Absolute space and Newton's theory of relativity

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I. Introduction

> ….[T]he deduction from the phenomena in Book III can be regarded as not only a deduction of the law of universal gravitation, but also a deduction—or at any rate a contribution of evidence; a "proof' in Newton's sense—of a major metaphysical element of Newton's science: his theory of space and time. (Stein 1990.)

To a follower of 20th-century debates over the metaphysics of space and time, this will seem to be an extraordinary claim. Mach, Einstein, and the logical positivists who followed them agreed that Newton's theory of gravity, and his physics generally, succeeded in spite of his metaphysics of space and time; the latter were seen as, at best, unnecessary metaphysical baggage and, at worst, signs of serious conceptual confusion. Subsequently, the work of Stein (1967) placed Newton's views in a new light, as more motivated by, and essentially connected to, his physical theory than philosophers had realized. Even on this comparatively sympathetic view, however, it is not quite Newton's "theory of space and time," but a reformed spatio-temporal structure that is in question. It was Stein himself who introduced philosophers to the distinction between "absolute space and time," as outlined in Newton's famous Scholium to the Definitions, and the spatio-temporal structure required by Newton's laws, which Stein called "Newtonian space-time" (Stein 1967).[1] That is to say, the success of Newton's project in the *Principia* might be said to

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[1] This is the structure usually known as "Neo-Newtonian" or "Galilean" space-time in subsequent literature. See, for example, Earman (1989). More recent literature has emphasized that even Newtonian space-time, though it embodies the relativity principle implicit in Newton's laws, is a stronger structure than is required for the physics of the *Principia*. See footnote 8 below.

confirm, not his theory of space and time, but a more modest geometrical structure of space time to which "absolute space" is an unnecessary metaphysical appendage.

Stein was undoubtedly right to assert that Newtonian space-time is a more suitable structure for Newtonian mechanics, and that absolute space as conceived by Newton introduces superfluous structure. Nonetheless, I will argue, Stein was not wrong to suggest that the work of the *Principia* confirms, in an important sense, Newton's metaphysical picture. The latter point only emerges clearly, however, from the history of Newton's conception of absolute space, and especially the moment in the development of his thinking when he first introduced this concept. That development, moreover, becomes fully comprehensible only as part of another development: Newton's increasingly profound understanding of the relativity of motion. This last point may seem paradoxical. Yet the study of the progression of Newton's thinking, during the years in which he was working out the *Principia*, will bear it out.

II. The origins of "absolute space."

My discussion deliberately focuses on the conception presented in the Scholium to the Definitions in the *Principia*, to the exclusion (provisionally) of issues raised in earlier writings, such as the unpublished manuscript *De gravitatione et aequipondio fluidorum* (Newton 1684a), and later writings such as the General Scholium (first added to the second edition of the *Principia,* 1713) and the manuscript *Locus et tempus* (cf. McGuire 1978). This is not because those issues were not important parts of his thinking. It is, indeed, impossible to arrive at a complete picture of Newton's metaphysical views of space and time without considering their relation to his view of the metaphysics of substance, his theological views, and perhaps other intellectual concerns. A complete picture of Newton's thoughts regarding space is not, however, necessary to the understanding of "absolute space." For "absolute space," taken with historical care, does not refer to the collection of Newton's thoughts on space and its links to his broader metaphysical outlook. It refers, rather, to the restricted account of space enunciated in the *Principia.* It is evidently consistent with Newton's broader outlook, and it differs from the view expressed in *De Gravitatione* chiefly in two points that will be discussed below. But Newton introduced this concept at a particular moment in the evolution of his physics, at a particular moment in the evolution of the *Principia* itself as a work of physics, and at a particular place in the *Principia*'s larger structure. It is necessary to ask, therefore, why Newton specified this concept in this restricted way, and what role it played in the argument of the *Principia*.

This last point is an unusual starting point for a study of Newton's views. This is because historical and philosophical commentators have tended to take "absolute space" as referring to a general metaphysical account of space, rather than as a conception peculiar to Newton—not as a theory set forth in the *Principia*, but as a generic position in a pre-established metaphysical debate. Certainly there was a standing metaphysical question whether space has a real existence independently of bodies, or is something ideal, or is indistinguishable from body as in Descartes' conception. The opposition between Descartes' view and that of Henry More, that space exists independently of matter, was certainly an important part of the philosophical context in which Newton's view developed. But to refer to any metaphysically realistic view of space as a belief in "absolute space" is a habit that formed after Newton's *Principia*. There is no prior history of usage of the term "absolute space" in any literature that Newton would have known. Obviously such a negative existential claim is difficult or impossible to establish conclusively. In any case, however, the phrase was not commonly or prominently used; it does not seem to have been used by More, though he is frequently cited as a prominent advocate of "absolute space."[2] It should be obvious, therefore, that in introducing this term, and in specifying exactly how it is to be understood— including its connections with "absolute time," "absolute place," and "absolute motion"— Newton was consciously not entering into a standing debate about the "absoluteness" of space and time. Instead, he introduced his own terminology in order to articulate what he took to be the spatial and temporal background specifically requisite to the physics of the *Principia*. It is true, as McGuire (1978)

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[2] Cf. More (1671) and Power (1970). Cf. also Charleton (1654), Book I, Chapters VI-VII.The nearest thing to an "exception that proves the rule"— in the original sense of that phrase— can be found in Leibniz's references to "absolute extension." The earliest occurs in (1676), which was not published in Leibniz's lifetime; the term also appears in the more familiar "Meditations on knowledge, truth, and ideas" (1684), which Newton is unlikely to have read. In any case, however, Leibniz did not mean the term in the sense introduced by Newton. Rather, he meant extension only, considered only with respect to its geometrical properties, as distinct from extended bodies. Clearly he did not intend it in any sense relevant to questions of motion and rest. When Leibniz eventually used the precise phrase "absolute space" in his own work on the foundations of mathematics (1715)— that is, when not making reference to Newton's view— it was well after the *Principia*, and again meant in the sense of "absolute extension". I am indebted to Vincenzo DeRisi and Adwait Parker for drawing my attention to this usage.

notes, that Newton returned to the other issues raised in *De Gravitatione* in a manuscript that was apparently written after the *Principia*. But it is striking that there, too, Newton does not use the terms "absolute space" and "absolute time."

It is also clear that there was some precedent for the use of the term "absolute motion," as contrasted with relative motion, and that Newton would have known this, most recently, from the work of Barrow (e.g. Barrow 1685). But this only reinforces the understanding that Newton coined the term "absolute space," emphatically, in order to characterize the spatial framework for his theory of motion. It is, in effect, a back-formation from the concept of absolute motion. To acknowledge this is not to say that Newton's conception had nothing in common with previous metaphysical views of space such as More's. But More's account was by no means an account of a framework for the dynamical treatment of motion and rest. The essential point is that in introducing a novel term, Newton intended to refer only to that theory of space that he articulated in explicating the term. With More and other philosophers of his time, Newton certainly shared various metaphysical presuppositions regarding space and time, including their relations to ontological and theological matters. In the Scholium, however, Newton evidently had no intention to place his account of space and time in that philosophical context.

The relevant context for Newton, instead, was entirely a theoretical context. Or, more precisely, for Newton there were two relevant theoretical contexts. One was the traditional problem in astronomy of distinguishing true from apparent motion, and determining the true structure of the planetary system. The second was a contemporary problem in physics, that of distinguishing states of motion by their physical causes and effects. The second included, of course, the complications added to that problem by Descartes' peculiar account of space and body, and his peculiar distinction between relative and "proper" motion. Newton's engagement with Descartes' views of space and motion, both in the *Principia* and in the earlier manuscript *De Gravitatione*, was first brought to light by Stein, and this essay has little to add.[3] It should be emphasized, however, that Newton proposed in the *Principia* to solve both of these problems at once: the true astronomical "system of the world" would be determined by a proper understanding of the causal influences of the bodies within the system among themselves. For the completion of this task, the

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[3] See Stein 1967, 1977; see also Rynasiewicz 1995a, 1995b, and DiSalle 2006, chapter 2, for some additional context.

concepts of “absolute space” and “absolute time” were intended to form the necessary and sufficient framework.

