The Mechanical Philosophy and Newton's Mechanical Force

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How does Newton approach the challenge of mechanizing gravity and, more broadly, natural philosophy? By adopting the simple machine tradition's mathematical approach to a system's covarying parameters of change, he retains natural philosophy's traditional goal while specifying it in a novel way as the search for impressed forces. He accordingly understands the physical world as a divinely created machine possessing intrinsically mathematical features and mathematical methods as capable of identifying its real features. The gravitational force's physical cause remains an outstanding problem, however, as evidenced by Newton's onetime reference to active principles as the "genuine principles of the mechanical philosophy."

1. Introduction. In one of his manuscripts, Newton conceives of the mechanical philosophy in a remarkable way, applying the term to his own theory. "We ought to inquire diligently into the general Rules or Laws ob-

Received December 2012; revised March 2013.

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†This article was written primarily during my stay as a visiting scholar at the University of Athens, and for that I would like to express my gratitude to Stathis Psillos, along with Dionysios Anapolitanos, Costas Dimitracopoulos, and the rest of the faculty of MIΘE. I am indebted to Peter Machamer and Ted McGuire for our discussions at Pittsburgh; much of this article elaborates my contribution to our coauthored paper, and the discussions benefited me for both works. I am also grateful to Mary Domski for comments on the coauthored paper and to Alan Gabbey for comments on both. An initial version of this article was presented at the University of Pisa, and for that opportunity I thank Pierluigi Barrotta as well as New Europe College and the European Community's Seventh Framework Programme within the European Institutes for Advanced Study Programme, for their support and financial contribution, respectively, during that presentation's preparation. I also extend my appreciation to the audience at the University of Athens, for discussion of a later version. Finally, for their close reading and comments, I thank the anonymous referees for this journal; shortcomings are my own, as always.

Philosophy of Science, 80 (October 2013) pp. 557–578. 0031-8248/2013/8004-0003$10.00

served by nature in the preservation or production of motion by these principles," he enjoins, in a draft variant of what would eventually become Query 31 of the *Opticks*, "as the Laws of motion on which the frame of Nature depends & the genuine Principles of the Mechanical Philosophy."[1] What are these genuine principles of the mechanical philosophy? They are nothing associated with the mechanical philosophy as usually conceived; they are neither the shapes and sizes of corpuscles that Boyle promoted nor the stolid, motion-transferring collisions that constituted mechanism for Descartes. Their identity is indicated by an earlier part of Newton's sentence, a part familiar from the query's published versions: "For we meet with very little motion in the world besides what is owing to these active principles" (*Opticks*, Query 31; Newton 1730/1952, 399). Active principles were something that the mechanical philosophy, as usually construed, had congratulated itself for eliminating. Yet when writing this manuscript passage, Newton went so far as to name active principles (together, presumably, with the *vis inertiae*, the passive principle grounding his three laws) the mechanical philosophy's genuine principles. Now it must certainly be acknowledged that this intriguing description belongs not only to a draft—indeed a draft of a speculative query—but to a passage that Newton crossed out after writing it. Nevertheless, the fact that he penned such words at all indicates just how far his ideas about what might qualify as mechanical and as a mechanical philosophy could diverge from the dominant conception.

The dominant conception of the mechanical philosophy—dominant both among early modern practitioners and, consequently, among historiographers today—is what might be called the contact action conception. It is one restricting the causal principle by which local motions are produced or altered to material contact action—to impulse communicated between bodies at their surfaces. Newton was of course conversant with the contact action sense of mechanism and the mechanical philosophy, and his uses of terms such as 'mechanical' sometimes denote it. In his 1713 General Scholium, for instance, he writes that whereas gravity acts in proportion to the quantity of solid matter, "mechanical causes" are wont to act in proportion to surface area (*Principia*, 943).[2] Similarly, in the *Opticks* he refers to the Cartesians and their physics of "dense matter," when accusing certain philosophers of feigning hypotheses so as to explain all things "mechanically" (*Opticks*, Query 28; Newton 1730/1952, 368–69). If he had limited his ideas about the

1. University Library, Cambridge (ULC), Add. 3970, fols. 255r–256r. The text, written in English, is quoted in McGuire (1968, 170–71), with his discussion found in those same pages. McGuire dates the text, which he identifies as a draft variant of what appeared as Query 23 in the 1706 *Optice* and as Query 31 in the 1717–18 *Opticks*, to ca. 1705.

2. Here and throughout, all *Principia* quotations and pages cited are from Newton (1726/1999).

mechanical to that dominant sense, it is difficult to see how he could have considered the core of his own natural philosophy to be mechanical. After all, his *Principia*'s theory not only was compatible with causal interaction between bodies separated by a void, it even seemed to imply it, making his gravitational force the thickest oil to the dominant mechanical philosophy's water.[3]

Newton did not so limit his ideas, however. Indeed, since the core of his natural philosophy is his rational mechanics, it hardly needs saying that he considered it mechanical in some sense. But in what sense, precisely? Among commentators calling Newton's theory a mechanical philosophy, the answer depends largely on such issues as the status assigned to forces. Richard Westfall, for instance, places Newton in the tradition of the mechanical philosophy in virtue of his corpuscularianism, while emphasizing that he transformed it by treating celestial motions as problems of mechanics and producing a dynamic theory that was quantitatively precise (see Westfall 1971, 398; 2001).[4] Yet Westfall reads Newton as ultimately attributing gravitational effects to God—a conclusion that I have opposed elsewhere—and thus as jettisoning natural philosophy's traditional goal.[5]

I will argue that Newton in fact retains natural philosophy's traditional goal, employing what he adopts from the simple machine tradition toward discovering real causes of natural phenomena. From the simple machine tradition, he adopts a mathematical approach to systems of interacting bodies, identifying and expressing mathematically a system's covarying parame-

3. The speculations of the *Opticks* queries offer little hope of reconciling his theory with material contact action, given the repulsive forces among the spatially separated particles.

