as "(virtually) embracing" this notion, especially when it is recalled that; (i) the circular tendency is only one of several directed tendencies that the body possesses at an instant, and (ii) the body, if unimpeded by the sling, will never manifest a circular motion (but move along the tangent instead). In short, what the critics need to establish their case is an instance where Descartes explicitly employed a Beeckman-ian form of unimpeded circular motion: that is, a motion which is "naturally" circular, and not constrained to follow a curvilinear path (or, alternatively, a "pure" tendency towards circular motion rather than just one of several such divergently directed instantaneous tendencies).

Although largely overlooked by commentators, there is one piece of evidence within the Cartesian cannon which strongly endorses a Beeckman-ian form of circular motion: viz., the letter from Descartes to Ciermans, 23 March 1638 (AT II 74). The context of the discussion is the Cartesian theory of the diffraction of light in a prism, first presented in the *Meteorology,* where Descartes ascribes a circular rotation to small spherical particles of air. (AT VI 330-331. Such particles constitute the means by which the pressure from a luminous source, i.e., light, is transmitted, while their different rotations account for the color spectrum.) In a previous correspondence (AT II 59-61), Ciermans had wondered why these small particles do not lose any of their rotational motion while traveling through space, to which Descartes responded:

> I do not see why it should seem to you that the particles of celestial matter do not maintain the rotational motion that gives rise to colors as well as the straight line motion of which light consists. We can equally well grasp both by our reasoning. I

> am convinced that, insofar as natural events are concerned, we can think of nothing more accurate, namely that which better answers the rigor of mathematical computation. (AT II 74)

On Descartes' hypothesis, the passage of the particles through the prism alters their rotational speeds in such a manner as to account for the observed color spectrum of diffraction. Yet, if their motion is not disturbed, he sees no reason why the celestial particles "do not maintain [their] rotational motion" in the same way that they maintain "motion in a straight line". Mathematical considerations are also invoked as favoring this conclusion, although just what type of "mathematical computation" he has in mind is not disclosed. The primary importance of this passage is quite evident, nevertheless, for Descartes is assigning to rotational *motion,* which is usually conceived as non-inertial, the same metaphysical/ontological status as straight-line, inertial motion. In other words, celestial particles retain rotational motion in the same manner that they maintain straight-line motion, the latter being subsumed under his second law of nature. If Descartes' commentators are keen on locating evidence that revealed a Beeckman-type notion of circular inertia--such that he "virtually embraced" this notion--the letter to Ciermans must naturally form the center-piece of any such allegations, and not the ambiguous reference to a circular tendency as implied in the rotating sling examples.

Unfortunately, the Ciermans letter raises more problems than it solves; particularly, the question of how Descartes' diagnosis of the case of the rotating particles relates to his example of the rotating sling. In the latter, as described above, the stone exhibits multiple tendencies towards motion at any one instant, which explains why it would move along the circle's tangent if released. But, what tendencies (towards motion) does the rotating particle possess, if any? And if the particle's tendencies are, in fact, different from the stone's, why are they different (since all matter is essentially identical on Descartes' scheme)?

One possible resolution of this general puzzle might be found in the Cartesian theory of the three elements. The three basic elements are completely solid on Descartes' estimation, and thus have no parts (see, Pr III 46-53). The celestial particles utilized to explain the phenomenon of light he identifies as the secondary elements of matter, which are elsewhere described as "globules", and are "in proportion to there size, as solid as body can be, because they do not possess pores filled with other matter." (Pr III 123)[13] Without parts, it could be inferred that rotating particles only partake in the striving towards circular motion, and not both circular and radial strivings (which together give rise to the tangential), since there are no parts which could strive to flee the particle along a radial direction. (Or, alternatively, that any attempt by a "potential" part of this particle to flee along the radial direction would be perfectly balanced by the inversely directed striving of a "potential" part situated on the opposite side of the particle.) As for the rotating rock, on the other hand, the fact that the rock is only an individual member of the entire circle of moving bodies thus entails that it is free to strive to move along the radial path. This explanation, while consistent, faces various additional difficulties, nevertheless: first, there exists no known textual support for this hypothesis; and second, the entire ring of circling bodies would seem to qualify as a single body given Descartes' criterion for identity: "by *one body,* or *one part of matter,* I here understand everything which is simultaneously transported; even though this may be composed of many parts which have movements among themselves" (Pr II 25) If the complete circle of rotating objects does constitute a single body, then an identical argument could be made to demonstrate that it possesses no parts, and thus no radially directed strivings, as well.

3. Conclusion.

Overall, as regards Descartes' understanding of circular tendencies/motion, we can provide the following brief summary of the results of our investigation : first, while the various rotating rock examples admit a role for circular tendencies in Cartesian physics, it is the postulation of a natural circular motion (in the letter to Ciermans) that reveals the full extent of Descartes' use of circular inertial concepts; and second, this appeal to circular motion owes much more to a Beeckmanian, as opposed to a Galilean, interpretation of the phenomenon (which is contrary to the views of, at least, a few commentators). Only in the light of his discussion of the rotating celestial particles--a case long neglected by commentators--can one begin to grasp the true extent of Descartes' use of circular inertial concepts.

