Reappraisals of the Scientific Revolution

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Metaphysics and the new science

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An understanding of the relationship between metaphysics and natural philosophy – or, as we might now say, between philosophy and science – is fundamental to understanding the rise of the "new science" of the seventeenth century. During the present century, thought about this relationship has been dominated by the work of Ernst Cassirer, E. A. Burtt, A. N. Whitehead, and Alexandre Koyré. These authors found a common metaphysical core shared by adherents of the new science: the doctrine that the material world consists of bodies having only mathematical properties and that it must therefore be comprehended and described in mathematical terms.[1] According to this interpretation – for which I will treat Burtt as spokesman – the "mathematization of nature" was induced by a common "Platonic" or "Pythagorean" metaphysical presupposition, on the part of such figures as Copernicus, Kepler, Galileo, and Descartes, that "the book of nature is written in mathematical characters." The shared acceptance of this presupposition is credited to the influence of Renaissance Neoplatonism.[2]

Although this picture has become a standard component of accounts of the rise of the new science (or of the "Scientific Revolution"),[3] it can no longer be accepted. For while it is indeed true that various early modern authors emphasized the importance of mathematics in their approaches to nature, a careful examination of the

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use and motivation of mathematical description in such authors reveals significant differences among them. The most that one can find of a broadly shared attitude toward the relationship between mathematics and nature amounts to a simple statement that mathematical modes of description are useful in the investigation of nature, a proposition that hardly qualifies as Pythagorean and Neoplatonic or as metaphysical. In order to determine properly the role of Neoplatonic (or Pythagorean) metaphysics in justifying the application of mathematics to nature, we need to know what such a justification would look like. I shall argue that once a historically and philosophically viable conception of such a justification is employed, the Neoplatonic contingent among the chief adherents of the new science is greatly reduced. Indeed, attention to the variety of justifications for and uses of mathematical description in early modern science reveals that no unified, historically efficacious metaphysical doctrine regarding the relationship between mathematics and nature is to be found.

Underlying the inadequacy of the received picture of the relationship between metaphysics and the new science is a particular attitude toward metaphysics itself, which, although it retains some currency, needs to be reexamined. As used most often by Burtt, the term "metaphysics" accords with the definition later developed by R. G. Collingwood: Metaphysics comprises the absolute nonempirical presuppositions of a thinker or an age. In this sense, every major thinker has a metaphysics, inasmuch as all have presuppositions. Accordingly, the philosopher's task is to tease a thinker's (usually unconscious) presuppositions out of his or her body of thought.[4] Burtt proposed to accomplish this through a detailed historical analysis of the major figures in the rise of modern science. In practice, this came down to discovering the influences in the intellectual environment or the biographical factors in the intellectual development of a figure that explained his acceptance of a given presupposition or assumption.[5] When metaphysics is treated as presupposition, each major figure may be assigned a metaphysics, but we shall find that the total set of such presuppositions, upon close examination, does not constitute a unified metaphysics for the new science.

The central difficulty with following Burtt's Collingwoodesque approach, however, lies not in the failure to discover unity, but in the fact that such an approach is blind to the types of intellectual activity actually recognized as constituting metaphysics in the sixteenth and seventeenth centuries. At that time, metaphysics was widely held to be a legitimate member of the sciences, if not the most basic science. It was indeed a science of presuppositions, or of "first principles," but not of *unconscious* first principles. The aim of metaphysics was to

argue for, or at least explicitly to portray, fundamental or basic principles and concepts. Whether defined by its subject matter (typically "being" considered in general) or, as came increasingly to be the case in the modern period, by its method (a priori intellection), metaphysics constituted a distinct intellectual enterprise. To be a metaphysician or to engage in metaphysics was to pursue a special subject matter, perhaps with a special method. It is, of course, possible that metaphysicians such as Descartes had unconscious presuppositions that it would be interesting to uncover, but such presuppositions did not constitute their metaphysics. We can probably learn something about a given metaphysician by teasing out aspects of his metaphysics that were blindly presupposed, but to do so is quite different from assuming that metaphysics was merely blind presupposition.

In this historically situated sense of the term "metaphysics," it is by no means clear that all of the adherents of the new science even had a metaphysics. Of course, a figure might blindly subscribe to a set of tenets developed by the metaphysicians of his or a previous age, in which case his presuppositions or assumptions might be regarded as metaphysical. However, before denoting a tenet as metaphysical because it echoes prior or contemporary metaphysics, one should be careful to see how it is functioning in the thought of the figure who subscribes to it. Furthermore, one should not assume that "acceptance through assumption" is the most interesting relation a nonmetaphysician might have to metaphysics. Indeed, I shall argue that by paying attention to the historically actual activity and content of metaphysics, we reopen the possibility that at least some of the adherents of the new science proceeded independently of metaphysics. If this sounds like the old positivist line that Burtt was seeking to undercut, it is not. I am claiming that because Burtt's strategy for undercutting the positivist ideal of a purely "factual," nonmetaphysical science relied upon treating assumptions as metaphysics, he gave short shrift to explicitly nonmetaphysical attitudes toward the justification of a mathematical approach to nature, thereby overlooking their place in the development of both modern science and modern philosophy.

This point is important for understanding the arguments and intellectual achievements of the major authors of the new science. Consider the belief that the propositions of mathematics accurately describe material objects. To view this straightforwardly as a metaphysical tenet[6] is to miss important differences in the attitude that one might hold toward the fit between mathematics and nature and toward the grounds for believing in it. Various figures in our story adopted different attitudes toward whether this "fit" should be considered problematic and in need of justification, some seeking to provide a metaphysical justification and some not. Attempting to capture such differences promises to be a lesson in distinguishing metaphysical from nonmetaphysical attitudes and styles of argumentation, at least in the seventeenth century. In particular, I believe that it allows us to discern a type of nonmetaphysical (and yet nonetheless philosophical) voice in the rise of modern science that has not heretofore been adequately recognized, a voice that speaks especially in the work of Galileo.

In examining the place of metaphysics in the rise of the new science, I will first provide a background sketch of the historically available metaphysical (and nonmetaphysical) attitudes toward the application of mathematics to nature. I will then examine the ways in which three major authors (Copernicus, Kepler, and Descartes) did and did not engage in metaphysics. Through an examination of their own specific conceptions of metaphysics (if any) and its role in their work, I will elaborate a rough typology of possible roles for metaphysics in early modern science. This typology will enable us to see what was distinctive and innovative in Galileo. Finally, once we have determined whether the attitudes and arguments of our authors should be regarded as metaphysical in a historically situated sense, we will be in a position to ask in what ways the rise of the new science itself altered the conception of metaphysics, and whether certain nominally antimetaphysical adherents of the new science implicitly advanced metaphysical tenets despite themselves.

In surveying historical conceptions of metaphysics, it would be foolhardy to attempt an exhaustive taxonomy even of those conceptions available in the sixteenth and seventeenth centuries. Given the wealth of ancient, medieval, and Renaissance materials at hand during those centuries, including texts in and translations from Greek, Latin, Hebrew, and Arabic, this effectively would amount to a survey of the prior history of metaphysics. If such a task were not overwhelming enough, one would also be faced with the notoriously eclectic and syncretic character of Renaissance philosophy, in which elements from Plato, Aristotle, and other philosophers were combined with Christian theology to produce a host of hybrid philosophies and conceptions of philosophy.

Nonetheless, some order must be introduced into the discussion of historically actual conceptions of metaphysics. To this end, I will characterize the chief conceptions of metaphysics in relation to mathematical science by focusing on classical formulations as they were received and modified in the sixteenth and seventeenth centuries.

This discussion will yield Aristotelian, Platonic, and nonmetaphysical attitudes toward mathematical science.