4. An anonymous referee for this journal suggests that Howard Stein similarly places Newton under the rubric of the mechanical philosophy, writing, "Stein (2002) argues that Newton transformed the meaning of the 'mechanical philosophy'. . . . On Stein's picture Mechanical philosophy now means principles governing forces of attraction and repulsion. . . . This argument is actually put forward [by] Howard Stein on pp. 282–83. . . . So, the concept has changed while [the] word has remained the same." Although there is presumably some sense of 'mechanical philosophy' that Stein would apply to Newton (since Newton undeniably transformed natural philosophy through mechanics), the referee's supposition that Stein intends such a sense in his 2002 article is incorrect. Stein in fact discusses the mechanical philosophy only in a sense that Newton abandons, as his earlier remarks indicate: "It is *from* the mechanical philosophy that the metaphysics, as well as the natural philosophy, of Newton *departed*" (Stein 2002, 261). Concerning the term 'dynamic', it is convenient although anachronistic; it was not used by Newton but introduced instead by Leibniz. On Leibniz's introduction of the term, see Pierre Costabel (1970).

5. See, respectively, Westfall (1971, 398) and Kochiras (2009, sec. 3). Arguments by A. Rupert Hall and Marie Boas Hall (1995, 76–83) are of interest in connection with Westfall's view; whereas he takes Newton's post-*Principia* aethereal speculations as a euphemism for God, the Halls disagree.

ters of change. Rather than supposing mathematical methods to be something extrinsic to physical systems and thus to natural philosophy, he recognizes the world as a machine operating by impressed forces—causal principles that arise within systems of bodies and that are expressible mathematically because they intrinsically possess geometric proportions. In making the search for those impressed forces the main business of his natural philosophy, he retains natural philosophy's traditional goal while specifying it in a novel way.

I develop this interpretation by focusing on a challenge concerning the gravitational force that was posed by Henry More. Narrowly, More's challenge asks how gravity, which operates a canonical simple machine, the balance, could itself be mechanical. Broadly, the challenge asks how natural philosophy could be mechanized. The next section of this article therefore reviews the division of labor that traditionally held between natural philosophy and mechanics. The subsequent sections consider the extent to which Boyle and then Descartes met More's challenge and the sense in which Newton understood his own theory to be mechanical. How does this interpretation, in which Newton sees mathematical methods as facilitating the discovery of the causally efficacious force, square with his ongoing search for gravity's cause? That question relates, clearly enough, to his earlier-quoted conjecture that a mechanical philosophy may be grounded in active principles, principles that Query 31's published version speculatively cites as being "the cause of gravity."[6] Although a full response lies outside the scope of this article, the conclusion remarks on the outstanding problem about gravity, tying it to the question of whether Newton meets More's challenge.

2. Conceptions of the Mechanical and the Mechanical Philosophy.

2.1. The Dominant Conception of the Mechanical Philosophy. The notion of the mechanical philosophy has been strongly associated with two practitioners, Descartes and Boyle.[7] It was Boyle who popularized Henry More's term, the *mechanical philosophy*, as a name for a new kind of philosophy of nature, along with the slogan designating its causal principles, "matter and motion."[8] That philosophy, which Boyle also called the cor-

6. *Opticks*, Query 31 (Newton 1730/1952, 399): "Seeing therefore the variety of Motion which we find in the World is always decreasing, there is a necessity of conserving and recruiting it by active Principles, such as are the cause of Gravity."

7. Marie Boas (1952) traced the concept of the mechanical philosophy back to ancient sources but investigated the seventeenth century by focusing primarily on Boyle. Other influential midcentury accounts of the mechanical philosophy include Dijksterhuis (1950/1986) and Westfall (1977).

8. On the introduction and popularization of the term 'mechanical philosophy', see Sylvia Berryman (2009, 244 n. 40), who notes several clarifications of the history communicated by Peter Anstey and by Alan Gabbey.

puscular philosophy, aimed to explain natural phenomena in terms of the qualities seen in machines, which to his nonmathematically oriented eye were the size, shape, local motion, and juxtaposition of parts. These qualities could rightly be called the "Mechanical Affections of Matter," he wrote, "because to Them men willingly Referre the various Operations of Mechanical Engines" (Boyle 1666, preface). It was Descartes, meanwhile, a theorist featured prominently on Boyle's list of mechanical philosophers, who attempted the most complete mechanical philosophy.[9] In Descartes's plenist universe, the natural executor of actions was what is sometimes called the Cartesian sense of 'mechanism', impact between the surfaces of adjacent bodies or their parts.[10]

That Cartesian sense of mechanism figured centrally in the version of the mechanical philosophy most prevalent among early modern thinkers, as noted earlier. While in connection with certain phenomena, the slogan "matter and motion" might refer to the sizes, shapes, and juxtapositions of the particles of a uniform matter, wherever local motion was concerned, the causal principle it denoted was the familiar phenomenon of bodies pushing one another. Such familiarity conferred an appearance of intelligibility on the principle. And although that intelligibility seemed to dissolve under close scrutiny, as Locke discovered,[11] adherents of a mechanical philosophy insisting on the restriction to contact action ranged from thinkers whose physics remained mainly qualitative, notably Descartes, to those working quantitatively, notably Huygens.[12] The dominance of this sort of mechanical philosophy among practitioners has been reflected in some historiographers' conceptions. For instance, McGuire wrote that despite considerable disagreement about a mechanical explanation's sufficient conditions, mechanical philosophers did

9. Boyle's list also includes the atomist Gassendi, among others. See the Proemial Discourse to the Reader of the 1667 edition of "The Origine of Formes and Qualities" (Boyle 1991b, 10). For a discussion of the list, see Garber (2013, sec. 3).

