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NEWTON'S ABSOLUTE TIME

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When Newton articulated the concept of absolute time in his treatise, *Philosophae Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), along with its correlate, absolute space, he did not present it as anything controversial. Whereas his references to attraction are accompanied by the self-protective caveats that typically signal an expectation of censure, the scholium following *Principia*'s definitions is free of such remarks, instead elaborating his ideas as clarifications of concepts that, in some manner, we already possess. This is not surprising. The germ of the concept emerged naturally from astronomers' findings, and variants of it had already been formulated by other seventeenth century thinkers. Thus the novelty of Newton's absolute time lay mainly in the use to which he put it.

NEWTON'S INTELLECTUAL AND HISTORICAL CONTEXT

Newton formulated his concept of absolute time on the heels of several significant developments, both conceptual and technological. At least some of these were critical preconditions for his mathematical physics, and all of them contributed in one way or another to his conclusion that no actual events could serve as infallible timekeepers.

Galileo's mathematical treatment of time

The first development to note was Galileo's innovative mathematical treatment of time. Galileo's finding that free-falling bodies naturally accelerate, and at a uniform rate such that distance is proportional to the square of the time interval (as eventually stated in 1638 in his *Discorsi*), would in itself be vital to Newton's gravitational theory. It was also critically important, however, for its treatment of time as a variable in a function, to speak anachronistically. The concept of a function, though it would be employed by Newton and Leibniz among others, would not be explicitly articulated in general form until the mid-eighteenth century.[1] Galileo lacked the concept, and his progress toward it was hampered by his adherence to Euclid's homogeneity condition for ratios (Book 5, Def. 3's condition, which restricted the magnitudes figuring in a ratio to those of the same kind). However, he took a critical step toward the function concept by representing time intervals geometrically, by line segments, and by then understanding distance of fall as dependent upon those intervals.

Increasing awareness of the celestial clock's fallibility

As a second development, the long-present awareness that celestial motions could not serve directly as an infallible clock was intensifying. That awareness reached back to the Hellenistic period, which brought challenges to the views found in Plato and Aristotle. In his *Timaeus*, Plato had actually identified time with the celestial bodies' wanderings. While Aristotle took a more moderate view by denying that identification, he nevertheless held that there cannot be time without change.[2] He further held that the celestial bodies' *telos* was perfectly circular motion, which meant that their motions could serve as a clock. By the second century, however, it was evident that the lengths of true solar days (i.e., the elapsed time between the sun's zenith of any two successive days) were uneven. Ptolemy's *Almagest* hypothesized the twofold cause of that variability to be non-uniform solar motion along an inclined ecliptic.[3] Introducing the concept of a mean solar day,[4] the *Almagest* then provided remarkably accurate means

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[1] On the concept of a function, see Youschkevitch, 1976; in particular, see pp. 49-50 on Galileo's steps toward the concept and their similarity to ideas of Nicolas Oresme; §6 on Newton's and Leibniz's understandings of the concept; and §7-8 and on Euler's general formulation in the mid-eighteenth century.

[2] *Physics*, IV.10-11. Interestingly, Aristotle does not take time to be a property of change (see Coope, 31), and thus takes time's relationship to change to differ from extension's relation to matter.

[3] Linton, 2004, 70.

[4] Linton, 2004, 70.

for reckoning it—the so-called equation of time (or correction of time).[5] Fast-forwarding from the Hellenistic to the early modern period, belief in an infallible timekeeper was under considerable pressure by the 1660's, by which point Kepler's elliptical orbits and the varying velocity implied by his area law had gained significant acceptance.[6] That pressure only increased with the advent of better clocks (see Matthews, 2000, 145, 178). For despite the regularity (in controlled circumstances) of the gravity-driven frequency of pendulums having the same length, one consequence of the Richer expedition (discussed below) was the realization that gravity is a local property and that pendulum frequencies vary accordingly.

Advances in timekeeping

A third development, then, was the invention of more precise clocks, which would underwrite discoveries in astronomy and terrestrial physics, and would also indirectly help reveal the distinction between mass and weight. The push for better timekeeping came from investigations of natural phenomena, but even more insistently from the commercially driven need for navigators to be capable of determining their longitude at sea. The celestial clock and its sundials were a long way from providing the precision required for either sort of endeavor, and for his investigations of free fall via inclined plane experiments, Galileo accordingly devised a water clock. Using a raised container of water, he opened the spigot upon releasing a ball at the top of the inclined plane, closed it when the ball hit the bottom, and weighed the water that had flowed into a receptacle during the time interval of the ball's descent.