The special and novel role of these concepts in the *Principia* is further confirmed by the manner in which they first appear in Newton’s unpublished drafts of the work. In one of the later drafts, “On the motion of bodies in regularly yielding media” (Newton 1685a), we find his first accounts of absolute time, space, place, and motion, in terms that are very nearly identical to those in the Scholium to the Definitions. Here, however, they are themselves definitions, indeed the very first definitions at the very beginning of the paper. For example:

> Def. 1. Absolute time is that which by its own nature without relation to anything else flows uniformly. Such it is whose equation Astronomers investigate, and by another name is called Duration….
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> Def. 2. Time looked at relatively is that which from something some other sensible passage or another flow or passage is measured in respect to the flow or passage of any sensible thing is considered as uniform….
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> Def. 3. Absolute space so-called is that which by its own nature and unrelated to any other thing whatsoever always remains immobile [immobile]. As the order of the parts of time is immutable, so also is that of the parts of space. Were these to be moved from their places they would be moved out of themselves. For times and spaces are just the places of themselves and all things. All things are located in time as long as the order of succession and in space as far as the order of position. The essence of those is that they are to be places, and [for] primary places cannot to be moved is absurd….
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> Def. 4. Relative space is that which is considered immobile with respect to another any sensible thing: such as the space of our air with respect to the earth….(1685a)

As he would afterward in the Scholium, Newton explained here that these distinctions were necessary in order to free the reader from certain “common prejudices,” and to avoid confusing ordinary talk of motion, which is always based on relative motion, with scientific discourse; thereby one would avoid misinterpreting the "sacred writings," for "both the sacred literature and Theological writings are always to be understood in terms of the relative, and he who would thereupon stir up philosophic debates concerning the absolute motions of natural things would be laboring under a gross prejudice" (ibid). A further purpose, not explicitly repeated in the Scholium, was that the reader "imbued with clear and distinct conceptions of Mechanical principles may agree to what follows" (ibid).

The foregoing should suffice to distinguish Newton's discussion of absolute space from broader philosophical discussions of his time concerning the metaphysics of space, as well as from those of our own time concerning "absoluteness" of space. The question whether space is absolute presupposes that the meanings of "space" and "absolute" are already well understood. Newton's Scholium makes no such presuppositions. It tells us only what Newton wished the reader to understand by "absolute space," "absolute time," and "absolute motion." This fact distinguishes the position of the Scholium, incidentally, from that of *De Gravitatione*: there, he had expressly denied that space is "absolute." He did so, however, having explained what he understood space to be, and why it should not be regarded as a substance; he also explained, though briefly, what he understood by "absolute" in this context, and why space did not seem to him to be a thing "absolute in itself" (1684a, p. 12). Though it could not be regarded as an attribute of things, its way of existing was not independent of the existence of things, because it was, according to Newton, an "emanative effect" of the first existing thing. Newton inferred from this that space was an emanative effect of the existence of God. Newton made it clear, however, that the ontological point was a more general one: "for if a thing is posited, then space is posited." This is not the place, however, to rehearse Newton's account of the ontology of space in *De Gravitatione* (see Stein 1967, 2002). For us it suffices to note two crucial historical facts. First, the discussion of "absolute space" in the Scholium clearly did not appeal to the notion of "absoluteness" taken for granted in *De Gravitatione*. Therefore we can't take for granted that *De Gravitatione* expresses precisely the same view of space that lay in the background of, or provides a more detailed account of, the view that Newton expressed in the Scholium. Second, the theory of absolute space outlined in the Scholium simply avoids the ontological questions about the existence of space, its relation to God and to material things, and its place among the accepted metaphysical categories. The account of absolute space in the Scholium, along with that of absolute time, only concerns what we would call its structure.

III. Newton on the relativity of motion.

This severe restriction in scope is not, however, the most important sign of Newton's conceptual development between *De Gravitatione* and the *Principia*. The crucial change is Newton's growing insight into the relativity of motion. During this time he developed, in fact, what may be called a "theory of relativity". The phrase "theory of relativity" is intended to distinguish Newton's broader view, on the one hand, from the specific physical "principle of relativity," and, on the other hand, from a general philosophical belief in the relativity of motion. The principle of relativity refers, here, to the dynamical indistinguishability of uniform motion and rest. This was obviously not an original idea of Newton's; Huygens stated it clearly for the first time in his work on impact, as "Hypothesis III":

> The motion of bodies, and their speeds equal or unequal, are to be understood respectively, in relation to other bodies which are considered as at rest, even though perhaps both the former and the latter are subject to another motion that is common to them. In consequence, when two bodies collide with one another, even if both together undergo another equable motion, they will move each other no differently, with respect to a body that is carried by the same common motion, than if this extraneous motion were absent from all of them. (1656, p. 32).

This principle is known as "Galilean relativity" for a very good reason, even though Galileo did not formulate it clearly: he was the first to understand the relativity of motion in a dynamical sense. In contrast to Huygens' later discussion, Galileo's seemed to suggest that any sufficiently uniform motion of a system, even a circular motion with a sufficiently large radius, might be physically indistinguishable from rest. This was connected with his discussion of the persistence of uniform motion, which seemed to suggest that this too might apply to uniform circular motions (cf Franklin 1976, p. 541). The classical principle that bodies naturally persist in uniform *rectilinear* motion— what would be known as Newton's first law of motion, and later as "the principle of inertia"— was also given its first clear formulation by

Huygens ("Hypothesis I," 1656 pp. 30-31).[4] Nevertheless, Galileo conceived of and defended the physical core of the relativity principle, by connecting it with the persistence of uniform motion and the composition of uniform and accelerated motions: the motions taking place among interacting bodies are simply composed with any uniform motion that all the bodies share. By these principles Galileo successfully undermined a classic form of argument against the motion of the earth, based on our inability to detect such motion in ordinary experience. Copernicus, for example, needed to explain why the earth's motion is not perceived; he was bound to assert that the earth, like a ship, might undergo a smooth motion that would be indistinguishable from a contrary motion of its surroundings. (1543, p. 6). But only Galileo explained the physical ground of this indistinguishability. It remained for Huygens to state the principle of relativity, along with the "principle of inertia," in the precise forms in which Newton eventually came to understand them.

This last point distinguishes the physical principle of relativity, as employed by Galileo, Huygens, and Newton, from the relativity of motion as a general philosophical principle. A commitment to relativity in the latter sense was much more widespread among philosophers. Its essential conviction is that, on grounds of epistemology or metaphysics or both, motion can be nothing but the observable changes of relations among bodies. From this it naturally follows that privileged states of motion, and motion with respect to space itself, are scientifically and philosophically illegitimate notions; space and time themselves are philosophically suspect theoretical entities, based on what would now be called a questionable "inference to the best explanation." At best, they are abstractions from observable relations, occasionally instrumentally useful, but not to be taken as real. The clearest example of this commitment, in Newton's time, was Leibniz's general "equivalence of hypotheses": in any system of interacting bodies, any hypothesis about which particular bodies are at rest is equivalent to any other. Copernicus' and Ptolemy's views of the planetary system are both merely possible hypothetical interpretations of the

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[4] Descartes is often credited with the first statement of the principle of inertia. This is, however, something of an exaggeration. Descartes' original "laws of nature" (1644, p. 54-55) affirmed that bodies naturally persist in rectilinear motion, so that any curvilinear motion, even uniform circular motion, implies a centrifugal force. The laws thus specified something that had remained unclear in Galileo's view, and that represented a crucial step toward Huygens' principle. But Descartes did not there specify that bodies move uniformly with respect to time. He did mention uniform velocity in other writings (e.g. 1638), but its absence from the statement in the *Principia Philosophiae* suggests, at best, indifference to the crucial role of time in the law of inertia as Huygens and Newton understood it.

same relative motions. Therefore neither one can be true, though the Copernican system may be the simpler (e.g. Leibniz,1694). The history, varieties, and merits of this view are the subject of a large literature (see Earman 1989 for an authoritative critical overview). Here, it suffices to note that this general philosophical perspective is conceptually disconnected from the physical principle of relativity, that is, from the Galileo-Huygens theory of physically indistinguishable states.