ENDNOTES

1 To resolve any later confusion concerning terminology, the term "inertia" as applied to Descartes' natural philosophy (or Galileo's, Beeckman's, etc.) will simply stand for his (their) theories of bodily motion which resemble the modern concept of inertia. In other words, this essay is not putting forward the view that any of these Early Modern theorists had a modern understanding of inertia.

2 I will identify passages from the *Principles* according to the following convention: Article 15, Part II, will be labeled "Pr II 15." Other passages are translated from the Adam and Tannery edition of the *Oeuvres de Descartes* (Paris: Vrin, 1976), with passages marked, "AT", followed by volume and page number.

3 See, e.g., M. Clagett, *The Science of Mechanics in Middle Ages* (Madison: University of Wisconsin Press, 1959) chap. 3-4; and, E. Grant, *Planets, Stars, & Orbs: The Medieval Cosmos, 1200-1687* (Cambridge: Cambridge University Press, 1994) chap. 18.

4 For a nice discussion of the various influences on Descartes' natural philosophy, see, S. Gaukroger, *Descartes: An Intellectual Biography* (Oxford: Oxford University Press, 1995), and, W. R. Shea, *The Magic of Numbers and Motion: The Scientific Career of René Descartes* (Canton, Mass.: Science History Publications, 1991).

5 On impetus theory, see A. Maier, *On the Threshold of Exact Science,* trans. by S. D. Sargent (Philadelphia: U. of Pennsylvania Press, 1982) chap. 4; and, J. E. Murdoch and E. D. Sylla, "The Science of Motion", in *Science in the Middle Ages,* ed. by D. C. Lindberg (Chicago: University of Chicago Press, 1978) 206-265.

6 Galileo Galilei, *Letters on the Sunspots,* trans. by S. Drake, in *Discoveries and Opinions of Galileo* (New York: Anchor, 1957) 113-114. For a recent discussion of these issues, see, W. Hooper, "Inertial Problems in Galileo's Preinertial Framework", in *The Cambridge Companion to Galileo,* P. Machamer, ed. (Cambridge: Cambridge University Press, 1998) 146-175.

7 I. Beeckman, *Journal,* I, C. de Waard edition (The Hague: M. Nijhoff, 1939) 24.

8 Or, better yet, "center-fleeing" motions/tendencies, to avoid the philosophical implications of the modern understanding of the term "centrifugal".

9 A Cartesian "tendency" is an instantaneous process, unlike motion, which occurs over several instants: "Of course, no movement is accomplished in an instant; yet it is obvious that every moving body, at any given moment in the course of its movement, is determined to continue that movement in some direction in a straight line, ..." (Pr II 39) However, one should resist the temptation to equate "tendency" (or "striving", as used in the rotating sling examples) with his additional concept of a "determination" (*determinatum*) of motion. The latter apparently refers to a body's direction of motion (or direction of quantity of motion): "there is a difference between motion considered in itself, and its determination in some direction; this difference makes it possible for the determination to be changed while the quantity of motion remains intact." (Pr II 41) Yet, as the passage from Pr II 39 seems to suggest, instantaneous tendencies may have determinations (i.e., directions), as well.

[10] The terminology Descartes employs for his concept of instantaneous tendencies is rather haphazard, with many terms apparently being used interchangeably: such as, "tendency" (*tendere*), "inclination" (*inclinatio*), "strive (or effort)" (*conatus,* as in Part III of the *Principles*), and even "first preparation for motion" (Pr III 63). D. Garber and D. Des Chene also accept this apparent interchangeability of terms: D. Garber, *Descartes' Metaphysical Physics* (Chicago: University of Chicago Press, 1992) 218-225; D. Des Chene, *Physiologia: Natural Philosophy in Late Aristotelian and Cartesian Thought* (Ithaca: Cornell University Press, 1996) 272-286.

[11] J. Herival, *The Background to Newton's 'Principia'* (Oxford: Oxford University Press, 1965) 47, 54. Westfall also points out this misreading of Descartes' theory, *The Concept of Force in Newton's Physics* (London: MacDonald, 1971) 93-94, fn. 49.

[12] W. R. Shea, *The Magic of Numbers and Motion: The Scientific Career of René Descartes* (Canton, Mass.: Science History Publications, 1991) 281-282.

[13] The concept of "solidity" in Cartesian natural philosophy is quite complex. See, E. Slowik, "Perfect Solidity: Natural Laws and The Problem of Matter in Descartes' Universe", *History of Philosophy Quarterly,* 13, 1996, 187-204, for an attempt to clarify this, and related, notions.