Classical and early modern metaphysics and mathematical science

A basic taxonomy of conceptions of the subject matter of metaphysics may be derived from the primary senses given the term itself. According to a widely repeated account (which apparently first arose in the sixteenth century), the term "metaphysics" originated when Andronicus of Rhodes, the editor of Aristotle's works in the first century B.C., arbitrarily placed the works in which Aristotle discussed (what he called) "first philosophy" after the works on physics and labeled the former works "meta-physics" to indicate their textual position (one sense of "meta" being "after"). Several modern and contemporary philosophers, including Kant, have questioned this story, on the grounds that the name fits the works too well to have been an accident. There are two senses in which this is so.[7] The first, which Kant had in mind, derives from taking "meta" in the sense of "trans," in which case the term "metaphysics" denotes the science of things above or beyond the physical (in particular, the divine). This accords with Aristotle's sometimes linking "first philosophy" with "theology" (the study of the prime mover). The second sense in which Kant's observation is apt depends upon Aristotle's fundamental distinction between things that are "prior with respect to nature" and things that are "prior with respect to us." Considered as "first philosophy," which investigates being qua being and is the science of first principles, metaphysics is prior with respect to nature. But it is not prior with respect to us, since metaphysics is the science that abstracts the farthest from sensory images and, therefore, comes after physics in the order of learning. "Metaphysics" is thus seen to be an apt description of "first philosophy" in the context of an Aristotelian account of the order in which philosophical cognition develops.[8]

These two characterizations of metaphysics suggest two ways in which it might have been regarded (in the seventeenth century) as providing a basis for the new science. Metaphysics as the science of first principles might be thought to provide the first principles of the special sciences. Aristotle raised the question of whether first philosophy could provide the principles of the special sciences, such as physics or geometry, and seems to have decided in the negative.[9] Yet his doctrine that the special sciences cannot establish their own first principles is suggestive of the idea that first philosophy might fill that role. During the Middle Ages and into the seventeenth century there was considerable discussion of this question among scholastic interpreters of Aristotle. Both conceptions of metaphysics had medieval and early modern adherents. In the seventeenth century, Descartes and Bacon conceived metaphysics as providing (at least some of) the principles of physics.[10]

A second way in which metaphysics might have functioned in relation to the new science proceeds from the idea that the key to understanding our world lies in the investigation of the transphysical. Burtt argued that for many early modern thinkers this key was to be found in the explicit or implied assumption that God is a geometer who has patterned the universe and its parts after geometrical Ideas, an assumption that he credited to the Neoplatonic revival of the fifteenth and sixteenth centuries.[11] In fact, mathematics played more than one role within Platonic thought. As discussed in Book VII of the *Republic* and by later commentators such as Proclus, mathematics was endorsed as a preparatory study for the contemplation of things divine; in this use, mathematics turns one's attention from transient corporeal things known by the senses to unchanging, eternal, immaterial objects known by the intellect, thereby leading one toward contemplation of the immaterial, unchanging Form of the Good, or, in Christian Neoplatonic terms, toward contemplation of God. A second role for mathematics stems from the "geometrical atomism" of the creating "demiurge" in the *Timaeus*, which becomes the Christian Neoplatonic conception of God as a geometer and of the universe as having a geometrical structure reflecting the *archai*, or Ideas, in the mind of God. While the first of these roles could at best serve the function of motivating mathematical studies (including those that pertain to nature), the second clearly could provide the basis for a view of nature as fundamentally mathematical.

Although the fact that an early modern author adopts a mathematical approach to nature is sometimes taken as providing sufficient grounds for ascribing to him a Platonic metaphysics, it does not. For beyond Platonic motivations for applying mathematics to the study of nature, there were several other traditions of thought that urged the application of, or actually applied, mathematics to nature. Among ancient authors, Aristotle himself endorsed the use of mathematics in such "mixed sciences" as astronomy, optics, and music. His doctrine that these sciences are "subalternate" to mathematics – applying mathematical principles to their own distinct subject matter – was well known to scholastic commentators.[12] According to typical scholastic Aristotelian doctrine, mathematics itself abstracts from the sensible matter of objects and treats their "intelligible matter" (that is, their pure extension). The objects of mathematics, while not existing apart from physical objects, are studied apart from the sensible properties of those objects. The mixed sciences treat mathematical objects not as mathematical (in connection with intelligible matter) but as physical (that is, as manifested in "sensible matter").[13]

In addition to attitudes toward mathematics that were linked with Platonic or Aristotelian thought, there were the attitudes implicit in the central texts of the mathematical sciences themselves. A limited number of mathematical works had been available throughout the Middle Ages, and the fifteenth and sixteenth centuries saw the recovery and translation of numerous Greek mathematical manuscripts. These works included not only "pure" mathematics, such as geometry, arithmetic, and algebra, but also treatises on astronomy, optics, and mechanics, each of which used mathematical constructions and modes of argument in the study of natural objects or heavenly phenomena.[14] Such works were sometimes embedded in one or another philosophical or metaphysical context; Neoplatonic strains were common in mathematical prefaces. Yet for a number of these works, a tradition of commentary and extension arose that must be viewed as fundamentally mathematical. For example, in Islam, and later in the Latin West, there were figures who were first and foremost technical astronomers, developing and altering the mathematical models of the *Almagest* and subsequent works and applying them to problems concerning astronomical tables and calendrical computations.[15]

These mathematical writings provide the basis for an alternative to a metaphysical grounding of the application of mathematics to nature. The notion of a nonmetaphysical grounding may be introduced through a proposal made by E. W. Strong. Writing in response to Burtt's thesis that the mathematical approach was basically Neoplatonic, Strong argued that mathematical writers in the Renaissance and early modern period must be divided into two groups, which he labeled "metamathematical" and "mathematical," or sometimes more generally as "metaphysical" and "scientific."[16] Into the first, or "metamathematical," group he placed such figures as Bartolomeo Zamberti, Giovanni Pico della Mirandola, D. Henrion, and John Dee, whom he saw as continuing an "archaic and scientifically divorced tradition" stemming from Nicomachus of Gerasa, Theon of Smyrna, and Proclus Diadochus. The emphasis here is on the importance of mathematics as preparatory study for the contemplation of the divine, or on mathematical objects as themselves of mystical significance. Into the second, or "mathematical science," group he placed Niccolò Tartaglia, Girolamo Cataneo, and Galileo, as continuers of an autonomous tradition of mathematical science stemming from Euclid, Archimedes, and Ptolemy. The emphasis here is on mathematical and scientific practice; as Strong put it, "Their science appears to be operational and autonomous in the sense that their distinctions are working distinctions and their definitions and concepts take their meaning from the limited method and subject-matter of their science. They are pragmatic in their approach and in their work."[17] The justification of their work derives from practice, not metaphysics, and so does the motivation of its concepts and distinctions. Nonetheless, Strong granted that even if the mathematical results achieved by a scientist did not derive from metaphysical considerations, the investigator might have been motivated by metamathematical or metaphysical impulses, and so he recognized an intersection of the two groups in such figures as Girolamo Cardano and Kepler.[18]

Strong's point that the motivation and justification of the application of mathematics to nature often derived from mathematical and empirical practice is an important one, even if parts of his analysis are questionable. (In particular, I question his strict separation of the mathematical and metaphysical in Kepler and his summary placement of Descartes within the metamathematical tradition.)[19] However, I would like to propose the thesis that mathematical science could be autonomous from metaphysics not only in practice, but also philosophically, insofar as mathematical practitioners developed and conveyed a distinctive attitude toward the application of mathematics to nature. In so doing, I am suggesting that some of the practitioners of mathematical science provided their own, nonmetaphysical answers to questions that excited metaphysics in other authors.