IV. Newton's development of a "theory of relativity."

Newton embraced the principle of relativity, and began to emphasize it in drafts of the *Principia*. What does it mean to say that he had, moreover, a theory of relativity? It means that Newton tried to expose all of the conceptual changes that must follow, throughout his theoretical system, of incorporating the relativity principle. Consider, for comparison, Einstein's theory of the electrodynamics of moving bodies (1905), which applied (essentially) the same relativity principle to electrodynamics. We know that, contemporaneously, Poincaré defended the relativity of motion, and expressed his belief that no experiments in electrodynamics would ever reveal a distinction between uniform motion and rest (e.g., 1908, pp. 253-254). It was Einstein, however, who first understood the conceptual changes that must follow from applying the relativity principle to electrodynamics as a fundamental principle, and reconciling it with the invariance of the velocity of light (1905). Einstein's theory of relativity incorporated all of the revisions that must result to the physical conceptions of time and space, and the consequent revisions to the principles of electrodynamics. In a broader sense, this entailed a critical analysis of familiar concepts—either from common sense or from scientific discourse— revealing the extent to which they represent partial or relative perspectives on the invariant quantities. To say that Newton presented a theory of relativity, analogous to Einstein's, is only to recognize that Newton engaged in an effort of conceptual revision with a similar scope. As soon as he had embraced the relativity principle, he began to work out its broader consequences for prevailing conceptions, especially those of matter, force, and motion. He introduced the theory of absolute space, time, and motion only after he had begun this effort, and as what he took to be an essential part of it. Since he maintained this non-relativistic account of space and time, it is evident that his effort was not entirely successful. Nonetheless

Newton went further along this path than any of his contemporaries[5], and indeed, than any of his successors for nearly two centuries. Any paradoxical air that this claim may have seemed to have, at the outset, is quickly dispelled by a look at Newton's manuscripts.

Newton's first statement of the relativity principle appeared in one of the earlier papers in the series that culminated in the *Principia*, "On the motion of spherical bodies in fluids" (1684b). As Huygens had done, Newton presented the relativity principle as a fundamental principle, "Law 3":

> The motions of bodies included in a given space are the same among themselves whether that space is at rest or moves uniformly in a straight line without circular motion. (1684b, p. 40r.)

Newton's statement evidently recapitulates Huygens' version. The same may be said of "Law 4" in this manuscript, the principle of conservation of the centre of gravity:

> By the mutual actions between bodies their common centre of gravity does not change its state of motion or rest. (ibid.)

It is possible, or even probable, that Newton came to these principles through the work of Huygens. Yet Newton's further reflection on them was original and unique. For, further on in the same paper, he placed them in a larger theoretical context, considering their significance for an outstanding question in natural philosophy: the question of the "system of the world." Newton directly grasped, from these principles, that this ancient question must be dramatically re-conceptualized. First, the system as a whole could be seen as contained, not in "space," but in a space of its own, "the whole space of the planetary system." This space, furthermore, may itself be either at rest or in uniform motion, without making any difference to the actions of the bodies among themselves. Since these actions will not alter the position of the centre

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[5] As Stein pointed out, in at least one respect Huygens went beyond Newton in developing the conceptual consequences of the physical principle of relativity: he saw that the dynamical distinctness of rotation could be understood without recourse to the notion of absolute velocity with respect to immobile space. (Stein 1977, pp. 8-10 and Appendix III.)

of gravity, it is the centre of gravity that must be considered the resting centre of the system. But the centre of gravity, evidently, may be in uniform motion or rest along with the entire system.

> Moreover the whole space of the planetary heavens either rests (as is commonly believed) or moves uniformly in a straight line, and hence the communal centre of gravity of the planets (by Law 4) either rests or moves along with it. In both cases (by Law 3) the relative motions of the planets are the same, and their common centre of gravity rests in relation to the whole space, and so can certainly be taken for the still centre of the whole planetary system. (ibid, p. 47r.)

The solution to the problem of the system of the world, in other words, requires only what Newton would later call a relative space, whose still centre is its centre of gravity.

Second, it followed that the controversy between the heliocentric and geocentric views of the universe had been mistakenly framed. The proper question about the frame of the system of the world was not "which body is at rest in the centre?" The question was, rather, "which body is closest to the system's centre of gravity?" For in a system of interacting bodies, only their common centre of gravity will be unaccelerated, and by "Law 3," the motions of the bodies in the system will be the same, whether its center of gravity is at rest or in uniform rectilinear motion. By explicitly asserting the dynamical equivalence of "whole spaces" that may moving uniformly or at rest, Newton made it clear that the solution to the problem of "the system of the world" is the same with respect to any such moving space as it is with respect to immobile space.

In the successive drafts of his *Principia*, Newton gradually clarified its conceptual structure, and in particular the frame-independent character of its concepts of motion, force, and interaction. He arrived at the new axiomatic structure whose only laws are the familiar "Newton's Laws of Motion"; the principle of the conservation of the centre of gravity, and the relativity principle, were no longer presupposed, but derived from the Laws as Corollaries IV and V:

> Corollary IV: The common centre of gravity of bodies does not change its state, whether of motion or rest, by the actions of those bodies among themselves; therefore the common centre of

> gravity of all bodies (external impediments excluded) rests or moves uniformly in a straight line. (1687, p. 17.)
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> Corollary V: When bodies are enclosed in a given space, their motions among themselves are the same whether the space is at rest, or whether it is moving uniformly straight forward without circular motion. (1687, p. 19.)

These principles illuminate the relationship between the theory of absolute space, as articulated in Newton's Scholium to the Definitions, and the overarching scientific problem of the *Principia*— what Newton described as "the aim for which he composed it": "to gather the true motions from their causes, effects, and apparent differences, and conversely, from the motions, true or apparent, to gather their causes and effects" (1687b, p. 11)— along with the specific aim of Book III, "to exhibit the constitution of the system of the world" (1687b, p. 401).

On the one hand, Corollary V, like "Law 3" in *De Motu*, precisely restricts what Newton's procedure can determine about the structure of the system of the world; it cannot determine anything about the velocity of the system as a whole, but only the position of the centre of gravity of the bodies that comprise it, and the configuration of those bodies with respect to that centre. In this sense it can, in principle, decide between a Keplerian and a Tychonic interpretation of the motions of these bodies: the system is indeed approximately Keplerian, since the sun has by far the greatest mass and is therefore little disturbed from the center of gravity. Therefore the sun remains very close to the common focus of the approximately Keplerian ellipses in which the planets orbit the sun. But by Corollary V, the actions of the bodies among themselves would not reveal whether their centre was moving uniformly or at rest. On the other hand, Newton recognized that motion with respect to absolute space is unknowable. The restriction imposed by Corollary V, therefore, meant that the solution to the system of the world is secure in spite of our ignorance. The nearly-Keplerian structure of the system is known completely independently of the system's state of motion in absolute space.

The Galilean relativity principle thus contained, in Newton's conception, a broader insight: that different states of uniform motion, or different uniformly-moving frames of reference, determine only different points of view on the interactions within a given system of bodies. This emphasis on the relativity principle suggests that *De Gravitatione* was written sometime before the *De Motu* drafts; the former focuses only on Descartes' peculiar form of relativism, but the Galilean principle is not mentioned. But this is perhaps merely circumstantial evidence. For more explicit evidence of Newton's conceptual progression after *De Gravitatione*, we may examine the evolution of Newton's concept of inertia. Newton had taken the term from Kepler, who had incorporated it into his physical theory of planetary motion. Having rejected the ancient idea that the planets are carried by rotating crystalline spheres, Kepler had dispensed with the idea of natural motions. Instead, he proposed that the planets have a natural tendency to rest in space. This tendency, or "natural inertia," had to be overcome by active powers in order for a body to maintain any motion through space. Newton, while maintaining Kepler's term, based his conception of inertia on the idea of Galileo and Huygens, that bodies naturally tend to persist in uniform motion or rest. In short, Newton redefined Kepler's term as resistance to change in motion.