This water clock was an improvement over available alternatives, but crude in comparison to the pendulum clocks that would soon follow. Those pendulum clocks would utilize some of Galileo's findings about pendulum motion, but as corrected and

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[5] Linton 2004, 70-72 is useful here; see also Neugebauer, 1975, 61-66.

[6] See John L. Russell; in Applebaum (1996, 456); see also Heidarzadeh, 2008, p. 80, note 190.

furthered by others, not least Christiaan Huygens.[7] Realizing that the cycloid—not the circle, as Galileo had thought—provides the curve of fastest descent, Huygens created a cycloidal pendulum clock, which he hoped would provide the key for solving the longitude problem. While in fact the solution was a century away, Huygens' pendulum clock was brought on Jean Richer's 1672 scientific expedition to Cayenne, and was unexpectedly found to have a longer period there, near the equator, than it had had at home. This suggested that gravity varied with latitude. For Newton, that variability with latitude indicated an oblate earth and, significantly, a distinction between weight and mass. (Also influential in Newton's realization was the 1680 comet; the precise role of the Richer expedition's findings for that realization is unknown (Cohen, 1999, 19-20).) Newton would reference the expedition's discovery in the *Principia*, while setting the problem of comparing bodies' weights at different locations on earth (Book 3, Proposition 20, Problem 4).[8]

Historical precedents of the absolutist concept of time

In a fourth development, by the eve of Newton's *Principia*, several thinkers had already concluded that no events could serve as an infallible clock, and had already formulated absolutist conceptions of time. While questions about Newton's intellectual debts and sources of influence are too complex to consider here, striking similarities may be found in the writings of Pierre Gassendi, whose ideas were largely accessible to Newton, at least through Walter Charleton, and of Isaac Barrow. Newton quite likely attended Barrow's geometrical lectures (Westfall, 1980, 99), and in any case he received the lectures in written form in 1670 (Feingold, 1990, 336).[9] As the most notable similarity among these thinkers, they repudiate the reductionist view,

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[7] On Huygens' pendulum clock and its consequences, see Yoder, 1988. On the extent of Galileo's contributions for Huygens' clock and questions of priority, see Yoder, 130-134. See also Matthews, 2000, chp. 5-6.

[8] *Principia*, Book 3, Proposition 20, Problem 4, pp. 826-832.

[9] While he foregoes any full investigation of Newton's sources of influence, Arthur does consider the question in his important 1995 study of Newton's concept of time and its connection to his theory of fluxions; see pp. 328-331.

concluding instead that time is independent of objects and motions. As Gassendi explains matters in his *Syntagma*, our common conception of time errs by supposing time to be the continued existence of things and hence an accident of them.[10] In fact, time is "a certain flux...that is no less independent of motion than of rest" (Gassendi, 1972, 394); and though we use the sun's motion as a clock (*Ibid.,* 395), "it is as far from the truth that time is the measure of celestial motion as that celestial motion is the measure of time" (*Ibid.,* 394). Indeed, he asserts, time would elapse at exactly the same rate even if the sun moved twice as fast (*Ibid.,* 396), or if the universe were destroyed (*Ibid.,* 390-391). Gassendi also considers this eternal flux to be actual; those philosophers who considered an eternal flux, independent of motions, to be only imaginary had caught only a "glimpse" of the truth (*Ibid.,* 394-395).

Unlike Gassendi, Barrow demotes his absolutist conception of time to the status often labeled 'imaginary', that is, a potentiality: "Time therefore does not imply an actual existence, but only the Capacity or Possibility of the Continuance of Existence; just as Space expressed the Capacity of a Magnitude contain'd in it"(Barrow, 1735, 7). Nevertheless, he denies that time can be reduced to actual motion or existence. Using some phrases similar to those that Newton would employ, he answers the question of whether time implies motion by asserting that its "absolute and intrinsic nature" does not imply motion any more than it implies rest; and that "Time flows perpetually with an equal Tenor" regardless of whether things move or stand still. Driving the point home, he adds, "If you suppose all the fixed Stars to have stood still from their Beginning; not the least Portion of Time wou'd be lost by this." (*Ibid.,* 7) To be sure, Barrow acknowledges, we have no direct access to time itself, and our attempts to measure it are accordingly fallible; in answer to the question of how we can know whether the times of two years are exactly equal, Barrow answers that apart from "what we gather from divine testimony", we can only attempt to determine this by comparing the sun's motion to other regular motions. (*Ibid.,* 10) Significantly, Barrow treats time