It will be useful to reflect upon various ways in which the mathematical sciences might have been regarded as autonomous from metaphysics. To begin with, consider two questions that might seem to threaten the autonomy of mathematics and the mathematical sciences by requiring metaphysical intervention. First, the question of the origin of mathematical certainty. There were at least two types of response to the question: the development of a metaphysical account of this certainty, perhaps in terms of the intellectual apprehension of Platonic Ideas, or, in the later Aristotelian tradition, in terms of the "intelligible matter" of mathematical objects; and appeal to the fact of agreement on basic arithmetic and geometrical propositions, without further elaboration. The latter was the attitude conveyed by some mathematical practitioners.[20] Second, there is the question of why mathematical constructions should fit nature. This question did not pose a problem to all practitioners of the mathematical sciences. For, although Plato and others emphasized the separateness of mathematical entities from the world-in-flux of the senses, at least some

practitioners of the mathematical sciences themselves took the object of their investigation to be natural objects or processes. Geometry ("earth measurement") was taken as the science of actual space (although when it became so regarded is disputed). Optics was the science of vision, statics of the balance, and astronomy the science of the heavens. There need be no gap between mathematical constructions and their objects, for mathematics is taken as describing actual things: light-rays insofar as they are straight, the earth insofar as it is (or approximates) a sphere, and so on.[21] The appropriateness of this attitude might be justified by the success in practice of the various sciences.

Mathematics also may become autonomous from metaphysics when methodological attitudes that originated in a metaphysical context are accepted among mathematicians in such a way that they become constitutive of mathematical practice. Whatever the historical origin of the ancient proclivity for using uniform circular motion to account for planetary motions, its justification through the idea that such motion is appropriate to divine and unchanging bodies certainly may be regarded as metaphysical. Yet when Ptolemy introduces the notion of uniform circular motion in his *Almagest*, he simply states that "the mathematician's task and goal ought to be to show all the heavenly phenomena being reproduced by uniform circular motion" and then offers a set of tables that use two uniform motions to capture the irregularity of the sun's apparent motion. He subsequently shows how the same principle can be extended to the apparently irregular motions of the planets. Only six books later does he give a metaphysical justification for doing so, and this is tossed off in a single sentence.[22] The point of the chapter in which it occurs is to reveal the observational and theoretical difficulties that Ptolemy overcame in constructing his planetary models. The principle of uniform circular motion was virtually constitutive of the practice of mathematical astronomy through the time of Copernicus and thus may be regarded as part of an autonomous mathematical practice, even if a "metaphysical" justification for it continued to be invoked on occasion.

Because arguments or phrases that recall a particular metaphysical doctrine may take on a life of their own when assimilated into mathematical practice, each should be examined carefully in the specific context in which it occurs, in order to see whether it is functioning metaphysically for a particular author.[23] Thus, when the sixteenth-century Italian mathematician Tartaglia speaks of mathematical constructions as "abstracting from matter," we can read this as an Aristotelian doctrine if we like, but if so, it is far removed from a systematic Aristotelian position (and therefore from a proper Aristotelian metaphysical argument or set of considerations). In fact, Tartaglia's own gloss on "abstracting from matter" refers to Euclid – presumably to Euclid's conception of lines without breadth and surfaces without thickness.[24] This is an appeal to prior mathematical practice, not to a theory of the cognition of mathematical objects as "intelligible matter."

Finally, the mathematical sciences may be viewed as autonomous in the sense that their adherents express the attitude that these sciences constitute their own distinctive "philosophical" approach to nature and carry their own justification through success in practice. Ptolemy claimed that mathematics was the only branch of theoretical philosophy to render real knowledge, physics and theology amounting to mere "guesswork." He justified this judgment by pointing to the greater hope for agreement in mathematical science, which he explained as deriving from its use of "indisputable methods, namely arithmetic and geometry."[25] With the mathematical revival of the fifteenth and sixteenth centuries, many authors heralded the certainty and agreement characteristic of mathematical reasoning as the basis for a reform of the liberal arts and put forward mathematics as a substitute for scholastic philosophy, with its insistence on the syllogism. Early modern mathematical authors sometimes made similar claims for the efficacy of mathematical reasoning and its centrality within philosophy.[26]

From this brief survey of historical conceptions of metaphysics and mathematics, it becomes apparent that in order for a figure to qualify as possessing a "Platonic–Pythagorean" metaphysics, he will have to do much more than argue or assert that mathematics can be useful within natural science, or even that it is definitive of the objects of the various sciences. He will have to make these arguments or assertions on Platonic grounds, within the context of a Platonic or Neoplatonic conception of the relationship between God (or the *archai*) and nature, or of the fundamentally mathematical character of nature's parts and their order. I contend that among the major authors of the new science, only Kepler meets these criteria. In order to make the contrast between Kepler and the others concrete, let us compare his position with that of Copernicus.

Copernicus and Kepler: Mathematical and metaphysical astronomers

Burtt opens his examination of Copernicus with a question that has motivated many investigations of Copernicus's heliocentrism: Why did Copernicus, and subsequent astronomers such as Kepler, accept

the new ordering of the solar system "in advance of any empirical confirmation"?[27] It has become widely accepted that the Copernican system achieved its first empirical confirmation only in 1610, with Galileo's observation of the phases of Venus (a discovery that, moreover, was equally compatible with the Tychonic system); that it was convincingly established only when Newton incorporated the new astronomy into a new physics (finishing what Kepler and Galileo had begun); and that the motion of the earth relative to the sun (assuming the stars as "fixed") received direct empirical "proof" only with F. W. Bessel's detection of stellar parallax in 1838 (long after the widespread acceptance of heliocentrism). Given such a state of affairs, it indeed becomes intriguing to understand how Copernicus, who appears to have been an exceptional mathematical astronomer and of sound mind, could have become steadfastly convinced of the truth of heliocentrism – especially in the face of the apparent stability of the earth, around which the dominant Aristotelian physics had been built. The customary answer is that Copernicus was swayed by "aesthetic," and therefore "subjective," factors that appealed to his "Platonic–Pythagorean" metaphysical tastes, leading him to prefer his own system on the basis of its "simplicity" and "harmony," along with its appropriateness to helio-divinity.[28]

This familiar account of Copernicus's reasons for preferring his system is a microcosm of the problems besetting the notion that authors such as Copernicus are best analyzed by digging out their implicit metaphysical assumptions. Such an approach, in straining to detect the background metaphysics that guided Copernicus's choice, shifts attention away from Copernicus's own arguments. In the present case, the reasoning seems to be that since his arguments were weak, the conviction with which he advanced them and the conviction they sparked in others must have resulted from shared metaphysical assumptions. The aim of interpretation then becomes to gain a sympathetic understanding of the psychological attraction of certain positions for someone with a given metaphysically conditioned aesthetic sensibility. From the perspective of this chapter, achieving an understanding of the psychological attraction of a novel conception to an author may be of interest; however, it is no substitute for the detailed analysis of his arguments as arguments. Granted, to the extent that the arguments are deemed weak, it may be reasonable to look for other sources of persuasion in order to understand their acceptance; but then the examination of such sources may also aid in understanding the acceptance of arguments that are deemed strong. Moreover, although I will presently suggest that Copernicus's arguments were not as weak as has often been assumed, I contend that even if they were weak, that gives no license for setting them aside as arguments. For even if an argument is unconvincing, the type of argument that it constitutes may be of interest and may be a part of the intellectual achievement associated with the presentation of the argument. In the present case, the shift of analytic focus from allegedly unconvincing arguments to background "metaphysical assumptions" has led to a misperception of the genre of the arguments themselves.