In spite of its comparative modernity, however, Newton's early understanding of inertia was essentially pre-relativistic. It implied a conceptual distinction between a resting body's power to resist external forces, and the power of a moving body to change the motion of another. It reveals, in fact, that *De gravitatione* must have been written before Newton fully recognized the importance of the relativity principle. For in the "Definitions" in this work, Newton Definitions distinguishes "conatus," "impetus," and "inertia" as conceptually separate properties:

> Definition 6. Conatus (endeavor) is impeded force, or force in so far as it is resisted.
> Definition 7. Impetus is force in so far as it is impressed on another.
> Definition 8: Inertia is the internal force of a body, so that its state may not be easily changed by an external force.(1684a.)

The view expressed here was widespread between the first versions of the principle of inertia and the acceptance of the *Principia*. A body was understood to persist in rectilinear motion by an active power distinct from its tendency merely to resist changes of state. Leibniz, for example, distinguished the "passive" power to resist motion from "moving force," or the "active" power of a body to continue in motion and to change the motion of another by virtue of its velocity (1696, p, 148). Which power the body would exhibit would depend on whether the body was taken to be uniform motion or at rest; and the degree of active power would depend on the velocity.

Sometime after writing *De gravitatione*, however, Newton came to understand that these are not separate properties, but merely different aspects of inertia, seen from different points of view. This new understanding emerges gradually in Newton's successive definitions of inertia after "De motu corporum in fluidis" (1684b), in which he had first set forth the relativity principle. In "On the motion of bodies in regularly yielding media" (1685a), Newton still maintained something like his previous distinction, here between the "inherent force" of a body, the impetus proportional to its motion, and the impulse causing changes in state. In a subsequent draft, however, Newton finally realized that this distinction is essentially relative. The significant property of a body was the inherent force that reveals itself when a body interacts with other bodies. If we take the body to be at rest, then it is seen as resistance to motion; if we view the same body as in motion, it is seen as impetus. The resulting definition is nearly identical to the one that would appear in the *Principia*:

> Definition 3: The internal force of matter is the power of resistance by which any body persists in its state of rest or of moving uniformly in a straight line: it is proportional to the body and does not differ from the inertia of matter except in our mode of conceiving it. A body truly exerts this force only in a change of its state brought about by another force impressed upon it, and the exercise of this force is both resistance and impetus, which are distinct from one another only relatively: resistance in so far as the body, to maintain its state, opposes the impressed force; impetus insofar as the same body, yielding only with difficulty to the force of a resisting obstacle, endeavours, to change the state of that obstacle. Resistance is commonly attributed to resting bodies and impetus to moving bodies; but motion and rest, as commonly understood , are only relatively distinguished from each other; and bodies commonly seen as resting are not always truly at rest. (1685b, p. 315.)

This explication of inertia is strikingly novel in two closely related senses. First, it shows that Newton recognized properties that were commonly regarded as distinct (e.g. in the Leibnizian distinction between passive and active) as merely frame-dependent representations of the same fundamental property, i.e. as one property that only appears as different properties when considered from different points of view.[6] Second, the definition emphasizes that a body exerts this force "only in a change of its state." This remark decisively separates Newton's new view from the older notion of a specific power that is required to maintain a body in motion. To many later commentators, Newton's use of phrases such as "innate force" and "force of inertia" suggested a conceptual confusion; these must indeed sound confused, if they imply that bodies must exert a force in order to maintain their states of motion. That Newton did not share this confusion appears in his specification that a body exerts this force "only in a change of state."[7] It is a capacity for entering into interactions that a body has in virtue of its mass, and in proportion to its mass. How it expresses itself will depend on the particular interaction; in a collision, it will depend on the other mass and the relative velocity of the two. Thus Newton's mature conception of inertia, in its relativistic form, united three properties that had been regarded as distinct: the tendency to persist in motion, the resistance to change in motion, and the power to react against an impressed force. All were essential to the explication of inertial mass as a measurable theoretical quantity. Indeed, as Stein pointed out, this is why Newton did not characterize inertia by his first law alone— in spite of its later isolation as "*the* principle of inertia." All three laws combined to characterize inertia in Newton's sense (cf. Stein 2002).

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[6] This aspect of Definition III was emphasized by DiSalle, 2006, p. 28. But that discussion takes no account of the evolution of this Definition from the views expressed in *De Gravitatione*.

[7] This change has been noted by modern commentators (see Herivel 1965, p. 26; see also DiSalle 2013, p. 453). But it was already noted in Newton's own time by George Berkeley, who noted Newton's grasp of the relativistic aspect of inertia, and emphasized the contrast between Newton's conception and that of Leibniz:

> Leibniz confuses impetus with motion. According to Newton, impetus is in fact the same as the force of inertia....Inert body acts just as body moved acts, if the truth be told. Newton recognizes that fact when he says that the force of inertia is the same as impetus. But a body, inert and at rest, does nothing; therefore a body moved does nothing. (1721, section 16.)
> ….Since experience shows that it is a primary law of nature that a body persists exactly in a state of motion and rest as long as nothing happens from elsewhere to change that state, on that account it is inferred that the force of inertia is under different aspects either resistance or impetus. In this sense surely a body can be called indifferent in its own nature to motion or rest. (Ibid, section 51.)

In short, Newton was profoundly aware of the connection between the relativity of motion and the characteristic actions of physical forces, and of the profound consequences of relativity for understanding the problem of "the frame of the system of the world." It was his recognition of these consequences, and his attempt to place them in a coherent larger picture, that extends his use of the relativity principle to a larger "theory of relativity." Moreover, by the time Newton wrote the *Principia*, he had extended it through a further Corollary to the laws of motion, defining a further class of physically indistinguishable systems: systems that are not moving uniformly or at rest, but which are influenced by forces that act equally and in parallel directions on all parts of the system.

> Corollary VI: If bodies are moved in any way among themselves, and are urged by equal accelerative forces along parallel lines, they will all continue to move among themselves in the same way as if they were not acted on by those forces. (1687b, p. 20.)

None of Newton's contemporary critics, even those with the strongest philosophical interest in and commitment to the relativity of motion, took particular notice of Corollary VI. This is puzzling, or at least interesting, given that it seems to suggest an extension of Galilean relativity to a wider class of motions. Newton understood, however, that it is not, in the context of Newtonian mechanics, a true relativity principle. For, in that context, the principle is essentially approximative: a system of bodies can be accelerated only approximately equally, and only in approximately parallel directions, by any finite Newtonian source. Jupiter and its moons, for example, are not equally accelerated by the gravitational pull of the Sun, given their varying distances, and their accelerations are not parallel, but converging on the centre of the Sun. Yet the Jovian system may be treated as if it is in nearly uniform motion, because its immense distance from the sun renders those differences negligible. Thus the system approximates the conditions of Corollary VI as nearly as may be required. Similarly, as Newton pointed out in "De motu Corporum Liber Secundus" (the "popular" draft of a concluding section for the *Principia*, afterwards published as *The System of the World*), the entire solar system may be treated as moving uniformly, even if it is being accelerated by some unknown external force: any acceleration produced by such a force is nearly enough equal and parallel in its action on all parts of the system, and so may be neglected.

> It may be imagined that the sun and planets are impelled by some other force equally and in the direction of parallel lines; but such a force (by Cor. VI to the Laws of Motion) no would not change the situation of the planets among themselves, nor would produce any sensible effect; but we are concerned with the causes of sensible effects. Let us, therefore, neglect every such force as precarious, and of no bearing on the phenomena of the heavens….(1687a, article VIII).

Indeed, on the assumption of central forces, a source that produced precisely the conditions of Corollary VI—say, a perfectly homogeneous gravitational field—would have to be infinitely large or infinitely far away, since the accelerations must otherwise vary with distance and converge on the source. By the same token, however, no local system could be regarded as completely isolated from such external forces unless every action within the system were precisely balanced, in accord with the third law of motion, by an equal and opposite reaction within the system. If such a balance could be established with infinite precision, as it were, then the effects of any external force would be known to be precisely equal and parallel. Moreover, the third law of motion requires that such an external force, too, belong to an action-reaction pair. When all such interactions have been accounted for, the third law implies that there can be no acceleration of the centre of mass of everything, for the law requires that such an acceleration have a source, and by hypothesis there is no source external to the system.