10. Gabbey cautions that one must tread carefully when interpreting Descartes's uses of such terms as 'mechanical'. In particular, Gabbey holds, when Descartes writes of "mechanica philosophia mea" in his letter to Plempus for Froidmont (October 3, 1637), he means to defend his philosophy's "ontological commitments and explanatory methods" but does not mean to introduce a new name for it (Gabbey 2004, 18–19). I thank Gabbey for personal correspondence (December 24, 2011) reminding me of his point there. Concerning Descartes's remarks in that letter, see also sec. 4, below.

11. As Locke remarks in his *Essay* (II.xxiii.28; 1975), although experience makes the communication of motion by impulse familiar to us, the causes and manner of production are obscure. More tries to dispel the mystery with a metaphor, suggesting that one body rouses the other, as if from sleep (More to Descartes, July 23, 1649, in Descartes 1990, 5:383; trans. in Gabbey 1990, 27–28), while Leibniz explains the communication of motion in terms of the active *vis viva*, introduced in his *Acta eruditorum*.

12. This is not to deny Descartes's mathematical approach to particular problems, notably his law of refraction.

agree on one necessary condition: “contact action is the only mode of change” (1972, 523 n. 2).[13] Similarly, Andrew Janiak recently wrote that a prohibition against unmediated distant action was “a crucial norm of the mechanical philosophy (in all its guises)” (2008, 53).[14]

2.2. A Broader View of Mechanical Philosophies. Nevertheless, the contact action conception of the mechanical philosophy was not a united front among practitioners, as historiographers increasingly acknowledge. Boyle, for instance, may not have consistently adhered to the view. In some texts, he does explicitly expect the motions that produce effects to be communicated only by surface contact; although attraction appears to be a motion very different from pulsion (impulse), Boyle writes, he has “not, yet, observ’d any thing which shews attraction cannot be reduc’d to pulsion” (1725, 2:711). Still, there are reasons for interpretive caution. One reason concerns Boyle’s tactical efforts to unite diverse thinkers. His list of mechanical philosophers included not only Cartesians but also Gassendi and other atomists, and he hoped that by emphasizing the similarities in their views, he might promote harmony.[15] The question of whether there is a true void is highly pertinent to the requirement of material surface contact, and another reason for interpretive caution is that Boyle did not insist on a material plenum. For a significant time, he withheld judgment on the question and at one point excluded it, along with questions about the origin of motion and the infinite divisibility of matter, as being outside the bounds of natural philosophy; these questions were, he wrote, “rather Metaphysical than Physiological Notions” (Boyle in Garber 2013, sec. 2).

Scholars of the period, meanwhile, have identified multiple meanings of ‘mechanical’ and multiple variants of the mechanical philosophy. Indeed, although McGuire’s article cast contact action as the necessary condition uniting mechanical philosophies, his list of such philosophies was diverse and extensive. Among the meanings that the term ‘mechanical’ had for various early modern thinkers, he included the rejection of occult qualities; the view that the investigation of nature must include experimental methods as well as first principles, that nature must be conceived of dynamically, and that it is governed by immutable laws; and a number of others (McGuire 1972, 523 n. 2). More recently, Alan Gabbey listed the following mechanical philosophy

13. For McGuire’s recent, different view, see Machamer, McGuire, and Kochiras (2012).

14. Janiak notes that he does not attempt to identify all variants of the mechanical philosophy, but he appears to take all variants to be united by a prohibition against distant action and insistence on action by surface contact action, as the quoted remark indicates. For his discussion of Newton’s understanding of mechanical causes, see Janiak (2008, 75–76).

15. For a recent discussion, see Garber (2013, sec. 2).

candidates, without citing contact action (or anything else) as a shared necessary condition: theories explaining phenomena nonqualitatively, in terms of the motions and configurations of the parts of a uniform matter; those treating the universe and its component systems as machines; those aiming to mathematize representations of phenomena; those postulating necessary laws of nature and motion; and those theories excluding everything spiritual or immaterial from the investigative domain (Gabbey 2002, 337–38; 2004, 15).

Whether these multiple conceptions of the mechanical and of mechanical philosophies might be unified by something other than contact action, such as a debt to the simple machine tradition, is a question that I will not pursue here. What matters for my purposes is that Newton, along with Boyle, Descartes, and others, explicitly invoked mechanics and machines when articulating their natural philosophies. Doing so meant looking over the divide that had traditionally existed between mechanics and natural philosophy.

3. The Promise of Simple Machines and the Challenge of Gravity.

3.1. The Traditional Division of Labor between Mechanics and Natural Philosophy. From ancient times, the simple machine tradition's core comprised five "mechanical powers" or machines—the lever, the wheel and axle, the pulley, the wedge, and the screw—together with the balance, often seen as fundamental.[16] This discipline of mechanics underwent a good many changes during the sixteenth and seventeenth centuries, as historians sometimes remark when attempting to demarcate their subject, not least its increasing attention to problems about motion and force.[17]

Although these changes would eventually lead to a union with natural philosophy—a union in which mechanics would both shape natural philosophy and be subsumed within it—the two disciplines had traditionally been considered quite distinct.[18] Natural philosophy (physics) had traditionally pursued knowledge of the causes of natural phenomena, thus of real features of the world. Mechanics, by contrast, was considered to be a

16. It may be noted that today's question of what constitutes a machine—i.e., whether it should be defined functionally or materially—was of little concern in earlier times. As Mark Schiefsky comments (2008, 18–19) in connection with Hero (Heron) of Alexandria, "The identification of these devices [i.e., wheel and axle, lever, pulley, wedge, and screw] as belonging to a special class . . . was quite independent of any theoretical understanding of their operation." Although the discipline of mechanics had undergone changes by the early modern period, these same simple machines still constituted its core, and to those hoping mechanics might help explicate natural phenomena, it was these machines themselves rather than the question of how to define a machine that seemed promising.