When one turns to the texts of Copernicus, a solid show of Platonic metaphysics is nowhere to be found. In truth, beyond mere references to Plato by name, one does find phrases with a Christian–Neoplatonic flavor, in references to the "best and most systematic Artisan of all" and to the establishment of things "in the finest order and directed by divine management."[29] There are also isolated allusions to ancient characterizations of the sun as a "visible God" (by "Trimegistus") and as the "all-seeing" (by Sophocles' Electra).[30] The question to be decided is whether these phrases and allusions are part of a sustained (or even sporadic) metaphysical argument for the truth of heliocentrism. When we go beyond reading the text in search of key phrases indicative of a hidden metaphysics and attend to its own argumentative structure, this mixed group of phrases fades into the background against the expanse of arguments that depend upon astronomical and mathematical considerations.

That the *Revolutions* is a work of technical mathematical astronomy is obvious and has not been disputed. The matter in question is the force and genre of the arguments for heliocentrism. In Copernicus's own primary statements aimed at "demonstrating" the truth of his system, three factors are put forward: (1) his account of the precession of the equinoxes; (2) his restoration of the ancient ideal of using only uniform circular motion in astronomical constructions (thereby banishing the equant); and (3) the "symmetry" of the solar system and the "harmony" in the motions of the planets revealed by his planetary hypotheses. In addition, he devotes some effort to removing a number of common objections to the notion that the earth moves.[31]

Of the three positive arguments, the second involves an appeal to a shared standard. If the shared standard is regarded as a piece of metaphysics, then the argument may be so regarded. We have seen that the preference for uniform circular motion was given both metaphysical and nonmetaphysical justifications. Copernicus invoked both types of justification.[32] But as he must have known, his equantless constructions could readily have been integrated into Ptolemy's system, so that while banishment of the equant might make his particular constructions preferable to Ptolemy's, it could not provide an argument for heliocentrism, and to my knowledge Copernicus did not claim that it could.[33] His case thus rests on the other two arguments, which exhibit a common pattern. Copernicus develops heliocentric models and shows that the phenomena can be "demonstrated" (derived through geometrical constructions) from them with as much accuracy as from the geocentric models; these are exercises in geometrical construction and trigonometric calculation. In addition, he brings forward reasons for preferring his "explanations" *(causae)* over geocentric models. These do the crucial work. In the case of precession, he argues that a better explanation is provided by attributing a single (if complicated) wobble to the earth than by ascribing the wobble to the sphere of fixed stars and introducing extra spheres to generate it; this is an argument from simplicity or economy.[34] His appeal to "symmetry" and "harmony" is more complicated, but it turns primarily upon the nonarbitrariness of his determination of the size and order of the planetary spheres and upon his unified explanation of certain planetary phenomena (such as the phase and period of retrograde motions) that Ptolemy's system could merely "save."[35]

But what about the idea that the "simpler" and "more harmonious" system is true? Surely here is a metaphysical assumption, to the effect that comparative simplicity and harmony are a sure sign of truth. But is this mode of argument inherently metaphysical? Two questions need to be distinguished. First, did Copernicus attempt to establish his criteria for selecting among astronomical hypotheses through metaphysical argument? Here I think it is clear that he did not. He employs the criteria without explicit defense; his arguments aim, not at establishing "simplicity" and "harmony" as criteria, but at showing that, given these criteria, his hypothesis has the advantage. The second and more difficult question is whether the criteria of simplicity and harmony are themselves inherently metaphysical. It is certain that they can be metaphysical, as when they are defended by considering nature as created and reflecting upon the intentions of the creator. But they need not be metaphysical, in the sense that they might be adopted because they have played a role in past practice in the mathematical sciences and are taken as constitutive of sound judgment about natural and heavenly phenomena. Therefore, what needs to be determined is whether in appealing, for example, to the commonplace that nature acts by the simplest means, Copernicus was accepting a metaphysical assumption or drawing upon what he considered to be sound astronomical practice in its own right (perhaps in the very act of reshaping such practice).[36]

Although it is difficult to answer this question in the absence of a systematic examination of the role of simplicity and harmony in the history of astronomical hypotheses from Ptolemy to Copernicus, two pieces of evidence are available. The first comes from what is known of that history, in particular from the fact that there were a number of Greek, Arabic, and medieval Latin astronomers (or commentators) who appealed to physical plausibility in assessing planetary hypotheses. Their position was well captured by Pierre Duhem (who mocked it): Unable to be satisfied by "abstract hypotheses reduced to geometrical fictions" that saved the phenomena, they insisted on "representing these hypotheses by means of bodies that a potter or sculptor might fashion, bodies so arranged that they can be made to revolve around one another," which satisfied their desire for "incarnate" or materially realizable constructions.[37] Planetary models are to be understood as concretely imaginable, corporeal contrivances, whose parts move with uniform circular motion. Simplicity and harmony then come to be regarded as dimensions of comparison found in judgments of the mechanical and kinematic plausibility of various configurations.[38]

Second, we can examine Copernicus's own text for hints about his attitude toward his criteria for hypothesis selection. In the preface to *On the Revolutions* he invokes coherence and unity as criteria without offering any justification; moreover, he admits that his remarks on these criteria may seem obscure but promises that they will become clearer "in the proper place." The proper place does not mean the references to divine workmanship quoted earlier, which occur long before he has presented any examples of his new system.[39] He ultimately claims to make good on his promise with Book V, which contains the planetary hypotheses. There he contends that the hypothesis of the earth's motion connects the order and size of the planetary spheres "with remarkable agreement and precise symmetry," and he later claims that it "forces all these phenomena into a precise and necessary regularity"; earlier (in an unpublished portion of the manuscript of *On the Revolutions*) he had suggested that these arguments would be sufficiently convincing to win over those who saw the possible equivalence between his and Ptolemy's accounts of solar and lunar phenomena. Although Copernicus was not one to provide second-order discussion of his principles of hypothesis selection, he can perhaps be seen here as making good on his claim in the preface to show that the Ptolemaic models, considered as describing the "structure of the universe and the true symmetry of its parts," are found to have "omitted something essential."[40] That is, they fail to bring the planetary models into a coherent system in which their size and order are fixed in a nonarbitrary fashion, and they fail

to explain the coincidences in the retrograde motions of the planets. Copernicus claims to have provided a more coherent ("harmonious") contrivance for the system of planets taken as a whole, thereby applying to the whole solar system the type of criteria that his predecessors had regularly applied to individual planetary constructions.

The suggestion that Copernicus conceived his arguments as judgments of plausibility rather than as applications of metaphysical principles is further supported by the workmanlike tone of his claims. In presenting his particular arguments, Copernicus claims that they provide a strong case for the truth of his system, not that they constitute an absolute proof. Thus, he claims that his arguments for the earth's diurnal rotation make it "more likely" (*probabilior*) that the earth moves than that it is at rest.[41] He admits more than once that the phenomena can be accounted for by Ptolemy and that specific heliocentric and geocentric models are equivalent. With respect to the choices between equivalent constructions in his own system, he remarks that he cannot decide which is real (though he assumes that one of them is), thereby indicating an appreciation of the difficulties in choosing among equivalent models.[42] But when the alternative constructions are heliocentric and geocentric, he finds reasons for choosing. Thus, in considering his own and Ptolemy's accounts of precession, he claims that "nobody will provide a better explanation [*causam*] of this, perhaps," than his own, based on the motion of the earth. This claim turns upon two appeals to economy: that his system avoids adding spheres beyond the sphere of stars solely to account for precession, and that it avoids the "absurdity" of putting the vast sphere of fixed stars – the very framework of space – into motion when the phenomena can equally well be saved through attributing motion to a much smaller body contained within that framework.[43]

Copernicus's arguments are best read as probable arguments from comparative simplicity and harmony. His arguments had force, even if they were not conclusive. One may even say that they had empirical support, insofar as they explained previously known phenomena that Ptolemy could merely save. Thus, Copernicus's invocation of simplicity and harmony may be seen as part of a claim to have provided a systematic account of the phenomena that makes sense of them in a way that Ptolemy could not. Such arguments are notoriously "qualitative" (that is, difficult to formalize). In a sense, they may be regarded as "aesthetic," insofar as they constitute standards of "taste" for choosing among alternative heavenly contrivances, but the aesthetic is that of the unified, coherent, physically plausible model. His mode of arguing was not metaphysical. If he held an implicit "metaphysical assumption," it was the idea that a systematic account of the configuration of the sun and planets that gives a more comprehensive and unified explanation of planetary phenomena should be accepted as true in preference to its rivals. In Copernicus's context, this amounts to the assumption that the astronomer should attempt to determine the true configuration of the solar system on the basis of a judgment of the physical plausibility of various models, which in fact had been a concern of (some) mathematical astronomers (*pace* Duhem) from the time of Ptolemy. One feels that Copernicus argued not as a metaphysician but as a type of classical mathematical astronomer; his arguments have more the feel of the model-fitter than of the metaphysician.