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[10] The view that time should be understood in terms of the existence of things (as opposed to motion) is found in Nicole Oresme (1320-1382).

as a quantity, and one that is fundamental for understanding force. Although as a mathematician, Barrow explains, he need not follow philosophers in their subtle disputes about the nature or causes of motion, he praises Aristotle's dictum that to be ignorant of motion is to be ignorant of nature. And he accordingly concerns himself with time, since "the quantity of motive Force cannot be known without Time". (*Ibid.,* 3-4)

TIME IN THE *PRINCIPIA*'S SCHOLIUM TO THE DEFINITIONS AND ITS PLACE IN NEWTON'S PHYSICS

The focal text for Newton's concept of absolute time is the scholium that appears directly after the *Principia*'s definitions, although the ideas there show a strong continuity with certain manuscripts, in particular the earlier *De gravitatione*, and the later *Tempus et Locus*.[11] Commonly known as the scholium on space and time, it enumerates absolute time, absolute space, place, and absolute motion as the quantities to be explicated.

Although time is the concept that Newton presents first, it is hardly possible to consider it apart from space, place, and motion, and so some mention of those must be given. Absolute space is a three-dimensional Euclidean magnitude (as is evident elsewhere), which is homogeneous, immobile and independent of all bodies (Newton, *Principia*, 1999, 408-409). Further, as Newton explains later, its parts are the only places that remain fixed in relation to one another from infinity to infinity (*Ibid.,* 412). Relative spaces, meanwhile, are bounded parts of that space, demarcated by bodies, an example being the hold of a ship, demarcated by the planks constituting its sides. If a

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[11] McGuire (1978) dates *Tempus et Locus* to the early 1690's. As for *De gravitatione*, the date of its composition has been a matter of considerable interest and controversy. Mordechai Feingold (2004) concludes that an original version "might be more precisely dated to around 1671, and to a course of lectures Newton delivered at Cambridge against Descartes' mechanics and Henry More's hydrostatics", but that the extant is a later reworking of those ideas: "A decade or so later, I would argue, Newton contemplated reworking his earlier lectures into a more sustained philosophical argument against Descartes" (Feingold, 2004, 26). Feingold dates the extant manuscript to approximately the mid 1680's, based upon its mention of inertia: "That the document in its present form is of late composition, albeit incorporating earlier material, can be deduced from its invocation of the concept of inertia, a term not used by Newton before the mid-1680s." (*Ibid.,* 194).

relative space is moving, it will consist in successive parts of absolute space. Turning to place, the next concept enumerated, a body's absolute place is the part of absolute space that it occupies (and most definitely not, as in an Aristotelian-Cartesian view, the body's outer surface or boundary with adjacent bodies); and its relative place is its part of a relative space. Finally, absolute motion is the change of a body's position from one part of absolute space to another, while relative motion is a change from one part of relative space to another. Since a body partakes of the motion of any relative space in which it is placed, and since such relative spaces may be nested, a body's true (absolute[12]) motion results from the combination of all such motions with respect to absolute space—e.g., when a marble rolls in a box set in the hold of a ship traveling the seas of a moving earth.

The scholium's concept of absolute time

The scholium opens with a twofold explanatory note concerning the need to distinguish between absolute and relative quantities, and it then proceeds to the details of those distinctions, beginning with time and then passing on to the concepts just mentioned.

> Thus far it has seemed best to explain the senses in which less familiar words are to be taken in this treatise. Although time, space, place and motion are very familiar to everyone, it must be noted that these quantities are popularly conceived solely with reference to the objects of sense perception. And this is the source of certain preconceptions; to eliminate them it is useful to distinguish these quantities into absolute and relative; true and apparent; mathematical and common.
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> Absolute, true, and mathematical time, in and of itself and of its own nature, without reference to anything external, flows uniformly and by another name is called duration. Relative, apparent, and common time is any sensible and external measure (precise or imprecise) of duration by means of motion; such a measure – for example, an hour, a day, a month, a year – is commonly used instead of true time. (*Ibid.,* 408)

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[12] Newton uses the terms 'absolute motion' and 'true motion' interchangeably in the passage presenting the concept. It is also clear that he takes 'absolute', 'true', and 'mathematical' on the one hand, and 'relative' 'apparent', and 'common' on the other, to be sets of co-referential terms. The precise meanings and interrelationships among the terms at each point in the scholium is another matter, however, and one beyond the scope of this article.