17. A valuable discussion may be found in Bertoloni Meli (2006).

18. On that traditional division of labor, see Laird (1986, 44), Gabbey (1993, 317–19), and Des Chene (2005, 246).

mixed science, also known as mixed mathematics.[19] Such disciplines, which also included optics, harmonics, and astronomy, were considered branches of mathematics in virtue of their methods but mixed in virtue of applying those methods to sensible objects. With the exception of astronomy, a mixed mathematical discipline did not concern itself with questions about the causes of phenomena.[20] Thus, a mechanics conceived as mixed mathematics did not include questions about the nature or origin of the forces driving the simple machines it investigated.

To be sure, forces could be investigated within the domain of mechanics, for the tradition of simple machines was not limited to statics.[21] Still, within traditional mechanics, questions about forces were confined to those concerning the forces' distribution and the effects thereof.[22] The lever and balance serve as notable examples. Through the distribution of effort and load, a lever permits one to move a large weight by applying a small force, and mechanics' law of the lever articulated the proportions: bodies on a balance will be in equilibrium if the ratio of their weights is inversely proportional to the ratio of their distances from the fulcrum. Texts such as Pseudo-Aristotle's *Mechanica* had invoked the lever in explaining a range of phenomena, yet such texts typically employed the heaviness of bodies, on which the balance's operation depends, without trying to explain it. To investigate a force's nature or origin would mean stepping outside mechanics and into the domain of natural philosophy.[23]

3.2. The Promise of Simple Machines. To those unconvinced by Aristotelian explanations of natural phenomena, the simple machine tradition suggested an alternative. It was not the only alternative, to be sure, and for those grappling with biological processes, vitalist traditions could be more

19. In the sixteenth century, these terms came to replace Aquinas's term, 'middle science'. For more details about disciplines and their classifications, a useful article is Laird (2000, esp. 681).

20. While there have been lively debates about the status that various thinkers (not least Copernicus himself) assigned to the Copernican theory, questions about realism typically attended astronomy alone. Nicholas Jardine (1988, 709–10) comments, "There is, at least for the sixteenth century, little evidence of views on the status of hypotheses in other mathematical sciences—optics, music, mechanics, and the like—comparable to those which were prevalent in astronomy." Discussions of the epistemological status of the mixed sciences, and of astronomy in particular, may be found in Gardner (1983), Jardine (1988), Barker and Goldstein (1998), and Biagioli (2006, 156–61). I thank Alan Nelson for discussion of this point.

21. On this point, see Laird (1986, 44); see also Machamer and Woody (1994).

22. Des Chene (2005, esp. 254) is illuminating on this point.

23. See again Des Chene (2005); see also Garber (2002, esp. 189) and Berryman (2009, 244–45).

persuasive. To an increasing number of thinkers, however, simple machines presented intriguing models for the functioning of natural processes.[24] If we consider the operation of a pulley, for instance, its functioning depends on such features as the shape of the wheels and the contact of the rope against the wheels. There is no need to suppose more than one fundamental kind of matter, and so long as we disregard the input force provided by a thinking agent, there is no need to think in terms of any kinds of causes other than efficient ones. Similarly with the lever and balance, it is the distribution of the effort and the resistance, relative to the fulcrum, that underwrites the possibility of easily moving a heavy body with a lever or of bringing light and heavy bodies placed on a beam, thus a balance, into a state of equilibrium. Observing the functioning of such machines does not lead one to think in terms of distinct bodies and their individual natures but, rather, in terms of a system and the covarying parameters of its related parts.

The mathematical expressibility of covarying parameters was inspirational to a mathematical approach to motions in nature. And since some simple machines could be understood as variants of the lever, which might in turn be reducible to the balance, the tradition of simple machines held out the promise of generality and parsimony.[25] For Galileo, for instance, simple machines served as important models for explicating natural phenomena. He invoked the balance when explaining problems of free fall, and in Day IV of his *Dialogue Concerning the Two Chief World Systems*, he used the motion of a pendulum, which he elsewhere reduces to a balance, in explaining the tides. In general, Peter Machamer (1998) has argued, the balance was a key model of intelligibility for Galileo since it provided a means of visualizing the phenomenon to be explained in terms of observable parts and their proportions and interrelations.

3.3. The Limitation of the Simple Machine Model and the Challenge of Gravity. Yet despite these explanatorily promising features, simple machines also seemed limited as a means of understanding natural phenomena. The difficulty is perhaps most evident with the balance. On the one hand, it provided a highly perspicuous means of modeling physical problems. Yet on the other hand, it operated by a power or force that was not understood and did nothing to render it intelligible; indeed, Galileo considered gravity to be mysterious. The illumination that the balance offered for understanding physical problems modeled on it therefore reached a natural end as soon

24. Compare Gabbey's discussion of mechanical explanations as structural explanations (1985, 10).

25. On efforts to reduce the various simple machines to the balance, especially the efforts of Hero (Heron) of Alexandria and, much later, of Guido Ubaldo, see Palmieri (2008) and Schiefsky (2008).

as one asked about its operative force. The troubling question was this: How far could machines illuminate the functioning of natural phenomena if the forces by which they operated remained unexplained?

This problem was raised by More. To be sure, the primary threat that More feared from the "pure mechanical philosophy," as he called it, was something else entirely. A theory attributing all natural phenomena to nothing more than "the mere rumblement of matter with ye motion" left no necessary role for God.[26] Atheism would be thwarted, however, wherever matter's mere rumblement failed to explain natural phenomena, and to More's mind, such phenomena as the resonant vibrations of strings, magnetism, color, biological structures, the origin of motion, and gravity were therefore sufficient evidence of a divinely directed Spirit of Nature.[27]

More's theological agenda aside, however, he did challenge Boyle directly with the aforementioned problem. Against Boyle's analysis of experiments with the air pump, he objected, "if this solution were truly mechanical, he must have assign'd the true mechanical cause of the gravity of all the parts, and of the whole atmosphere."[28] With these words, More may be seen as issuing a challenge. If a natural philosophy is to be truly mechanical, operating by the principles of simple machines, then gravitational effects too must be explained in those same terms. Considered more broadly, More's challenge asks not merely about gravity but about how natural philosophy could be mechanized.