Contrast this with Johannes Kepler, who was not only a mathematical astronomer but a metaphysician to boot. Here the analysis of Cassirer, Burtt, and others can stand virtually without alteration. They portray Kepler as having metaphysical – even mystical – tendencies in his Platonic–Pythagorean vision of a mathematical universe. Yet they view him as a metaphysician with a difference: "The difference between Kepler and the early philosophers like Nicholas of Cusa who had taught that all knowledge is ultimately mathematical and that all things were bound together by proportion, is that the later thinker insists on exactly applying the theory to observed facts."[44] There was a close interplay between Kepler's metaphysical conceptions and his discoveries concerning the planetary paths. Kepler discovered his first two laws in the context of applying his master hypothesis that the planetary orbits inscribe and circumscribe the five regular (or "Platonic") solids to Tycho's exceptionally accurate data on planetary positions; his third law was discovered as part of his search for the "harmony" of the world system. Moreover, early on he saw the sun, the embodiment of the world-soul, as controlling the motions of the planets by direct influence. This animistic notion of the sun's force came to be displaced by a more physical one. Kepler came increasingly to emphasize the importance of relating the shape of the planetary paths to the forces moving the planets, insisting on the unity of astronomy and physics and holding out the ideal of achieving a "mechanical" explanation of the planetary motions, no longer through the mechanics of crystalline spheres but now of solar forces. In sum, in pursuing his Platonic (or Pythagorean) hypotheses, he brought Tycho's excellent observations to bear, reasoned as a well-trained mathematical astronomer, and sought mechanical or physical explanations of the paths of the planets – none of which was incompatible with the metaphysical motivation and content of his astronomical pursuits.

But why categorize Kepler as a metaphysician and Copernicus

not? Although there are some elements of metaphysical language and argumentation in Copernicus, his arguments for heliocentrism turn upon the comparative advantages of his system in accordance with classical standards for interpreting nature. By contrast, metaphysical arguments are at the core of Kepler's astronomical project: the hypothesis of the five Platonic solids and the claim to have discovered the harmony of the planets. These central aspects of Kepler's astronomical work constitute metaphysical argumentation in two ways. First, they constitute an attempt to bring the transcendent to bear on the physical. Kepler regards himself as having divined God's plan, as having penetrated the essential order of the universe through his sense of geometrical perfection. His search for "harmony" is not simply a search for a coherent system of planetary motions that fit the phenomena (although, following Copernicus, he does search for that); in addition, he seeks a harmony that is expressed as a fit between the planetary paths and his intuitions about the divine sense of proportion and the divine preference for the five regular solids.[45] Copernicus's "harmony" is found *within* the system of planetary motions; Kepler's is found in the relationship *between* the physical system of the planets and a geometrical archetype in the mind of God. Second, we modern readers are likely to regard Kepler's mode of argumentation as metaphysical, inasmuch as he attempts to give an account of the relationship between the mind and reality that would explain how he (or anyone else) could get things right. And Kepler himself explicitly labeled this account "metaphysical," although whether he did so for our reasons is not clear. In any case, in Book IV of the *Harmonice* he gives an extended account of the sense of geometrical harmony, explicitly relating his doctrine to a Platonic conception of geometrical archetypes in the minds of both creator and creature, as expressed in the *Timaeus*. He holds that because our sense of harmony reflects the divine sense, we are in a position to intuit the divine blueprint. He came to interpret the arguments of his earlier *Mysterium* in the same manner.[46] Thus Kepler not only argued on the basis of transcendental harmony and perfection; he also attempted to establish a priori that such arguments can succeed.

In comparison with Kepler's own direct avowal and development of his metaphysical position, Copernicus's quotations from literary and philosophical sources to second his astronomical position read like isolated allusions scattered among the primary arguments. And indeed (lest anyone think that this is simply an anachronistic reading), Kepler himself explicitly distinguished Copernicus's style of argumentation from his own. Thus, he characterized his arguments for the earth's motion as "physical, or rather metaphysical," by contrast with Copernicus's "mathematical arguments," tendered "a posteriori."[47] This distinction between "metaphysical" and "mathematical" is decidedly not the familiar distinction between the belief (shared by Kepler) that astronomy should seek to discern the true physical constitution of the universe and the attitude (common in the late sixteenth century) that astronomy should aspire merely to the mathematical calculation of apparent planetary positions. Kepler well knew that Copernicus had considered his mathematical devices to express the true constitution of the solar system. Here Kepler is distinguishing between his own mode of arguing for a particular picture of astronomical reality and that of Copernicus. On several occasions Kepler reconstructed those of Copernicus's arguments for the reality of his system that were based on its superiority as an explanation of the planetary motions.[48] Kepler endorsed those arguments and went on to offer his own original arguments, which he considered to be of a different genre – that is, "metaphysical" rather than "mathematical." By Kepler's lights, Copernicus argued for the physical reality of the heliocentric system on "a posteriori" grounds – that is, on the basis of explanatory superiority – while Kepler himself added "a priori" arguments, based on insight into the divine plan.

Nonetheless, it must be reiterated that Kepler was a metaphysician with a special quality: He was willing to put his metaphysical conjectures to the test and to reject them if they would not fit the astronomical data.[49] This willingness to consider the possibility of an empirical refutation of a metaphysical result may seem odd to us, since we are likely to see the metaphysical, following Kant, as that which not only is known independently of sensory experience but in fact is brought to experience by the knower, and which therefore it would not make sense to test; or, following Burtt and Whitehead, as those presuppositions that are so deeply held that they become invisible to their adherents and so specifically could not be put to test; or, perhaps, with other writers, as those groundless presuppositions, based in philosophy or religion, that prejudiced thinkers refuse to test. This seeming oddness reveals the distance between our post-Kantian conceptions of metaphysics and historically actual sixteenth- and seventeenth-century conceptions. For not only do we find a willingness to mix the metaphysical and the empirical (or the empirically conditioned) in Kepler; we also find it in Descartes, who is the very paradigm of a metaphysician claiming to establish his results independently of the senses.

Descartes: Metaphysician and natural philosopher

Among the early adherents of the new science, Descartes alone developed a systematic metaphysics. In this way he differs from Kepler, whose metaphysical argumentation was directed specifically toward astronomical knowledge or its foundations. Descartes's metaphysics not only aimed to provide the basic principles of his physics, but it also spoke to a broader set of issues, such as the status of the embodied soul, the legitimacy of sensory knowledge, and the source of certainty as well as the remedy for error in judgment. His metaphysical writings were of interest to later authors such as Spinoza, who were not primarily concerned with natural philosophy, and they have retained their interest for philosophers long after the demise of Cartesian physics.