> All motions can be accelerated and retarded, but the flow of absolute time cannot be changed. The duration or perseverance of the existence of things is the same, whether their motions are rapid or slow or null; accordingly, duration is rightly distinguished from its sensible measures. (*Ibid.,* 410)
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> As the order of the parts of time is unchangeable, so, too, is the order of the parts of space. Let the parts of space move from their places and they will move (so to speak) from themselves. For times and spaces are, as it were, the places of themselves and of all things. All things are placed in time with reference to the order of succession and in space with reference to the order of position. (*Ibid.,* 410)

Here Newton presents absolute time as a quantity of infinite, linear extension, characterized by the successive order of its parts, and indicates that it is unidirectional via the metaphor of flux or flow.[13] The rate of that flow is immutable, since time as presented here is absolute in the sense of being wholly independent of corporeal bodies and their motions. Absolute time, like absolute space, is imperceptible in itself, giving rise to the need for relative times. Relative time, then, is not an alternative conception of time itself (as it is for Leibniz, who later champions a relationalist conception in his correspondence with Samuel Clarke), but a measure of some bounded part of infinite, absolute time, taken by means of perceptible bodies and their motions. As Newton remarks later on in the scholium: "Relative quantities, therefore, are not the actual quantities whose names they bear but are those sensible measures of them (whether true or erroneous) that are commonly used instead of the quantities being measured."(*Ibid.,* 411)

Although relative times (and spaces) are benign in themselves and moreover indispensible, the scholium's central aim is to prevent the "preconception" that our reliance upon them could induce. We might mistake sensible object-based measures of time for time itself (and we might make a similar mistake with space).[14] Newton most

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[13] Extensive analyses and very different interpretations of Newton's understanding of time's flow may be found in Earman (1989); Arthur (1995). Arthur is particularly concerned with connections to Newton's theory of fluxions; on that, see also Guicciardini (1999, esp. 42, 245-246).

[14] Gassendi's discussion of "mere time" similarly refers to both measured parts of time itself, and to the error we make when we suppose that time itself consists in only those measured parts, and more specifically, that it is the duration of things and hence an accident of them. In the following passage, "mere time" is the measured components of duration itself.

clearly describes that problem (mentioned also by his predecessors) in *Tempus et Locus*, an aforementioned manuscript from the early 1690's which draws directly upon the scholium: "Time and Place in themselves do not fall under the senses, but are measured by means of sensible things, such as magnitudes of bodies, their positions, local motions, and any changes uniformly made. And the vulgar take these measures to be the things measured, for example days, months, and years to be times."[15] What is not communicated by those dispassionate words, yet certainly lies behind them, is the consequence of such a mistake (one discussed further below): to fall into a Cartesian physics, undercutting the very possibility of distinguishing inertial states from accelerated ones, and hence of identifying the causes of natural phenomena involving local motion.

The aim of eliminating that preconception is expressed as part of the twofold explanatory remark that opens the scholium, and the other part is noteworthy too. It is because we are already familiar with time, space, and motion that Newton discusses them in a scholium, which is a further explication, rather than in the definition section, which he reserved for the unfamiliar. Yet that familiarity does not obviate the need for clarification, due to the aforementioned risk of error. Those remarks communicate Newton's quite interesting and significant belief that this concept of absolute time (like that of space) is the one that, in some manner, we already possess. (How it is that we possess the concept of absolute time or space, even as we employ relative times and spaces, is suggested by his presentation of the latter as measures of the former; we are led to absolute time or space by imaginatively removing the bodies measuring the parts, and taking a broader view.)

> "There seems to exist some incorporeal duration independent of bodies, which, though called imaginary, *is the same as the one which constitutes the measure of time*. For just as that space extends through every position beyond mere place, which belongs to the universe and all is parts, *so this duration goes beyond mere time*, which belongs to the universe and everything existing in it and is conceived as having been extended beyond any beginning of the universe and as extending without limit even if the universe were destroyed." (Gassendi, 390-391, emphasis added)

[15] Newton, *Tempus et Locus*, in McGuire, 1978, 117, his translation.