4. Two Responses to the Challenge: Boyle and Descartes.

4.1. Boyle's Response to the Challenge. The problem is a serious one, and Boyle does not come to grips with it in his response. In *An Hydrostatical Discourse, By way of Answer to the Objections of Dr. More*, he opens his reply by pointing to exemplar mechanicians. Archimedes's propositions are recognized as mechanical, Boyle writes, even though he took gravity for granted. "I am not obliged to treat of the cause of gravity in general, since

26. Henry More to Henry Hyrne, August 21, 1671, ULC MS Gg.6.11; in Gabbey (1990, 26–27).

27. The problem of resonance is one of the many objections More raises in his correspondence with Descartes (letter of March 5, 1649, in Descartes 1990, 5:314–15; trans. Gabbey 1990, 22; see also More 1668, 1671). These phenomena were regularly cataloged by critics as insurmountable explanatory hurdles, not least by Locke in his *Essay* (1975). For a discussion of a shift in More's views, see Gabbey (1990); he denies the shift that most commentators see, from initial acceptance to later repudiation of Cartesian ideas. The question of why More took the mechanical philosophy's current failure to provide an explanation as evidence that it would never be able to do so has been explored by Gabbey (esp. 32).

28. More's remarks are quoted by Boyle (1725, 2:347–48).

many propositions of *Archimedes, Stevinus*, and others, who have written of statics, are confess'd to be mathematically, or mechanically, demonstrated; tho' those authors do not assign the true cause of gravity, but take it for granted, as a thing universally acknowledg'd" (Boyle 1725, 2:347–48). Boyle then turns to an exemplar simple machine, the balance, and to the traditional practice within mechanics of accepting gravity as a given.

> If in each scale, of an ordinary balance, a pound weight, for instance, be put; he who shall say, that the scales hang in equilibrium, because the equal weights balance one another; and; in case an ounce be added to one of the scales, and not to the opposite, he who shall say, that the former is depress'd, because urg'd by a greater weight than the other, will be thought to have given a mechanical explanation of the equilibrium of the scales, and their losing it; tho' he cannot give a true cause why either of those scales tends towards the center of the earth. Since, then, to assign the true cause of gravity, is not required, even in statics, tho' one of the principal, and most known parts of mechanics; why may not other propositions, and accounts, that suppose gravity in the air, and prove it too, be look'd on as mechanical? (Boyle 1725, 2:348)

In other writings, Boyle asserts that mechanical principles are "so universal and therefore applicable to so many things" that any other hypothesis grounded in nature will be compatible with mechanical principles or deducible from them (Boyle 1991a, 145). Yet in this passage, Boyle denies that giving a mechanical natural philosophy requires mechanizing gravity too.[29] Instead of acknowledging that mechanical principles could be universal only if they accounted for gravity too, and instead of attempting a mechanical explanation of the force, he settles for it as "a thing . . . acknowledg'd," insisting at some length that he is justified in taking it for granted because that is what the discipline of mechanics has always done.[30] Thus, he is not revoking the optimism he expressed elsewhere about the universality of mechanical principles or giving reason to think that gravitational effects are unlikely to be mechanically explicable. Nor is he invoking the experimentalist's right to demarcate limited research questions, while leaving other

29. Further questions might be raised here, of course. As noted, Boyle sometimes refrains from engaging in certain debates, e.g., about atomism and about the void, and some controversy attends the question of why he does so. Concerning atomism, e.g., Garber (2013, sec. 2) has recently emphasized Boyle's tactical motivations—his "irenic program" of neutralizing disagreements among those he considers mechanical philosophers—whereas James Hill (2004) attributes Boyle's reluctance to embrace atomism to his recognition of a foundational problem about cohesion.

30. This point was noticed by Berryman (2009, 245), and it was her important book that alerted me to the exchange between More and Boyle.

questions for later. Rather, he is simply denying the need to determine whether gravitational effects are mechanically explicable and justifying that denial by pointing to disciplinary conventions. Boyle thus leaves the traditional division of labor intact; in his view, giving a mechanical philosophy of nature does not require that mechanics and natural philosophy be integrated. It is this view of mechanics and of its proper relation to natural philosophy that Newton will repudiate.

4.2. Descartes's Response to the Challenge. Although Boyle himself does not come to grips with More's challenge, one theorist at the top of his list of mechanical philosophers might usefully be seen as having done so, namely, Descartes. (That deceased philosopher did not actually reply, of course; I mean only that his physics, and subsequently Newton's, may be usefully so construed.) In Descartes's physics, phenomena are explicated in terms of matter and motion, more specifically, the shapes and sizes of matter's parts and the motions produced by material surface contact.[31]

Like Boyle, Descartes explicitly connects his natural philosophy to the discipline of mechanics, as seen in his reaction to Libert Froidmont (Fromondus). When that professor from Louvain criticizes his *Meteorology*'s account of earth, water, and air as being "excessively gross and mechanical,"[32] Descartes comments, "If my philosophy seems to him excessively gross because it considers shapes, sizes, and motions, as happens in mechanics, he is condemning what I think deserves praise above all else"; in fact, to belittle his physics for resembling mechanics is tantamount to belittling it because it is true.[33] Unlike Boyle, however, he applies the principles that he considers mechanical to gravity.[34] By explaining the fall of terrestrial bodies and the circulation of celestial ones in terms of material contact action in the vortex, he puts the question and answer about gravity's causal basis into his physics. In addition to providing a physics that addresses More's challenge, Descartes also considers the relationship between mechanics and natural philosophy in general terms. In the same text quoted just above, in which he reacts to Froidmont's criticism, he asserts a different relationship between mechanics and natural philosophy than was traditionally thought to exist. Although Aris-

31. Although I merely mention central features, the nature of Descartes's mechanical philosophy and its debt to the simple machine tradition is an area of ongoing research. Some investigations find his physics drawing on machines in more and different ways than usually recognized; see, e.g., Mark Wilson (1997).