That Descartes attempted to found his physics on his metaphysics is well known. Burtt's account of this attempt is accurate in its emphasis on the centrality of mathematics in Descartes's thought, on his geometrical characterization of the material universe, and on his mind–body dualism. However, Burtt's account seeks to explain these aspects of Descartes's thought by uncovering the "biographical reasons" and "logical prejudices" behind his positions; Descartes's own argumentative structure is pushed aside.[50] Burtt's account thus does not explore Descartes's own conception of metaphysics nor its relation to the dominant conceptions of metaphysics in his day. Although other philosophers have done much to illuminate Descartes's metaphysical arguments, including those purporting to ground his physics, little attention has been paid to his own conception of metaphysics in its historical context.[51]

By Descartes's account, the metaphysical portions of his published writings were the *Meditations on First Philosophy* and parts of the *Principles of Philosophy*. In what sense are these works metaphysical? They fit each of the conceptions of the subject matter and role of metaphysics discussed earlier: They examine divine or immaterial beings – God and the soul – that transcend the physical; they give a general account of being, dividing all being into three substances (one "true substance" – God – and two created substances – mind and matter); and they provide the "first principles" of Descartes's natural philosophy, in the doctrine that the essence of matter is extension, and some of the specific principles of his physics, in the three laws of motion.[52] But the two works are metaphysical in an additional sense, which does not precisely fit earlier conceptions of metaphysics. They contain a general account of knowledge and the knowing mind. Descartes sought to derive his results about the subject matter of metaphysics from what he termed the "principles of knowledge," and in particular from the principle that whatever is clearly and distinctly perceived by the intellect (operating independently of the senses) is true.[53] In taking the investigation of the knower as his metaphysical starting point, Descartes offered a new conception of metaphysics. For although Plato and Aristotle each had things to say about the knower, neither of them placed the investigation of the knower prior to the investigation of being itself, and while Kepler used his inquiry into the knower's sense of geometrical harmony to explain how a mere human could intuit the divine plan, he did not develop this inquiry into a general metaphysics. In the *Meditations*, the doctrine of being arises out of an exploration of knowledge of being, which is not to say that metaphysics comes to rest upon epistemology but that method becomes a central metaphysical concern – to such an extent that an appeal to a priori intuition later became a defining feature of metaphysics (whereas it had not been a part of Aristotelian metaphysics).[54]

Although Descartes fits the historically situated category of "metaphysics" in several ways, it is unclear where he should be placed with respect to the two chief historical traditions of metaphysics, Platonic and Aristotelian; he partakes of elements of each tradition, while exactly fitting neither.[55] There are two elements of the high scholastic Aristotelian tradition in Descartes: his terminology, and his conception of metaphysics as the fundamental science of being. Although he rejected or was silent on such scholastic Aristotelian terms as "substantial form," "genus," "species," and "differentia," along with the apparatus of Aristotelian logic, his basic metaphysical terminology remained scholastic: "substance," "essence," and, on occasion, "form," as well as more arcane terminology such as "objective reality," "formal reality," and "eminent reality."[56] In using this terminology to construct a metaphysical system, Descartes continued the Aristotelian emphasis on substance in the analysis of being. Yet, at the same time, he broke the rules of Aristotelianism, for example, by assigning to material substance the passive essence *extension:* In the Aristotelian conception, essences or natures are active principles of change, and extension is an "accident" of natural substances.[57]

In addition to this aberrant conception of natural substance, Descartes gave a non-Aristotelian picture of how the essence of substance is known. According to the Aristotelian conception of philosophical cognition, knowledge of essences is achieved by a process of intellectual abstraction from sensory particulars. Intellectual intuition plays a central role but only when fed by "images" from the senses. In Descartes's account of clear and distinct intellectual perception, primary knowledge is attained independently of the senses and imagination. For Aristotelians, even being qua being can be known only by a process of abstraction, just as specific substances are known. According to Descartes, pure rational intuition provides knowledge of the essence of material substance.[58]

His intuitionist account of knowledge, together with his emphasis on geometrical properties as constituting material substance, no doubt explains why Descartes is sometimes designated a Platonist. However, Descartes's actual metaphysics forsakes a mainstay of Renaissance Platonism: the doctrine that the eternal truths as known by man reflect *archai* in the mind of God, with the implication that the material world should be understood by reference to such *archai*. Descartes effectively separates knowledge of the material world from knowledge of the divine mind in his adherence to the doctrine that God's creation of the eternal truths depended solely upon the divine will and hence was not conditioned by antecedently given intellectual constraints.[59] Indeed, it might be argued that this was one of the significant contributions of Descartes's conception of knowledge, for it allowed him to separate questions pertaining to natural philosophy and its first principles from theological doctrine or speculation. Although notorious for making human knowledge depend upon a "divine guarantee," and although (as we shall see) he called upon a notion of the deity as "first cause" in his account of the laws of motion, it remains that he separated the substance of natural knowledge from knowledge of the divine. Unlike Kepler, he was not trying to re-intuit the divine plan.

Descartes remarked more than once that his metaphysics contained "all the principles" of his physics and that his physics was "nothing but" geometry.[60] The sense of the latter phrase is ambiguous. It may be taken as a reference to his geometrical *methodology*, in accordance with his emphasis, in the *Discourse on Method* and elsewhere, on deriving all conclusions by means of self-evident small steps from self-evident principles. It may also be read as a statement about the geometrical *content* of his account of nature. While acknowledging the acceptability of the first reading, I will emphasize the second in my examination of Descartes's use of metaphysics to ground physics. I hope thereby to shed light on the senses in which Descartes's account of nature was "mathematical."

In one use of metaphysics to ground natural philosophy, Descartes explicated the cognitive procedure through which essences are known (clear and distinct intellectual perception) and proceeded to determine the essence of matter. The metaphysical doctrine that the essence of matter is "pure quantity" (understood geometrically as pure extension) then provides a framework for his natural philosophy. The conception of matter as "pure extension" leads to the view that the primary properties of matter are the modifications of an extended expanse, divided into shaped portions of specific sizes that have specific positions and motions with respect to one another – that is, to the view that matter is wholly describable in terms of the geometrical properties of size, shape, position, and motion. These properties are "quantitative" inasmuch as, say, size or volume is a quantitative notion, but Descartes's geometrical conception of matter does not necessarily lead to a "quantitative" approach to nature of the sort that we are likely to associate with the early modern period; it does not lead to a notion of nature as governed by quantitative laws and of scientific reasoning as principally concerned with mathematical derivation. The idea that the essence of matter is extension guarantees only that the fundamental properties of every particle of matter can be described geometrically, not that the instances or values of the properties are lawfully related to one another. And indeed, in Descartes's mature natural philosophy the ultimate emphasis is on mechanisms, not laws. His account of matter as extension worked to provide a conceptual environment conducive to the analysis of natural objects and processes "mechanically" – that is, in terms of the configuration and motion of their constituents. In this context, "mathematization" amounts to "mechanization."[61]

Of course, a mechanistic account of nature such as Descartes's is unthinkable unless it is supposed that matter in motion moves with lawful regularity, and Descartes did invoke the required regularity in his three laws of motion and seven rules of impact. These laws are cast in quantitative terms – as relations between the fundamental magnitudes, "quantity of matter" and speed. But the possibility of such quantitative laws is not established by the doctrine of extension, even if this is taken to include the idea that motion is a geometrical (kinematic) property and hence is a "mathematical" property; a kinematic (purely descriptive) treatment of motion does not prescribe laws of motion, nor even entail that the patterns of motion in the world should be describable by simple laws. In a second use of metaphysics, Descartes went outside the notion of matter as extension and introduced God as a "dynamic" element to fix these laws: The laws are understood as a manifestation of God's immutability; specifically, of his conservation of the same quantity of motion in the material world as at the creation. The metaphysical appeal to divine immutability allows a conceptual home for causal agency in the face of the doctrine that matter is pure extension and therefore inert. Here, metaphysics seems to be used directly to establish quantitative laws,

although the "derivation" of the laws from divine immutability is not particularly tight. Moreover, the laws themselves must be understood as God's prescriptions in accordance with his immutability, not as descriptions of "force" as a fundamental magnitude inhering in matter.[62]

The role of metaphysics, including metaphysical appeals to the deity, is thus quite complex in Descartes. He does appeal to the deity in order to establish a "fit" between mathematical knowledge and nature, by invoking the divine guarantee of clear and distinct perception, under which falls the perception of matter's essence. This is not, however, a claim pertaining to the content of God's intellect, but to the divinely established relation between human mathematical cognition and a world of material objects that exists independently of the human mind. In addition, he appeals to a divine attribute – immutability – to ground the laws of motion. Here he does claim to grasp the natural through the divine, but his appeal is less to a knowledge of God's providence than to a conception of the deity as a "first cause."