An additional feature of Newton's concept of time is absolute simultaneity. That presumption, universal before relativity theory, is both implied by the scholium and directly evident in *De gravitatione*. In the latter text, Newton tries to explain how a mind might be spatially located by invoking, as an uncontroversial case, the belief that "the moment of duration is the same at Rome and at London, on the earth and on the stars, and throughout all the heavens."[16]

Also worth noting—especially in light of later charges that Newton's absolutist concepts were nothing but metaphysical interlopers—is the very different way that Newton answers the question of whether time is absolute in the *Principia* as compared to *De gravitatione*. *De gravitatione* is famously dominated by a philosophical digression addressing a range of metaphysical questions, including the ultimate ontological status of time and space and their relation to God. There, since he has extended the domain of entities to include God, Newton argues that space and time are not absolute; for to be absolute is to be independent, and he takes space and time to be emanative effects of God and thus dependent. The *Principia*, by contrast, has the more restricted domain of entities appropriate to a treatise of rational mechanics;[17] the question of whether space and time are independent is posed solely with respect to corporeal bodies, and Newton therefore considers time and space to be absolute. That he considers them absolute in the domain of physics, because independent of corporeal bodies and their motions, yet denies that they are absolute in the domain of metaphysics, because they are dependent upon God, does not answer the charge that his purportedly physical concepts are in fact metaphysical, that is, without empirical grounding. Still, it prepares the way for an answer, by reminding us of his intention to keep the two domains apart.

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[16] *De gravitatione*, in Newton 2004, 26.

[17] I disregard here the 1713 General Scholium, which extends natural philosophy's domain to God, if the deity is considered from phenomena.

The equation of time and Newton's stance toward his concept

Given just how controversial Newton's concepts of absolute time and space would be, it is interesting to note his utter insouciance when presenting them. One indication that he does not expect controversy is that the discussion is free of caveats, and their absence is especially apparent because the scholium follows the definitions. In particular, it immediately follows the wagon-circling remarks that close his definition of motive force: "I use interchangeably and indiscriminately words signifying attraction, impulse, or any sort of propensity toward a center....Therefore, let the reader beware of thinking that by words of this kind I am anywhere defining a species or mode of attraction or a physical cause or reason."(Newton, *Principia*, 1999, 408).) Had Newton wished to diminish the impact of his concept of absolute time (or space), he might have added some comparable remarks. Specifically, he might have cautioned his readers to beware supposing absolute time to be actual—as opposed to the potentiality ("capacity or possibility") that Barrow allowed. Instead, he says nothing to diminish the impact. Furthermore, he does not present absolute time as a concept requiring defense against any viable competitor; as already noted, Newton's relative time is a measure of some part of absolute time, not the reductionist, relationalist conception of time that Leibniz will later promote.[18]

Newton's reasons for supposing that his absolutist concept is the one that we already in some manner possess are evident in later passages of the scholium. Those passages indicate how naturally the concept emerges from astronomy's correction or equation of time.[19] That is to say, the concept emerges from the equation of time when

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[18] As commentators have regularly acknowledged since Stein's 1967 article, Newton's target in this scholium was not Leibniz but Descartes, just as it was in his attack upon the Cartesian doctrine of motion in his unpublished *De gravitatione*, with which the scholium is largely continuous.

[19] Cohen (*Newtonian Revolution*, 174), is eloquent on this point and on the place of Newton's concepts in his physics: "For Newton, time is 'absolute, true, and mathematical' or 'relative, apparent, and common'—as he put the matter in the scholium following the definitions in the *Principia.* This distinction was a natural one to any astronomer, who must be aware of the difference between mean time and local apparent solar time: an artificial and absolute time, regular and uniform, and a local or common time. And, since this absolutely flowing time, which occurs in Newton's mathematics and also analogously in his physics of motion, is measured (as Newton says) by a velocity; it follows that there must exist an absolute velocity; and such an absolute velocity necessarily defines and requires an absolute space. Much

considered in connection with Galileo's lesson that "in philosophy abstraction from the senses is required". (*Ibid.,* 411) It is possible for any actual motion to be accelerated or retarded, Newton notes; and in the following passage, he indicates that what the astronomers' correction produces is not true time but only a "truer" one.