Corollaries V and VI play importantly different roles, then, in the Newtonian theory of motion, and therefore in Newton's theory of relativity. Corollary V expresses a true relativity principle, asserting the absolute indistinguishability of different states of uniform motion, based on the invariance of acceleration and the relativity of velocity. Corollary VI, however, expresses something like a relativity principle, but as Newton conceived it, it does not truly extend Galilean relativity to a fundamental relativity of acceleration. What it expresses, instead, is the inevitably partial character of any account of true accelerations within a system of bodies— except in the ideal case of an infinitely precise measurement, or an absolutely isolated system that encompasses all the matter in the universe.

Newton's grasp of the relativity of motion, and his growing sense of its role in the conceptual framework of physics, constitute a decisive step beyond his thinking at the time of *De Gravitatione*. They help to explain, therefore, another important difference between his critique of Descartes in *De Gravitatione* and that in the Scholium on space and time. Both discussions emphasize the well known argument from centrifugal effects: the centrifugal effects are genuine effects of non-rectilinear motion, and so provide a dynamical criterion of such motions that cannot be accounted for by relative motions alone. Descartes' definition of proper motion, as motion relative to contiguous bodies, is particularly incoherent with the dynamics of rotation and of orbital motion; it makes nonsense of Descartes' own vortex theory of planetary motion. But there is another argument in *De Gravitatione* that is omitted from the Scholium, namely, that Descartes' definition makes nonsense of the principle of inertia, and especially its role in the physics of celestial motion. If the motion of a body is defined with respect to contiguous bodies, then, among the swirling particles of the vortical fluid, it is impossible to assign it any trajectory at all.

> [N]o one can assign the place according to Descartes at which the body was in the beginning of the motion undergone, or rather he has not said from where it is possible for a body to be moved. And the reason is that, according to Descartes, it is not possible to define and assign the place except from the position of the surrounding bodies, and that after any motion having been undergone, the position of the surrounding bodies is no longer the same as it was before. For example, if the place of the planet Jupiter were the same as it was the year before, then having been accomplished it would be at rest; by what reasoning, I ask, will the philosopher, Descartes, describe it?
> ……It follows that Cartesian motion is not motion, for it has no velocity, no determination, and there is no space or distance that it traverses. Therefore it is necessary that the definition of places, and so of local motion, be referred to some immobile thing, such as extension alone, or space insofar as it is viewed as truly distinct from bodies.(1684a, pp. 9-11.)

Evidently, Descartes' account of motion was incompatible with the law of motion that formed the basis for all causal explanation in physics, for Descartes and his successors in Newton's time.

Stein was undoubtedly right to suggest that if Newton had raised this objection with Huygens and Leibniz, it would likely have led to a more fruitful discussion of their philosophical differences concerning true and relative motion (1967, p. 186). Perhaps it would have challenged them to confront their views on the relativity of motion with their central physical assumption, namely the privileged character of uniform rectilinear motion. Given the subsequent development of Newton's thinking, however, we can understand why he would not have published it in the *Principia*. The arguments from centrifugal forces, clearly, are not affected by the principle of relativity. The effects of the earth's rotation, or of the motions of planets in orbits about the Sun, are clearly the same, whether the space in which those motions occur is at rest, or in uniform motion, or even accelerating in accord with Corollary VI. The situation is quite different for the argument about Jupiter and its trajectory. It is one thing to say that Descartes' conception of "proper" motion cannot be reconciled with the laws of motion accepted by Huygens and Newton, or even with Descartes' own "laws of nature"— or, perhaps, with any physical laws founded on the idea of a privileged trajectory. It is another thing to show that, in order to make sense of such a law, we need to be able to trace the motion of a body from place to place in space. How would Newton make use of this argument in the context of his new emphasis, after *De Gravitatione*, on the relativity principle? He had now shown that, for the purpose of discovering the centre of the system of the world, or of any system of interacting bodies, it suffices to determine a relative space that may be in uniform motion or at rest. Jupiter, in particular, provides a striking case for this new perspective: it is part of a system of bodies "enclosed within" a relative space, whose motions among themselves may be treated without regard to the uniform motion of that space in the encompassing immobile space. With respect to immobile space, we do not know where Jupiter was a year ago, but we do not need to know in order to analyze Jupiter's interactions with other bodies according to the laws of motion. By the time of writing the *Principia*, indeed, he understood how and why we can set aside, not only the possible uniform motion of Jupiter's system, but also its accelerated motion as it orbits the Sun.

This is not meant to deny Newton's belief that Jupiter, or any body, really did have a trajectory consisting of the successive positions that it actually occupied in immobile space. This belief was inseparable from his belief that his theory of "absolute space" characterized the real structure of the world in space and time. It only shows why Newton would no longer invoke those absolute places in order to treat trajectories according to the laws of motion, since this analysis could be accomplished within a relative space. The task of his theory of relativity was precisely to show that such a dynamical treatment of bodies could succeed, and produce genuine physical understanding, in spite of the impossibility of determining the motion of that relative space in immobile space.

Putting these considerations together with Newton's other criticisms of Descartes' definition of motion, we arrive at a summary of Newton's mature view. The only univocal criterion for a body's true motion is its displacement, not with respect to contiguous bodies— or any other particular bodies— but with respect to absolute places in absolute space. We cannot hope to know any such absolute motion. Thanks to the relativity principle, however, our insurmountable ignorance of these displacements is no obstacle to understanding the physical structure of any given system of bodies; determining the causes and effects of these motions, through their interactions with each other, suffices to determine the "frame of the system of the world." Now, looking back on the last-mentioned argument against Descartes from *De Gravitatione*, we see that Newton had good reason to omit it from the *Principia*. It does not demonstrate the need to refer Jupiter's motion to places in immobile space, or to know its trajectory in absolute space. Using conceptual resources unknown in Newton's time, one could present a reformed version of this argument: what was needed was a structure strong enough to support the dynamical distinctions that Newton was concerned to make, without the superfluous structure that absolute space introduces. Two centuries later, the the concept of inertial frame was developed: the relative spaces in which forces can be determined by Newton's procedure form an equivalence class of frames, corresponding to the relative spaces of Corollary V, and no immobile background space is required (cf. DiSalle 2020). Newtonian space-time in Stein's sense (1967) is just the four-dimensional formulation of this structure. Indeed, as Newton inferred from Corollary VI, and as we saw previously, his actual application of the laws, in developing the theory of universal gravitation, did not even require a uniformly-moving space as in Corollary V. It sufficed to find a nearly dynamically closed system (cf Stein 1977, pp. 35-36 n.27), such as the Jovian system or the solar system. A sufficient space-time structure for this problem is one still weaker than Newtonian space-time.[8] To consider any of these possibilities,

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[8] The question of the most appropriate space-time structure for Newtonian physics is discussed in recent work by (e.g.) Saunders (2013), Knox (2014), and Weatherall (2018).

however, one would have to understand absolute space as a particular case of a more general idea of a dynamical space-time structure. The only alternative to absolute space known to Newton, or to anyone else for the next two centuries, was the purely kinematical space-time in which motions are reduced to changes of relative position.[9]

Newton's new appreciation of the relativity principle, in the first drafts of the *Principia*, did not displace his conviction that all motion must ultimately be understood against the background of "immobile space." For the reasons just given, he did not imagine a weaker alternative structure compatible with the laws of motion. At the same time, however, he evidently understood that his dynamical treatment of actual motions did not require any reference to positions in immobile space. He had no reason, therefore, to pursue the argument from *De Gravitatione* concerning the motion of Jupiter. What we would recognize as the appropriate argument— from the laws of motion to an appropriate space-time structure that incorporates the relativity principle— he was in no position to make. Instead he remained silent on this point. His analysis, in the *Principia* and its drafts, focused on determining the motions of a system of interacting bodies "among themselves," independent of the motion of the "whole space" within which the system is "enclosed."