32. See Gabbey (2004, 18–19); having identified a number of meanings of the term 'mechanical', he takes Froidmont to intend the manual and mean senses of the term.

33. Descartes to Plempus for Froidmont, October 3, 1637: Gabbey's translation (2004, 18–19); Latin original in Descartes (1990, 1:420–21).

34. This point has been made by Garber (2002, 193).

totelians failed to realize it, mechanics is actually "a small part of the true physics," he writes; mechanics "took itself off to the mathematicians, since it found no place with the supporters of the common philosophy."[35]

Descartes's vortex theory is empirically inadequate, and Newton's assessment of it notorious. Since the proportions of the planetary orbits and the eccentric motions of comets are possible only without vortices, the Cartesian vortex is "beset with many difficulties," even a fiction (respectively, Newton, General Scholium, 1726/1999, 939; *De gravitatione*, 2004, 14). Still, Newton will agree generally with the relationship between mechanics and natural philosophy that Descartes has articulated here.

5. Mechanizing Natural Philosophy and Newton's Mechanical Force.

5.1. Simple Machines in the Principia and the Geometric Compositionality of Forces. There is little indication in the *Principia*'s most detailed discussion of simple machines that Newton means to redefine mechanics or reconfigure its relationship to natural philosophy. This discussion, which occurs in corollary 2 to the laws of motion and the scholium to those laws, concerns the geometric compositionality of forces. A direct force AD may be composed from oblique forces AB and BD, and the direct force may be resolved into those oblique forces. The forces of machines can be derived in this manner, example cases of a wedge, screw, and unequal spokes of a wheel providing confirmation. The corollary can be used extensively, Newton asserts, because "the whole of mechanics" depends on it (*Principia*, 419–20). In the scholium to the laws, he describes cases confirming the third law, including experiments with oscillating pendulums, experiments with a lodestone and iron to demonstrate the law for a case of attraction, and various machines including the balance, wedge, and clocks.

Throughout this discussion, which focuses on problems traditionally considered the province of practical mechanics, Newton allows disciplinary boundaries to stand. Much as he sometimes employs terms such as 'mechanical' in senses that he would not apply to his own theory, here he speaks within the confines of practical mechanics, a disciplinary category that he will elsewhere reject. When he speaks of machines, he means only "devices," and when he explains that he means only to show the third law's "wide range and certainty" and that his "purpose here is not to write a treatise of mechanics" (*Principia*, 429–30), he refers to the discipline of practical mechanics without challenge. Nevertheless, a challenge is implicit in the connection he draws between machines, specifically those that are merely devices, and his laws of motion, which belong to natural philosophy. He spells out that challenge in his Author's Preface.

35. Descartes to Plempus for Froidmont, October 3, 1637 (Gabbey 2004, 18–19).

5.2. A Single Science of Motion and the World as a Divinely Created Machine. In the main text of the *Principia*, there are occasional indications as to how to regard the theory. That forces have real causal efficacy is indicated, for instance, as Newton explicates his definition of centripetal force. The magnetic force is that "by which iron seeks a lodestone," while gravity is the force "by which bodies tend toward the center of the earth," and indeed, as the third book reveals, it is that centripetal force "by which the planets . . . are compelled to revolve in curved lines" (*Principia*, 405).[36] In the Author's Preface, written for the *Principia*'s first edition and retained in all subsequent editions, he elaborates.[37] While the treatise's title, *Mathematical Principles of Natural Philosophy*, as translated, asserts that certain mathematical principles are internal to natural philosophy, the conjunction of several remarks in the preface further identifies those principles as mechanical. Specifically, those mathematical principles are identified as being mechanical via the conjunction of his claim that the (mathematically identifiable) forces are demonstrable from phenomena with this exclamation: "If only we could derive the other phenomena of nature from mechanical principles by the same kind of reasoning!" (*Principia*, 382).

Throughout the passages preceding that exclamation, Newton explains why natural philosophy must be mechanized and mechanics subsumed within it. He explains this by rejecting an ancient, persistent distinction, although not without first claiming an affinity with both ancient and modern thinkers; like the ancients, he assigns mechanics "the greatest importance in the investigation of science and nature," and like the moderns, he has rejected substantial forms, instead reducing "the phenomena of nature to mathematical laws." Turning his attention to practical and rational mechanics, he then repudiates the long-standing belief that they properly constitute distinct disciplines, with distinct goals and domains.

> *Practical mechanics* is the subject that comprises all the manual arts, from which the subject of *mechanics* as a whole has adopted its name. But since

36. The revelation that the centripetal force keeping planets in orbit is gravity comes in bk. 3, proposition 5, scholium (*Principia*, 806).

37. I do not mean to imply that this is Newton's only intention in the preface. As several commentators have recently shown, Descartes's *Géométrie* is the preface's specific target. When he asserts that "*geometry* is founded on mechanical practice and is nothing other than that part of *universal mechanics* which reduces the art of measuring to exact propositions and demonstrations," he is opposing the Cartesian epistemological view of geometry. See Domski (2003) and Guicciardini (2009); see also Garrison's discussion (1987, 614) of Cartesian analysis as a target. Additional draft prefaces, never completed, were written in the years just before and after the publication of the second edition in 1713. See Cohen (1999, 49–54) for his translation and discussion of one of these drafts, the "Unpublished Preface to the *Principia*," as Cohen calls ULC MS 3968, fol. 109. See also Guicciardini (2009, 303–95), who refers to that same draft as the "Intended Preface."