> In astronomy, absolute time is distinguished from relative time by the equation of common time. For natural days, which are commonly considered equal for the purpose of measuring time, are actually unequal. Astronomers correct this inequality in order to measure celestial motions on the basis of a truer time. (*Ibid.,* 410)

This "truer time", or mean solar time, is in itself an abstraction, and Newton soon indicates why further abstraction, away from all motions, is required: "It is possible that there is no uniform motion by which time may have an exact measure." (*Ibid.,* 410) The possibility that no motion is uniform appears quite dramatically in Newton's pre-*Principia* manuscript *De Motu*, as he describes the consequences of the planets' mutual perturbations: "Each time a planet revolves it traces a fresh orbit.... Unless I am much mistaken, it would exceed the force of human wit to consider so many causes of motion at the same time, and to define the motions by exact laws which would allow of any easy calculation."[20] (The possibility becomes more dramatic still in the speculative Query 31, as Newton forecasts the eventual disruptions of the orbits, and intimates the need for divine intervention.) Given the possibility that no motion is uniform, Newton sees the need for absolute time in physics.

The place of absolute time in Newton's physics

Fundamental to Newton's physics is the distinction between inertial states and the accelerated ones produced by impressed forces, with his three laws providing the means to draw that distinction. The second and third laws provide positive characterizations of impressed forces, describing what happens in their presence; and the first law provides

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has been written on Newton's concepts of absolute space and time, including the suggestion that his belief in an absolute space may have been caused by his psychological needs, without taking cognizance of this basic aspect of Newton's mathematical dynamics and dynamics-based mathematics."

[20] *Unpublished Scientific Papers of Isaac Newton*, 281.

the negative characterization, describing what happens in their absence: "Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed"(Newton, *Principia*, 1999, 417). The laws, which appear in the *Principia* just after the scholium, depend upon its concepts of absolute time and space, as will be discussed below.

The *Principia*'s muted presentation of the need to distinguish inertial and accelerated states, and its concomitant claim that doing so requires reference to absolute time and space, has a more aggressive ancestor in *De gravitatione*, where one of Newton's main preoccupations is to analyze the failings of Cartesian physics. The connected roots of the problems are Descartes' identification of matter with extension, his Aristotelian definition of a body's place in terms of its contiguous neighbors in the plenum, and his related doctrine of motion. According to that doctrine, a body's one true or proper motion is its motion in the "philosophical" sense—the sliding away from the formerly contiguous bodies that had defined its place. Given this definition, Descartes can both assert a heliocentric cosmos and insist that the earth is at rest; for because there is no mutual translation of surfaces between the earth and the fluid vortex that carries it as it swirls around the sun, the earth is at rest in his true or philosophical sense of motion. The earth may be said to move, Descartes holds, only in the common or vulgar sense that he denies is true motion—the change of a body's place relative to other bodies with which it is not contiguous, as when the earth is considered with respect to the sun.[21]

Newton sees this doctrine of motion as having consequences that are fatal for Cartesian physics. One is the unacceptable consequence that a body that was not subjected to any impressed force could nevertheless be said to accelerate. For instance, Newton explains, if God stopped the fluid vortex from gyrating, then there would be a mutual translation of surfaces between that fluid aether and the earth, whereas there had been none before; but instead of implying that the vortex decelerated, Cartesian physics implies that the earth accelerated, even though no force was applied to it. (The

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[21] Descartes, *Principles of Philosophy*, II.54; II.25.

Principia's scholium will therefore explain that while relative motion can be generated or changed without impressing force on a body, true motion can be generated or changed only by impressing forces "on the moving body itself"(Newton, 1999, 413).) Another unacceptable consequence is that it is not possible to define rectilinear motion or to determine any distances, directions or speeds. Since Cartesian physics provides nothing motionless against which places and trajectories could be defined, "not even God himself could define the past position of any moving body accurately and geometrically now that a fresh state of things prevails, since, on account of the changed positions of the bodies, the place does not exist in nature any longer."[22]

Having shown that something motionless is required in physics, Newton emphasizes the need for absolute space, both in *De gravitatione* and then in the *Principia*'s scholium. No bodies will serve the purpose, since as he writes in the scholium, "It is possible that there is no body truly at rest to which places and motions may be referred."(Newton, *Principia,* 1999, 411). And though one of his remarks appears, given hindsight, to formulate the concept of a frame of reference ("we reckon all places on the basis of the positions and distances of things from some body that we regard as immovable, and then we reckon all motions with respect to these places" (*Ibid.,* 410)), he does not in fact pursue the thought to full development. He therefore sees physics as requiring absolute space.[23]

Although in *De gravitatione* Newton gives the stage to absolute space—and understandably, since he elaborates his own ideas by opposing a physics that fails because of its notions of place and space—absolute time is no less fundamental to his

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[22] *De gravitatione*, in Newton, 2004, p. 20. The inability to define any location, as needed to determine such things as the distance a body has traveled, its trajectory and speed is, to be clear, a consequence of Descartes' official position, with its philosophical sense of motion; Newton points out that in noting the planets tendency to recede from the sun, Descartes implicitly invokes the vulgar sense of motion that he claims to reject (see Newton 2004, 15).