It might seem doubtful whether, by this maneuver, Newton could really solve the problem of the appropriate reference for the laws of motion. In Newton's analysis, however, this problem was quite straightforward. For the analysis had to start with the apparent motions, and these were referred, according to time-honoured practice, to the observed positions of the fixed stars. Of course, there could be no a priori guarantee that the space in which the fixed stars are at rest is, itself, at rest in immobile space, or moving uniformly (cf. Corollary V), or even undergoing a uniform acceleration in a family of parallel directions (cf. Corollary VI). But there was no need for an a priori assumption on this question. On the

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[9] An illustrative case from the late 19th century is that of Maxwell, who upheld the relativity of motion and, unlike Newton, held that absolute rest "has no scientific meaning" (1878, p. 70). He maintained this view even in the context of his theory of electromagnetism, on the grounds that velocity with respect to the ether is still, after all, a relative velocity (ibid). He also emphasized the form of relativity of acceleration implied by Corollary VI (ibid, pp. 51-52; see also Earman 1989, pp 31-32). Yet Maxwell continued to maintain that absolute space is the necessary background structure for physics (ibid, pp. 29-30). An even more striking case is that of Poincaré: even after the introduction of the concept of inertial frame, Poincaré did not see that rotation could have a distinct status within a properly relativistic account of Newtonian mechanics. He continued to maintain that absolute space was philosophically embarrassing, yet necessary to the understanding of rotation (1902, p. 138, 1912, p. 43).

contrary, Newton treated it as an empirical question. If the fixed stars did not provide a sufficiently quiescent relative space— in the sense either of Corollary V or of Corollary VI—then the effects of its non-uniform motion would eventually reveal themselves to observation in the course of the analysis. Unbalanced forces would reveal themselves, more subtly, but just as surely, as centrifugal forces will do when the rotating earth is taken as a resting frame. Newton himself argued fairly explicitly along these lines. The orbits of the outer planets were, within the limits of observational accuracy, stable with respect to the fixed stars; that is, their apsides did not measurably precess as does that of Mercury. But a relative space in which these apsides are stable is a sufficient approximation to the spaces described in Corollaries V and VI (cf. Book III, Proposition XIV, 1687b, p. 420).

Newton introduced "absolute space" into his theoretical framework, and his theoretical vocabulary, at a remarkable moment in his philosophical development. He did so just at the time when, thanks to his emerging understanding of the relativity of motion, he understood how to treat the motions in a system of bodies dynamically, without regard to the motion of the system as a whole with respect to immobile space. The theory of absolute space undoubtedly reflected the same view of space, as an immobile background for moving bodies, that Newton had expressed in *De Gravitatione*. At the same time, however, the theory as articulated in the *Principia* clearly formed a part of his developing theory of relativity. After all, what he announced in the Scholium was not simply the notion of absolute space, but the *distinction* between absolute and relative space. "Absolute space" signified the immobile space in which every body has some complicated and inherently unknowable motion; relative spaces provided a sufficient framework for answering the empirical questions about the true structure of our planetary system.

IV. Realism, instrumentalism, and physical causation.

I would like to close by considering the connection between the issue of absolute space and the larger issue between realism and instrumentalism. There can be little doubt that Newton was a metaphysical realist in some sense, and indeed has been characterized as a realist of a particularly naive sort. Stein, in contrast, has argued that Newton's metaphysics was deeply connected with his empiricism, and that Newton had good reason to regard the work of the *Principia* as a “contribution of evidence” for his metaphysical picture. How should we understand this claim? Moreover, how does this account square with Stein’s “skeptical remarks” on realism and anti-realism (Stein 1989)? There he argued that the issue between realism and instrumentalism was badly drawn. When both positions are sufficiently qualified, no significant difference remains between them, and, moreover, a “dialectical tension” between the two is “characteristic of the deepest scientists” (1989, p. 64). If this argument is a persuasive one— as I think it is— the question arises, how to reconcile it with the notion that empirical inquiry could provide evidence for a metaphysical picture of the world such as Newton’s.

We can approach this question by way of a question that Stein posed regarding the view that theories are “mere instruments”: “First of all, instruments for what?” (1989, p. 49.) His answer, briefly, was that a physical theory is an instrument for “representing the phenomena” (ibid), and that this means something more than just prediction and control. A satisfying explication of this answer is best sought in Stein’s article; here it suffices to consider its bearing on Newton’s theoretical framework. One traditional difficulty of realism is the emphasis that it tends to place on belief in scientific theories, as veridical representations of the physical world (whether of its ontology or of its underlying “structure,” according to the variety of realism in question). What most disturbed Newton’s contemporary critics about his theory was its failure to represent gravity as a real mechanical interaction, which implied a failure to satisfy contemporary canons both of ontology and of scientific explanation. This objection is generally characterized as an objection to action at a distance, which is certainly suggested by Newton’s account of gravity as a mutual action between two bodies.

Newton famously resisted the implication that this mutual action is immediate, even admitting the possibility that it is mediated by an immaterial medium (Newton 1692, p. 7r). But he did assume, at crucial points in his reasoning, that this interaction depends explicitly only on the bodies’ masses and the distance between them. No intervening ponderable matter plays any physically significant role— unless, of course, it is massive enough to be a noticeable gravitational source in itself. As Huygens argued, Newton was not able to establish beyond doubt that gravity is in fact such a direct interaction:

> …I do not agree with a Principle that [Newton] assumes in this calculation and elsewhere; which is, that all the small parts that one can imagine in two or more different bodies attract or tend to approach one another. This I could not admit, because I believe I see clearly that the cause of such an attraction is in no way explicable by any principle of mechanics or rules of motion; as I am no more persuaded of the necessity of the mutual attraction of entire bodies, having shown that, even if there were no earth at all, bodies would not cease, by what one calls their weight, to tend towards a center. (1690, p. 471)

This passage illustrates what Stein referred to as Huygens' "imbalance" between realism and instrumentalism, on the realist side: Huygens rejected Newton's theory out of hand, because he could see no way to explain it according to his own metaphysical realism regarding the kind of interaction that is truly intelligible, that is, mechanical interaction by immediate contact.

> In order to find an intelligible cause of gravity, it must be seen how it can come about while presupposing in nature only bodies that are made from the same matter, and considering in these neither any quality nor any tendency to approach one another, but only their different magnitudes, figures, and motion. (Ibid., p. 451.)

Yet the first passage also makes an important point that goes beyond the dogmatic insistence on action by contact. Newton's argument depended on his supposition that gravity, even of a satellite toward the distant body that it orbits, must be subject to the third law of motion— more strikingly, that the interaction satisfying the third law is an interaction precisely between these two. Newton understood that this was a bold supposition, but he did not see it as a fatal objection. He was content, instead, to rest on the empirical scope and power that his theory gained by treating gravity as a mutual attraction.

> What that great man Huygens has remarked on my work is acute…But… since all the phenomena of the heavens and of the sea follow accurately, so far as I am aware, from gravity alone acting in accordance with the laws discovered by me, and nature is most simple; I have judged that all

> other causes are to be rejected and that the heavens are to be stripped as far as may be of all matter lest the motions of the planets and comets be impeded or rendered irregular. (Newton 1693, p. 287; see also Stein 1967, p. 180).

In the third edition of the *Principia*, well after this remark, Newton added the fourth "rule of reasoning in philosophy," which defended inductive arguments such as this one against "mere hypotheses." The inductive case for mutual gravitation as the sufficient cause for the phenomena in question, in Newton's view, could be properly defeated only by contrary evidence; they were not to be set aside for the sake of a mere hypothesis such as Huygens' concerning a merely possible mechanism. Huygens, in contrast, would resist Newton's induction even in the face of empirical evidence. But do Newton's remarks suggest, in spite of his general realism, a choice of instrumental success over real physical understanding?— an imbalance like that of Huygens, but on the opposite side?