> those who practice an art do not generally work with a high degree of exactness, the whole subject of *mechanics* is distinguished from *geometry* by the attribution of exactness to *geometry* and of anything less than exactness to *mechanics*. Yet the errors do not come from the art but from those who practice the art. Anyone who works with less exactness is a more imperfect mechanic, and if anyone could work with the greatest exactness, he would be the most perfect mechanic of all.
>
> . . . But since the manual arts are applied especially to making bodies move, *geometry* is commonly used in reference to magnitude, and *mechanics* in reference to motion. In this sense *rational mechanics* will be the science, expressed in exact propositions and demonstrations, of the motions that result from any forces whatever and of the forces that are required for any motions whatever. The ancients studied this part of *mechanics* in terms of the *five powers* that related to the manual arts [i.e., the five mechanical powers] and paid hardly any attention to gravity (since it is not a manual power) except in the moving of weights by these powers. But since we are concerned with natural philosophy rather than manual arts, and are writing about natural rather than manual powers, we concentrate on aspects of gravity, levity, elastic forces, resistance of fluids, and forces of this sort, whether attractive or impulsive. And therefore our present work sets forth mathematical principles of natural philosophy.[38] (*Principia*, 382)

In these passages, Newton identifies and contests two related presumptions arising from the same fundamental error. First is the presumption that there is exactness only in mathematics and that because abstract, mathematical entities are not causally related, rational mechanics—the mathematically expressed science of motion and of Archimedes's idealized machines—cannot tell us about forces as causal principles of change. Contesting this first presumption, Newton asserts that there is exactness in the world, and consequently, to make material bodies the objects of mathematics does not bring anything extrinsic or foreign to bear on them. Mathematical methods instead provide the means of discovering features intrinsic to a system, notably the

38. The preface has, of course, invited considerable attention, and one lucid discussion may be found in Stein (2002, esp. 282–83). While I cannot attempt here to catalog the points on which I agree and disagree with other scholars' discussions, the questions I consider are closely related to some of the many issues Stein discusses, although he considers the mechanical philosophy in different terms, as indicated in n. 4. Stein's (2002) article covers a great deal of ground, and I might note that I elsewhere agreed with his claim (278–79) that *De gravitatione*'s creation story reduces bodies to attributes alone, unified by God's action, while disagreeing with his conclusions (281–82) that Newton sets aside the question about dualism and eliminates the concept of substance; see Kochiras (2013, 332–33, 342–44).

geometric proportions of the forces by which component bodies causally interact.

The second presumption is that the part of mechanics investigating real machines—traditionally, practical mechanics—properly includes only the imperfect machines produced by imperfect, human mechanics. Against this, Newton indicates that a discipline investigating real machines must also investigate natural phenomena and the natural powers, such as gravity and other forces. For those powers too are mechanical, and although the world, having God as its creator, is no imperfect device, it is nevertheless a machine. Admittedly, here Newton only hints at that latter thought, by stating that anyone able to work with "the greatest exactness" would be "the most perfect mechanic of all" (Author's Preface to the *Principia*, 381).[39] That it is such a hint, however, is suggested by his later reference to God, in a letter to Richard Bentley, as a "cause . . . not blind & fortuitous, but very well skilled in Mechanicks & Geometry."[40] Certainly this is not a world machine in Descartes's sense, not least because the heavens are mostly void; for Newton, the world is mechanical in that the forces by which its systems operate manifest geometric proportions. Nor should we suppose any conflict between Newton's understanding of the world as a divinely created machine and the voluntarism he expresses elsewhere, for much as a human mechanic might interrupt or adjust the functioning of an imperfect, artificial device, so might the deity interrupt and adjust processes functioning by secondary causes, notably the planetary orbits.[41]

In casting mathematical features as intrinsic to the world—a point expressed by his choice of the term 'rational mechanics' for the single science of motion he asserts—and mathematical methods as capable of identifying real features of the world, Newton voices ideas expressed earlier by Isaac Barrow. Barrow (a likely influence, since Newton is thought to have at-

39. An anonymous referee for this journal objects, "In context, no claim about God is implied." But the interpretation that Newton has God in mind is supported by one of his remarks to Bentley (quoted next). Precedents for Newton's thought include a remark by the mathematician and physician Henri de Monantheuil, who held the world to be "a machine, and indeed of machines, the greatest, most efficient, most firm, most beautiful," and its creator to be "the most accurate and incessant Geometer" (Monantheuil's remarks are translated and discussed by Hattab [2005], 113–15; cf. Guicciardini 2009, 300, 315).

40. Newton's first letter to Bentley, in Newton (1959–71, 3:235).

41. Newton's voluntarism is evident in this well-known remark: "Some inconsiderable Irregularities . . . may have risen from the mutual Actions of Comets and Planets upon one another, and . . . will be apt to increase, till this System wants a Reformation." In Leibniz's view, Newton's God was most certainly not the most perfect mechanic of all but rather an imperfect watchmaker, and his criticism was probably provoked by the quoted remark (*Opticks*, Query 31, 402—but Query 23 in the edition on which Leibniz was commenting). Leibniz levels his charge in 1715, in his first letter to Samuel Clarke (see Alexander 1956, 11 n. a).

tended his inaugural lectures as Lucasian chair; see Westfall 1980, 99) gave reasons for recognizing mixed mathematical disciplines as part of natural science: "Magnitude is the common affection of all physical things, it is interwoven in the nature of bodies, blended with all corporeal accidents, and well-nigh bears the principal part in the production of every natural effect."[42] Barrow, too, had his predecessors, of course, and in rejecting traditional disciplinary categories—along with their names, something Barrow had not done (see again Gabbey 1992, 312)—Newton articulates long-brewing changes in the relationship between mechanics and natural philosophy.