[23] If one adopts a less historical perspective by considering concepts not fully available to or articulated by Newton, one might ask what "Newtonian physics" requires. This is the question DiSalle poses, and he answers that the laws presuppose only absolute time, not absolute space; in particular, since they cannot determine absolute velocities or distinguish between absolute rest and absolute rectilinear, uniform motion, "Newton's laws require not absolute space, but a four-dimensional structure known as "Newtonian space-time." (DiSalle, 2002, 35).

physics. In particular, absolute time is presupposed by Law 1, since the perseverance of the same state requires the notion of equal times; uniform rectilinear motion, for instance, requires that equal distances be traversed in equal times. Absolute time then draws empirical warrant, despite being itself imperceptible, through the success of the theory that presupposes it. That point was made, although overoptimistically, by Euler as he defended Newton's absolutist concepts against "metaphysicians" such as Leibniz. "There is not the least doubt that bodies of themselves behave in accordance with these principles", he writes, dividing Newton's first law into distinct principles concerning rest and uniform rectilinear motion; and "if it is not possible to conceive the two principles adduced from mechanics without being involved in the ideas of space and time", one may justifiably conclude "that both absolute space, and time, such as are represented by mathematicians, are real things."[24] Although he was writing near the zenith of confidence in Newton's physics, well before relativity theory revealed its limitations and the need for a concept of space-time, we can appreciate the rudiments of Euler's point.[25]

As for Newton, he establishes empirical credentials for absolute time indirectly, via his discussion of absolute motion. The fact that absolute space and time are imperceptible raises the epistemological question of how any absolute motions could be identified. Although the inertial states of uniform rectilinear translation and absolute rest are indistinguishable, as Newton acknowledges in Corollary 5,[26] he focuses upon a particular class of absolute motions when addressing the epistemological question, namely, those involving absolute rotation. Although it is "certainly very difficult" to differentiate true from apparent motions, he acknowledges, "the case is not utterly

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[24] Leonhard Euler (1748, 117).

[25] A discussion of the weaknesses in Euler's remarks may be found in Van Fraassen, 1970, 114.

[26] "Corollary 5. *When bodies are enclosed in a given space, their motions in relation to one another are the same whether the space is at rest or whether it is moving uniformly straight forward without circular motion.* For in either case the differences of the motions tending in the same direction and the sums of those tending in opposite directions are the same at the beginning (by hypothesis), and from these sums or differences there arise the collisions and impulses [literally, impetuses] with which the bodies strike one another. Therefore, by law 2, the effects of the collisions will be equal in both cases….On a ship, all the motions are the same with respect to one another whether the ship is at rest or is moving uniformly straight forward." (*Principia*, 423.)

hopeless", since there is some available evidence. One source of evidence is apparent motion, which is the difference between true motions; for instance, if we observed motion between a sphere and a shell enclosing it, we would know that at least one of those bodies was rotating, even if we did not know which. Another source of evidence is "the forces that are the causes and effects of the true motions."(Newton, *Principia*, 1999, 414) Here Newton refers on the one hand to the impressed forces that generate or change true motion; and on the other to inertial effects, specifically, to "the forces of receding from the axis of circular motion". (*Ibid.,* 412)

Within the scholium, Newton then provides such evidence by way of a thought experiment involving a revolving system of two connected globes.