Two aspects of Newton's remarks argue against such a reading. First, Newton's remark was not merely setting aside mechanical explanation because he had found an empirically successful theory without it. The remark also invoked detailed arguments from the *Principia* that placed severe limits on possible mechanisms. The extremely regular motions of planets and comets show that they move more or less freely in space, seemingly unimpeded, or nearly so, by any ambient fluid matter (cf. Book III, Proposition X; Newton 1687b, pp. 416-417); these are the motions that would be "impeded or rendered irregular" by interactions with a fluid medium. The chief target of such arguments was, doubtless, the vortex theory of Descartes; they were part of his broader effort to show that Cartesian vortices could not move the planets in accord with Kepler's laws, and to determine an upper bound on the density of any possible celestial fluid. But Huygens clearly saw the implications for his own theory: Newton had narrowly confined the space of possibilities for particle mechanisms by which the planets could be impelled toward the sun, and satellites toward their primary planets. Yet Huygens was undeterred. On the one hand, he remained confident that he could develop his mechanical theory within the bounds proposed by Newton (1690, p. 474). On the other hand, he saw the difficulties that the rarity of the celestial medium would impose on his mechanistic program as an argument against Newton's claim: "Such a rarity being supposed, it does not seem possible to explain either the action of gravity or that of light, at least by the means that I have used" (Ibid., p. 473).

The second noteworthy aspect of Newton's remark is that it by no means sets aside causal explanation. On the contrary, it demands the acknowledgement of gravity as a cause, and of the laws by which it acts as a cause; the proposed etherial mechanisms are merely possible "other causes." It is perhaps too easy to miss this point because of the sequel to the quotation:

> But if meanwhile someone explains gravity together with all its laws by the action of some subtle matter, and shows that the motions of the planets and comets will not be disturbed by this matter, I shall be far from objecting. (1693, p. 287.)

One might infer from this that Newton had simply abandoned inquiry into the cause of gravity, leaving it to others and wishing them a fine day for it. But to do so would be to overlook the stringent requirement that Newton was imposing on any causal explanation of gravity. It must not only overcome the difficulties regarding the resistance of the medium; it must also explain "gravity together with all its laws" —that is, "the laws discovered by [himself]." For these characterize the behavior of gravity as a causal power— as a kind of causal power, moreover, whose workings are unlike those of mechanical causes. The obstacles to mechanical explanation were not features of his theory, but lawful features of the physical world that his theory identified for the first time.

The difficulties went beyond the seeming emptiness of space and the incompatibility, as discussed in Book II of the *Principia*, of the properties of vortical motion with the actual Keplerian motions of the planets. The feature that most defied mechanical explanation was the one that, in hindsight as well as in Newton's view, is perhaps the most distinctive and remarkable feature of gravity: its action is proportional to the masses of the bodies acted upon:

> …it operates not according to the quantity of the *surfaces* of the particles upon which it acts (as mechanical causes use to do), but according to the quantity of the *solid matter* which they contain. (1713, p. 484)

This was, without doubt, among Newton's reasons for testing this feature with such care through his experiments on pairs of pendulums. Initially, he had identified gravity with the centripetal accelerations of the planets on the basis of the celebrated "moon test" of 1666, i.e. the comparison of terrestrial gravity to the moon's centripetal acceleration by way of the inverse-square law. (Cf. *Principia* Book III, Proposition IV; 1687b, p. 406-407.) But in constructing the *Principia*, he took care to establish that the centripetal accelerations of the planets do behave like gravitational accelerations in precisely this definitive respect, i.e. that they really are proportional to the respective masses. He examined, for instance, possible differences between the actions of the sun on Jupiter and on its moons, by calculating the effects that any such differences would produce in the orbits of the planets. Evidently astronomical measurements could not be as precise as Newton's pendulum experiments. Even so, Newton was able to place an upper bound on any differential accelerations (Book III, Proposition VI; 1687b, pp. 409-10). In this way Newton achieved a remarkable generalization of the principle first suggested by Galileo, in his experiments with small terrestrial bodies. The fact that this generalization was so little remarked by his contemporary critics, in particular Huygens, underscores their exclusive emphasis on features of gravity that seemed more amenable to mechanical explanation. The features emphasized by Newton, in contrast, are those that continue to distinguish gravity from the other forces of nature.

This last point is supported by a better known remark of Newton's on the subject of causality. In defining the measurement of centripetal forces, Newton made this celebrated proviso:

> I call attractions and impulses accelerative and motive in the same sense; and I use the words Attraction, Impulse, or Propensity of any sort towards a centre, promiscuously, and indifferently, one for another; considering those forces not physically, but Mathematically: wherefore the reader should take care not to take from those words that I anywhere define either the kind, or the manner of any action, the causes or the physical reason thereof, or that I attribute forces, in a true and physical sense, to certain centres (which are only Mathematical points); when at any time I speak of centres as attracting, or as endued with attractive powers. (Definition VIII, 1687b, pp. 4-5.)

Here, at least, Newton explicitly seemed to set aside physical intelligibility in the sense demanded by Huygens, and appeared, implicitly, to endorse an instrumentalist view of the mathematical methods that he employed in the *Principia*. Yet the "merely" mathematical representation of centripetal forces was precisely what enabled Newton to reveal further strange features of gravity as a causal power— and, moreover, to show that they were empirically well grounded, even if they seemed incomprehensible from the mechanistic view of causation. The most striking example is the composition of different centripetal accelerations, toward different centres, in one and the same body. Newton set down the procedure of composition in Proposition III of the *Principia*:

> Proposition III, Theorem III: Every body, that, by a radius drawn to the centre of another body, in any way moved, describes areas about that centre proportional to the times, is urged by a force compounded out of the centripetal force tending to that other body, and of all the accelerative force by which that other body is impelled.(1687b, p. 39).

Evidently, this presupposed that gravitational accelerations do, in fact, compose with one another as simply as the mathematical objects that the Proposition describes. From a mechanistic perspective, this must have seemed to be an extremely precarious assumption. Huygens, for one, thought that a body's gravity toward a centre must result from a complicated interaction with ethereal particles in complicated motions. On Huygens' view of the relativity principle, a uniform rectilinear motion shared by the bodies in a given system may be simply added to the motions produced by collisions among those bodies. But the addition of forces to other forces is not provided for in his theory of gravitation. Newton's assertion that we may simply compose accelerative forces, therefore, might have been taken to reflect indifference to the distinction between mathematics and physics.

Such a reading overlooks the physical significance of Newton's mathematical method. What happens when two centripetal forces act on one body, for instance a satellite of Jupiter, is not a mathematical question, but a physical one. Yet it did not appear to be a serious question for mechanical philosophers. On Huygens' theory, each gravitational centre is surrounded by its own system of ethereal particles moving in all directions, and the net effect of collisions between these and larger bodies is supposed to drive the latter toward the centre. These centripetal accelerations result, however, only on the assumption that the whole system is bounded within in an enclosed space from which its particles “cannot escape because of the other bodies that surround it” (1690, p. 131). Huygens derived the model, in the first place, from the centripetal accelerations of small balls of Spanish wax in a rotating, sealed cylinder filled with water (1690, p. 132). He supposed, for example, that that there is “a spherical space that surrounds the earth and all the bodies that surround it to a great distance,”and that the fluid matter in this space “cannot leave this space, which is surrounded by other bodies” (1690, p. 135.) Though Huygens did not give a detailed account of all of the planets, he must have presumed that each would have a contained medium like that of the earth. This model thus avoids the extremely complex problem of what will happen when the mechanism of one gravitating system interacts with that of a larger system. As Stein has noted, Huygens’ mechanism “could hardly be reconciled with Newton’s unrestricted linear superposition of gravitational fields” (1967, p. 179). Newton’s mathematical treatment, in sharp contrast, requires no such imaginative hypothesis to maintain the solar system in its regular order. Because gravitational accelerations can be composed mathematically, there is no essential difficulty in understanding the acceleration of any planet, or satellite, as composed of accelerations toward each of the other bodies in the entire system. Jupiter and its moons may be treated as a system satisfying the conditions of Corollary VI, because the accelerations of each body toward the Sun may simply be added to the accelerations within the system. Unlike in Huygens’ system, the shared acceleration of the whole may be added to its internal accelerations just as straightforwardly as an inertial motion of the whole. Because the accelerations toward the Sun are so nearly equal and parallel (for practical purposes), the former shared motion is approximately indistinguishable from the latter.