Despite his far-reaching appeals to metaphysics, there was also an empirical side to Descartes. For, while he believed that metaphysics could provide the fundamental tenets of physics, he also maintained that one cannot derive all of physics a priori from these tenets. This aspect of Descartes's attitude toward natural philosophy has often been missed, and with good reason. Descartes maintained the futility of seeking empirical manifestations of the laws of motion and, notoriously, dismissed Galileo's law of fall.[63] Moreover, he claimed to know his laws of motion a priori, and to our post-Newtonian sensibilities it is likely to seem that once one has established the laws of motion, the lion's share of the work has been done. For if Newton's laws could be established a priori, it would seem of small consequence that, say, the masses of individual bodies could not be. But in Descartes's mechanistic account of natural phenomena such as magnetism or plant growth or the properties of water, it is precisely the properties of individual bodies (or types of body) – say, the configuration of their particles – that does the chief explanatory work. Yet the a priori "fit" between mathematical cognition and nature reveals only that the fundamental properties of matter are geometrical; it does not disclose which specific geometrical properties are possessed by which bodies. Interestingly, Descartes's infamous claim to "deduce" all natural phenomena from his first principles leads to the conclusion that the correct explanations of particular phenomena cannot be known a priori, once it is seen that the same phenomenon may be "deducible" in more than one way. Too many worlds are consistent with the vision of matter in motion to permit derivation of the details of this world a priori, even if one is given a list of (empirically obtained) phenomena to be accounted for (for example, astronomical data and meteorological, animal, plant, and mineral phenomena). Multiple explanatory accounts are consistent with the first principles, and so the best that one can do is to put forward one or more hypotheses and consult experience in the hope of finding evidence favorable to one or another of them. But owing to the difficulty of choosing among alternative hypotheses, only "moral" certainty is available, and so Descartes must allow that the truth or falsity of many of his particular mechanistic explanations cannot be ascertained with absolute certainty.[64]

On some occasions, Descartes extended the scope of his attempted empirical justifications to the mechanistic mode of explanation in general. Thus, in the *Meteors* and his subsequent letters of 1638, as well as in *The World*, Descartes argued for the superiority of a mechanistic conception of the universe on grounds that he characterized as a posteriori, as opposed to a priori.[65] These "a posteriori" arguments appealed to the superior clarity, simplicity, and explanatory power of explanations framed in accordance with the mechanistic hypothesis; they asserted that, on the whole, mechanistic explanations do a better job of coming to grips with the phenomena than their Aristotelian counterparts.[66] The oddity that we find in the suggestion that metaphysical tenets such as those underlying Descartes's physics might be given or subjected to empirical verification should not lead us to view Descartes's practice as internally contradictory. For he did not view metaphysical tenets as untestable assumptions or as constitutive of experience. Rather, he viewed metaphysics as providing knowledge about a mind-independent world, of the highest degree of certainty; but because this knowledge pertained to a mind-independent world, it therefore might be contradicted by evidence showing that the world was other than that indicated by his first principles.[67]

Descartes provides a paradigm of what it was to argue metaphysically in the early modern period. He argues for a version of the "nature of reality" in an a priori manner, on the basis of an account of the knowing subject and with the aim of achieving absolute certainty. He claims to have penetrated to the essences of things and to have provided a basic taxonomy of being. His metaphysics provides a general account of the created world: It includes everything that exists, considered generally, within its subject matter. From the point of view of physics, metaphysics provides an external source for the knowledge of the general categories of physics and also for the specific laws of motion that govern interactions among bits of material substance. Descartes the metaphysician (ostensibly) provides the basic justification for the concepts and modes of explanation to be employed by Descartes the natural philosopher, as well as part of the specific content of natural philosophy, in the form of the three laws of motion. And he does all of this by explicitly engaging in metaphysical activity, with the aim of establishing a permanent framework for knowledge.

Galileo: Philosophy without metaphysics

Our examination of metaphysics and mathematical science in three major authors has revealed no unified metaphysics for the new science. Copernicus did not engage in metaphysics; although a few metaphysical-sounding phrases occur in his writing, the force of his arguments derives from considerations proper to the mathematical astronomer whose aim is to discern the true configuration of the heavens. His allegedly metaphysical proclivity for simplicity and harmony may better be seen as the application of criteria of judgment that were embedded in the practice of this type of mathematical astronomy. Kepler also engaged in mathematical astronomy of the Copernican sort, with the difference that he replaced the physics of crystalline spheres with that of solar forces. But he brought what he considered to be an additional, and perhaps primary, source of knowledge to bear on his astronomical pursuits: metaphysical knowledge derived from an attempt to re-intuit God's geometrical blueprint for the universe. Descartes was a systematic metaphysician who sought to ground the first principles of his natural philosophy in his metaphysics. These principles included a conception of matter as "geometrical," which was conducive to a mechanistic approach to nature, and a proposed set of quantitative laws of motion. If I am correct, there was no unified metaphysical foundation for the new science, and certainly none for the application of mathematics to nature; indeed, there was not even a unified mathematical approach to nature that might have been supplied with such foundations.

None of the categories used to characterize Copernicus, Kepler, and Descartes – mathematical astronomer, Neoplatonic metaphysical mathematical astronomer, and original metaphysician (with an eye on natural philosophy) – provides a fully adequate characterization of Galileo. He may be viewed as a mathematical scientist, inasmuch as he continued the type of mathematical science pursued by Copernicus (and sometimes by Kepler). But he was more than a mathematical scientist; for while Copernicus simply pursued mathematical astronomy, Galileo, in repeating and elaborating Copernicus's arguments for heliocentrism and adding some of his own, not only presented those astronomical arguments but also reflected upon their form and status. Rather than simply presenting a bare treatise pertaining to a given mathematical science (as had been the norm from Euclid to Copernicus), he attempted to establish the appropriateness of a mathematical approach, not only to astronomy, but to other domains of nature as well (including motion, the home turf of Aristotelianism). Such discussions add a philosophical dimension to his work. Yet they are not metaphysical, either in form or content, and he was not a metaphysician of either the Keplerian or Cartesian variety. Galileo did not compose a methodological treatise or attempt to develop a systematic metaphysical-theoretical framework to support mathematical science; rather, his reflections and his justifications occur as he engages in the practice of mathematical science. This is most obvious in the *Discourses and Mathematical Demonstrations Concerning Two New Sciences*, which contains a treatise on motion laid out in the form of mathematical (Euclidean) demonstration and written in Latin, surrounded by commentary in Italian written as dialogue and containing explication of, reflections on, and replies to objections to the treatise; a similar conjunction of demonstrative argument with methodological reflection occurs in the *Dialogue Concerning the Two Chief World Systems* and in many of his polemical writings. Let us examine the character of these discussions and their philosophical dimension, while exploring the senses in which Galileo was not a metaphysician.

Galileo: Platonic, Aristotelian, or neither?