> For example, if two balls, at a given distance from each other with a cord connecting them, were revolving about a common center of gravity, the endeavor of the balls to recede from the axis of motion could be known from the tension of the cord, and thus the quantity of circular motion could be computed. (*Ibid.,* 414)

Here the tension in the cord enables us to determine that there is an impressed force acting, one preventing the bodies from following inertial trajectories by which they would recede from the axis of motion. It further enables us to measure quantity of motion. As the passage continues, Newton explains how the direction of motion could be found, in both (i) the case of the bodies being in a vacuum, such that they could not be compared to other bodies, and (ii) the case of their being surrounded by bodies akin to the fixed stars (i.e., fixed in their positions relative to one another). In that latter case, Newton supposes relative motion between the globe-system and the surrounding bodies; but while the apparent motion tells us only that at least one of these two systems is rotating without telling us which, we can determine from the tension in the cord that it is the globe-system that revolves, not the surrounding bodies. The bulk of the evidence, however, will of course come in the rest of the *Principia*, as Newton indicates with the scholium's closing words: "But in what follows, a fuller explanation will be given of how to determine true motions from their causes, effects, and apparent differences, and, conversely, of how to determine from motions, whether true or apparent, their causes and effects. For this was the purpose for which I composed the following treatise." (*Ibid.,* 415)

Then, in one of the treatise's crucial moves, by which Newton develops his gravitational theory, absolute time underwrites the equal intervals of time that he supposes when passing from a force acting by impulse to one acting continuously. Articulated first in *De motu* (a manuscript he produced, in five extant versions, following Halley's inquiry about the orbit produced by a central inverse-square force) and then in the *Principia*'s Book I, Proposition 1, the process begins by supposing that "time be divided into equal parts". It then supposes that a body moving inertially with respect to a point S will experience "a single but great impulse" (*Ibid.,* 444) at each of those equal intervals of time. As a result, the point S is a center and the impulses are centripetal forces directed toward it, such that as the body moves around S, it describes a polygon whose sides indicate, by their number, the number of impulses delivered. Radii drawn from the endpoints of those sides to the center produce triangles of areas proportional to the times. Newton then passes to a continuously acting force: "Now let the number of triangles be increased and their width decreased indefinitely, and their ultimate perimeter...will...be a curved line; and thus the centripetal force by which the body is continually drawn back from the tangent of the curve will act uninterruptedly." (*Ibid.,* 445; see 444 for the diagram) Each decrease in the triangles' width corresponds, clearly enough, to a decrease in the length of the time interval.[27]

THE AFTERMATH

If Newton saw his concepts of absolute time and space as innocuous, a good number of commentators disagreed. Leibniz was not the only critic among Newton's contemporaries, but his attack was by far the most visible and influential, being communicated through his widely circulated correspondence with Clarke. Resurrecting the reductionist, relationalist conception of time, Leibniz faulted the absolutist concepts

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[27] On the proper understanding of Newton's second law, as able to accommodate both a succession of forces and a continually acting force, see Cohen, *Newtonian Revolution,* 173-174.

for violating metaphysical principles that were fundamental to his natural philosophy and his conception of God. Asserting in his fourth letter that "metaphysics becomes real and demonstrative through the grand principles of sufficient reason and of the identity of indiscernibles",[28] he dismisses Clarke's claim that a free and perfect deity could have chosen to create the world earlier, as only absolute time allows. On Leibniz's view, such a proposition cannot be reconciled with a perfect deity, since there could be no reason for choosing to create at one instant rather than another. Subsequent evaluations of Newton's concepts turned upon a quite different question, that of empirical warrant. Euler gave an excessively sanguine defense of Newton's concepts, as we saw earlier, while Ernst Mach later attacked them "monstrous" metaphysical conceptions, because they failed to meet his positivism-informed empirical criteria.

With the demise of absolute simultaneity and the advent of relativity theory, space and time gave way to space-time. Newton's own concepts were accordingly no longer at issue, and the debate focused upon successor concepts, with a good number of commentators, such as Hans Reichenbach, rushing to proclaim victory for relationalism. Those assessments have not survived, but greater sensitivity to the philosophical implications of new physics has not ended debate, instead shifting it to more subtle and branching questions.[29]

As for Newton's own concepts, historians are left with a number of problems. These include questions about Newton's early ideas about space and time and their relation to his atomist ideas (e.g., Palmerino, 2013); questions about the role of his theory of fluxions for fostering his ideas about time in physics (e.g., Cohen, 1978; Arthur, 1995; Guicciardini, 1999, 2009); and of course the relationship between the concepts figuring in his physics and those in his metaphysics (e.g. McGuire, 1978 and Arthur, 1995 toward one end of the spectrum, and DiSalle, 2002, toward the other).

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[28] Leibniz, fourth letter to Clarke, paragraph 5 (ed. Robinet, 1957), p. 84; my translation.

[29] Some years ago, Earman (1989, 2) listed a considerable number of positions and debates, and the literature has of course grown since then.

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