A mechanist of the 17th century might doubt whether Newton’s method had really answered the question, “what happens?” What is the guarantee that his method of composition must actually work? or, in other words, that the linear superposition of gravitational fields must hold? The answer, simply, is that Newton’s method provided, not a guarantee, but an argument from evidence. It provided an empirical method of determining precisely how far these principles do hold— for example, how accurately we may distinguish the forces holding Jupiter’s moons in orbit from the force holding the system in orbit around the Sun. As we've already seen, Newton showed that it was an empirical claim, established to reasonably high approximation, that gravity toward the sun acts equally and in parallel directions on Jupiter and its moons— sufficiently equally and in sufficiently parallel directions, that is, to permit a dynamical analysis of interactions within the system as if it were quite beyond the influence of the Sun. Of course, this empirical fact alone would not strictly rule out Huygens' account of Jupiter's isolation (setting aside its fanciful character). It might be argued that the evidence that Newton appealed to, in Book III, Proposition IV, would equally support the view that Jupiter's gravitational system is physically isolated from that of the Sun, rather than superposed upon it. But Newton's method provided a kind of consistency check on itself: he had another gravitating system to compare it with, so much nearer to the Sun that the accelerations toward the Sun were far from equal and parallel—far enough, at least, to make the system's motions almost intractable. The system of the Earth and its moon, evidently, provides what we might call a "near-field" test of the Sun's gravity, because the differences between their distances and directions to the Sun are large compared with the size of the system's orbit. Newton spelled out the mathematical method for making this comparison, too: when a system of lesser bodies is, as a whole, revolving around a greater body, we have a quantitative measure of how closely the motions of the lesser system approximate the conditions of Corollary VI:

> Book I, Proposition LXV, Case 2: Suppose that the accelerative attractions towards the greater body to be among themselves reciprocally as the squares of the distances; and then, by increasing the distance of the great body till the differences of the straight lines drawn from that to the others in respect of their length, and the inclinations of those lines to each other, are less than any given, then the motions of the parts of the system, will continue with no errors except such as are less than any given. And because, by the small distance of those parts from each other, the whole system is attracted as if it were only one body, it will therefore be moved by this attraction as if it were one body….(1687b, p. 172.)

Evidently the Proposition deals mathematically with an abstract case. But it enabled Newton to address the physical fact of the variation in the Sun's gravity, and its consequences for the superposition upon it of lesser gravitating systems. Thus Newton's mathematical representation of accelerative forces, and their composition, provided an insight into the physical workings of gravity that was hidden from his mechanistic contemporaries.

V. Conclusion.

On the matter of "representing the phenomena," Stein suggested that the conceptual difficulties of quantum mechanics "arise from the fact that the mode in which this theory 'represents' phenomena is a radically novel one." (1989, p. 59) We may safely say that Newton introduced a radically novel way of representing the phenomena of accelerated motion; it certainly gave rise to conceptual difficulties, at least for the mechanistic thinking of his time, even if the difficulties were finally not as formidable as those of quantum mechanics. And we may say that, like that of quantum mechanics, the form of representation peculiar to Newton's theory brought to light certain features of the physical world that could not be comprehended within the prevailing conceptual framework. In particular, the mathematical form of Newton's theory could not be reconciled with prevailing conceptions of causality. But it identified previously unknown features of the operation of gravity as a cause: not only that it is the common cause of certain classes of terrestrial and celestial phenomena, but that its behaviour is unlike that of any other causal power contemplated by early modern science.

By the same stroke, Newton's form of representation led to a more profound understanding of the relativity of motion. The composition of inertial and accelerated motions, as we have seen, was already understood by Galileo and Huygens as the basis for the relativity principle, and Newton was in one sense only following their work, particularly that of Huygens. In another sense, however, he explored the implications of this principle for the broader conceptual framework of mechanics, especially for the concept of inertia and the concept of "the frame of the system of the world". This was crucial to understanding the causes at work within the solar system, and the independence of their workings on the state of motion of the system in space. In Corollary VI, Newton's method led to something analogous to an extended relativity principle, in an approximative sense: he was able to identify a family of practically equivalent states of motion, through his novel representation of accelerative forces and their composition.

He thereby made it possible to reach robust conclusions about the causes working within a system of bodies, without knowing what larger, yet-unknown systems it might be interacting with. And, above all, he was able to exhibit a wide range of phenomena that could be treated successfully by this method, to a high level of approximation.

This, then, is the metaphysical picture for which Newton had found strong empirical evidence: that bodies exist and interact in space and time; that in addition to the natural inertial tendency of all massive particles, there must be natural "powers" or forces of interaction that account for the formation of structures such as cohesive bodies, or planetary systems; that gravity is one such interaction, operating in accord with the laws outlined in the *Principia*, which suffice to account for celestial motion, terrestrial gravity, and the tides; finally, that Newton's mathematical representation of gravity, as an accelerative force, captures what is physically distinctive and metaphysically challenging about its manner of acting. That his theory of absolute space and time was not the correct spatio-temporal framework for his physical principles is, in the context of this larger metaphysical picture, a comparatively minor point. The same may be said for the fact that, from our perspective, the physical principles themselves are not true. For Newton's realism— to return to a theme from the previous section— did not depend on any conviction that his theoretical principles were literally correct. The theory was, for him, an instrument for the discovery of systematic and profound physical features of the world.

This may sound like an extremely bizarre interpretation of a scientist whose metaphysical realism seems beyond question. One might try to defend it simply by appealing to a modest, fallibilistic remark from the Preface to the *Principia*: "I hope that the principles here laid down will afford some light either to that, or to some truer, method of Philosophy" (1687b, p. ii). I would defend it, instead, by considering what Newton claimed to know about gravity, on the basis of the arguments of the *Principia.* In his final analysis, he spoke with great precision about what he had actually established about the operation of gravity as the dominant cause of the planetary motions. Immediately after his familiar remark that he had not found the cause of gravity, he wrote:

> This much is certain: that it must proceed from a cause that penetrates to the centres of the sun and planets, without undergoing the least diminution of its force; that it operates not according to

> the quantity of the surfaces of the particles upon which it acts (as mechanical causes tend to do), but according to the quantity of the solid matter which they contain; that it propagates its power on all sides to immense distances, decreasing always in the duplicate proportion of the distances. (Newton, 1713, p. 483-484).

It is worth emphasizing the extreme caution of Newton's statement. That gravity is propagated to "immense distances," varying inversely as the square of the distance, is a strikingly weaker claim than that the inverse-square law holds *simpliciter*. Indeed, Newton carefully specified the qualified and conditional sense in which he considered the action of gravity to be known:

> in receding from the sun [it] decreases accurately in the duplicate proportion of the distances as far as the orb of Saturn, as evidently appears from the quiescence of the aphelions of the planets; and even to the most remote aphelions of the comets; *if* those aphelions are also quiescent (1713, p. 484). [emphasis added.]

He was not willing to claim, evidently, that the inverse-square law was established beyond the reach of contemporary observation or the limits of observational accuracy; he considered its application beyond the solar system to be conditional on further information about the orbits of comets. This suggests, I think, the qualified and conditional sense in which we should interpret a more celebrated statement that closely follows:

> it is enough that gravity does really exist, and acts according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea.(Ibid.)

In other words, in drawing inferences from his mathematical method, he made a very careful distinction between establishing certain systematic features of nature, and establishing the truth of a mathematical law of nature.The former is inherently limited, approximate, and contingent. But the latter necessarily exceeds the scope and precision of our evidence.

Every instrumentalist knows that a scientific theory may be empirically successful, and useful for prediction and control, without being true, and even without the question of its truth being well posed. Newton's instrumentalism consisted in knowing that a good theory could be, without being true, an instrument for inquiry and understanding, and that the resulting insight into the true nature of things might long outlive the theory itself. It should go without saying that this was the fate of Newton's theory of space, time, and gravity.

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