5.3. The Transformation of Natural Philosophy's Traditional Goal. Midway through his preface, Newton affirms the traditional goal of natural philosophy, but with a crucial modification. In general terms, natural philosophy's traditional goal was the discovery of real causes of natural phenomena. The Peripatetics had specified that goal in terms of their four causes, which looked not to systems but to powers possessed by individual bodies. Descartes in his turn specified the goal in terms of his mechanism of contact action, producing a complete explanation of gravity, but within a system that foundered empirically and resisted quantification. Newton now specifies that goal as the discovery of forces, writing these well-known words: "For the basic problem of philosophy seems to be to discover the forces of nature from the phenomena of motions and then to demonstrate the other phenomena from these forces" (*Principia*, 382). These forces are, in particular, impressed forces (interestingly connected, however, to Definition 3's inherent force, the *vis inertiae*), which are defined without restriction to contact action and have various sources, including "percussion, pressure, or centripetal force" (Definition 4, *Principia*, 405). The *Principia*'s centerpiece is of course of that latter kind. As a real cause—Newton's language, once again, indicating its causal efficacy—the gravitational force belongs to natural philosophy. Yet since the covarying quantities of force, mass, and distance arise only within a system of at least two particles, that real cause is not a power belonging to any individual body. And he has been

42. The remark is from the second of Barrow's lectures, *Lectiones mathematicae*, 1683, in Gabbey (1992, 311, citing the 1734 translation). Gabbey comments, "the foundations of all practical and theoretical mechanical disciplines, though they might bear the traditional names Barrow retains for them, become identical with the principles of natural philosophy" (312). Other discussions of related ideas in Barrow and of his influence on Newton include Westfall (1980), Garrison (1987), De Gandt (1995, 209), Malet (1997), and Guicciardini (2009). Garrison remarks on Newton's own probable influence on his ideas about generating geometrical figures kinematically: "its probable that D' Barrows Lectures might put me upon considering the generation of figures by motion, tho I not now remember it" (Newton, *Geometrical Lectures*, in Garrison 1987, 614).

able to derive it from celestial phenomena "by means of propositions demonstrated mathematically" because geometric proportions are intrinsic to the force (*Principia*, 382).

6. Conclusion. In terms of the sense in which Newton considered his own natural philosophy, or more precisely, its core, to be mechanical, his gravitational force is its best exemplar, clearly enough. But has he met More's challenge? The well-known words of Newton's critics indicate just how seriously he had failed, in their eyes. They charged, variously, that his demonstrations are "only mechanical," for "he has not considered their Principles as a Physicist, but as a mere Mathematician" (this from the review of the *Principia* in *Journal des Sçavans*);[43] that his principle of attraction is "not explainable by any of the principles of mechanics" and is, in fact, "absurd" (this from Newton's chief intended reader, Huygens);[44] and that by attributing attractions to a law of nature without explaining how the ends are achieved, Newton takes refuge in a "miracle," although the task was "to find out a natural cause" (this from his antagonist Leibniz).[45] In short, since he had failed to specify the physical means by which gravitational effects are produced, he had not given any natural philosophy at all, mechanical or otherwise.

In asking about Newton's own response, we may recall More's words and the meaning they could have had when he posed them. When he asked after "the true mechanical cause of the gravity of all the parts," More could only have meant the cause of the parts' heaviness, which is to say their tendency earthward. To the question about such tendencies, Newton can claim to have provided the answer. He had discovered the cause, and he had mechanized it. Instead of taking gravity for granted, he had shown that the earthward tendencies of a balance's load and effort, on the one hand, and the celestial bodies' orbits, on the other, acted by the same force. He had mechanized it by revealing its proportions, in terms of distance and the novel concept of mass, and by revealing it as an impressed force, another novel concept, a cause that could not be localized to one body but must rather be assigned to a system. More broadly, he had mechanized natural philosophy, by transforming its traditional goal into a search for impressed forces.

If we import Newton's own force of gravity into More's words, however, the meaning changes, and we confront the vexed question about gravity's "physical causes and sites" (Definition 8, *Principia*, 407). Newton famously acknowledges ignorance in the General Scholium, and his ongoing struggle

43. The review, of August 2, 1688, was probably written by Pierre Silvain Régis, as Cohen notes (1980, 96–97; his trans.).

44. In Cohen (1980, 81, 80).

45. Leibniz to Hartsoeker, in *Memoirs of Literature*, February 11, 1711 (in Newton 2004, 109; on the translation, see xxxviii).

to answer the question motivates his earlier-quoted thought that active principles are genuine principles of the mechanical philosophy. A variant of that idea appears in the published Query 31, which suggests active principles as "the cause of gravity."[46] That suggestion would ground the gravitational force in active principles, much as he grounds his three laws in the passive principle, the *vis inertiae* (thereby dividing the sources of that impressed force's features between the two sorts of principles). But while the three laws' basis in the passive *vis inertiae* is not speculative, since the query's claim has a counterpart in the *Principia*'s Definition 3 (see, respectively, *Opticks*, Query 31; Newton 1730/1952, 401; *Principia*, 404), Newton's remarks about active principles are.[47] For although he seems confident that they exist, he makes no claim about their location, and drafts reflect his uncertainty about their relationship to matter (Query 31; Newton 1730/1952, 399).[48] Suffice it to say, then, that Newton had met More's challenge in part, and by conceding the limit of his knowledge, he could expect that his theory would not be regarded as fiction in the disciplinary realignment to come.

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46. Discussions of this causal structure may be found in McGuire (1968, esp. 172, 186), who associates it with the chain of being, and Ernan McMullin (1978, 82; see also 146 n. 160, for his commentary on McGuire), who cautions against supposing that Newton consistently adhered to such a "two-tier ontology."

47. Discussions of the *vis inertiae*'s relation to the three laws include McGuire (1968, 172–73; 1994, 328–29), Stein (1970, 270; 2002, 284), and Gabbey (1971/1980, 284–85).

48. John Henry (1994) disagrees, arguing that Newton holds active principles to be inessential powers of matter, superadded by God. Another opposing view may be found in Schliesser (2011a, 163; 2011b, 85, 90, 91–92, and 97). See also Kochiras (2011), which addresses Schliesser's misrepresentations (2011a) of my view about active principles and other issues.

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