In my view, the traditional approach of treating metaphysics as a set of implicit presuppositions goes farthest wrong on Galileo. It has been customary to assign Galileo a Platonic metaphysics to explain his insistence on a mathematical approach to nature. More recent interpretations, while recognizing that Galileo was not a systematic metaphysician, persist in attempting to assign him to one or another metaphysical tradition: Platonic, Aristotelian, or to a mixture of the two. I think, however, that it is better to resist assimilating him to a background metaphysical tradition, not because early modern thinkers never presupposed metaphysical tenets that they absorbed from their background, but because such assimilation masks Galileo's philosophical achievement. Galileo's distinctive philosophical contribution to the rise of the new science was to show how one can seek to establish the appropriateness of one type of approach to natural science over its competitors without first establishing a metaphysical framework as foundation and support.[68]

The Platonist interpretation of Galileo's work has had numerous adherents, among whom Cassirer, Burtt, and Koyré are perhaps most prominent.[69] There are three aspects of Galileo's work that are taken as evidence of Platonism. First, there are the various Platonic trappings: his numerous allusions to Plato, as well as to a pseudo-Platonic cosmological myth, and his choice of the dialogue form for his chief works. Then there are his allusions to the Socratic method and to the doctrine of reminiscence, which have been taken as evidence that Galileo held to an apriorist conception of scientific method. Finally, there is his general hankering for mathematical descriptions and geometrical demonstrations, together with his declaration that the book of nature is written "in mathematical language," which has seemed to reveal his commitment to a mathematical ontology.[70]

Against this Platonist interpretation, others have argued that Galileo's mathematical approach to nature should be seen in the context of the Aristotelian attitude toward the mixed sciences. A. C. Crombie and William Wallace, especially, have argued that Galileo's conception of scientific method was formed through his contact with the methodological writings of the Jesuits at the Collegio Romano.[71] Their respective analyses of Galileo's early notebooks on Aristotelian physics and logic have established that much of the notebooks' content was derived from work originating at the Collegio. Each has argued that these notebooks do not merely show Galileo's familiarity with the Aristotelian conception of science as demonstration, and with the associated methodological problems, but also indicate a "philosophical stance" that guided him throughout his mature career, as evinced by his continued use of key terms associated with Aristotelian methodology. This stance allegedly extended beyond the conception of science as demonstration to the Aristotelian search for causes and to a conception of mathematical science in accordance with the Aristotelian notion of the mixed sciences, which, together with the example of Archimedes' various mathematical treatises (perhaps as interpreted at the Collegio), formed Galileo's basic attitude toward the application of mathematics to nature.

Of these lines of argument for Galileo's Platonism or Aristotelianism, the most important is the claim that Galileo manifested either a Platonic or an Aristotelian conception of knowledge and of the place of mathematics in nature and natural philosophy. Galileo's allusions to Plato, and his use of dialogue and of a pseudo-Platonic myth, might be part of a larger commitment to Platonism, or they might better be read simply as the use of allusion and of a literary genre for his own purposes. Similarly, his copying of Aristotelian treatises and his use of Aristotelian terminology could be taken to reveal deep Aristotelian commitments, or they might rather be viewed as the study and subsequent employment of a common philosophical corpus and terminology for his own ends. A decision about how to read various local passages and what to make of the dialogue form or the Aristotelian terminology must await a decision about the controlling conceptions of nature and our knowledge of it. Hence it is to these conceptions that we must turn.

Evidence for a Platonic conception of human knowledge has seemed easy to find in Galileo. One frequently cited passage occurs at the end of the First Day of the *Dialogue*. Salviati (Galileo's spokesman) makes the bold pronouncement that with respect to those few propositions of the pure mathematical sciences that are known by the human intellect, "its knowledge equals the Divine in objective certainty." One can see how this phrase, in isolation, might be taken as a reference to a Platonic theory of knowledge, in which man's knowledge coincides with divine Ideas. However, its effective role in the surrounding dialogue is to underscore the doctrine that in mathematical demonstration one achieves the highest certainty possible, and the quoted phrase continues in exactly that vein: "Its knowledge equals the Divine in objective certainty, for here it succeeds in understanding the necessary, beyond which there can be no greater sureness."[72] Galileo does not elaborate on this "necessity" and seems to have meant no more than that it represents the highest degree of certainty that propositions possess. And he does not, any more than had Euclid or Archimedes, present a theory of this certain knowledge (as did Descartes and Kepler); he simply accepts mathematics as the paradigm of certainty and holds it up as such at various points in his writing.

The most striking and most frequently discussed instance of Galileo's alleged Platonic conception of knowledge occurs in the Second Day of the *Dialogue*, where Salviati announces to Simplicio (the spokesman for Aristotelianism) that he knows, prior to any observation, that a rock dropped from the mast of a uniformly moving ship will fall at the foot of the mast: "Without experiment [*esperienza*], I am sure that the effect will happen as I tell you, because it must happen that way; and I might add that you yourself [Simplicio] also know it cannot happen otherwise, no matter how you may pretend not to know it – or give that impression."[73] This passage has been taken to support the view that Galileo, far from being the father of the modern empirical approach to nature, actually subscribed to a "rationalist" or apriorist conception of scientific method, for Salviati's boast that he will draw the conclusion out of Simplicio appears to be a clear instance of the Platonic method of interrogation and the doctrine of anamnesis.[74] It will be useful, first, to examine Galileo's (Salviati's) further explicit pronouncements on the doctrine of reminiscence, and then to consider the actual character of the arguments he constructed for this "a priori" prediction of the outcome of the mast experiment.

Perhaps the strongest support for Galileo's direct avowal of the doctrine of reminiscence occurs in the following interchange between Salviati and Simplicio, which immediately follows the discussion of the mast experiment and related problems:

> *Simp.*: I have frequently studied your manner of arguing [*ragionare*], which gives me the impression that you lean toward Plato's opinion that *nostrum scire sit quoddam reminisci* [our knowledge is a kind of reminiscence]. So please remove all question for me by telling me your idea of this.
>
> *Salv.*: How I feel about Plato's opinion I can indicate to you by means of words and also by deeds. In my previous arguments I have more than once explained myself with deeds. I shall pursue the same method in the matter at hand, making it easier for you to comprehend my ideas about the acquisition of knowledge [*scienza*] if there is time for them some other day.[75]

There is no doubt that here Galileo has Simplicio directly attribute a Platonic doctrine to Salviati, and additional evidence along this line is not hard to find. Nonetheless, we must ask whether these Platonic *allusions* in Galileo's work are woven into a Platonic *conception* of our knowledge of nature. It is true that Salviati repeatedly tells Simplicio that he is simply drawing from him things that he already knows, through a process of "interrogation"; whether these statements amount to the Platonic doctrine of reminiscence is, however, another question, and one about which Salviati says his opinion has been and will be expressed through his deeds. In order to determine what Salviati has shown about his manner of arguing, then, we must examine his previous arguments and those of the ensuing discussion.

The succeeding interchange between Salviati and Simplicio provides an immediate clue to Salviati's attitude toward Simplicio's attribution to him of the Platonic doctrine of reminiscence. His attitude turns out to be ironic. The passage that I have quoted is preceded by Salviati telling Simplicio that he will cause him to resolve the objection of "extrusion" – the prediction that if the diurnal rotation of the earth were real, objects would be cast off from the earth's surface – by means of "data well known and believed by you just as much as by me," the significance of which Simplicio had failed to see ("Because they do not strike you, you do not see the solution"). It is followed by Salviati focusing on a particular example of extrusion, in which a small boy casts a stone by whirling it around in a notch near the end of a stick. At Salviati's bidding, Simplicio affirms that when the stone is in the notch, its path of motion is a circle around the shoulder of the boy. Salviati then asks what path it follows upon being cast:

> *Simp.:* It certainly does not go on moving around, for then it would not fly away from the thrower's shoulder, and we should not see it go extremely far.
>
> *Salv.:* Well, then, what is its motion?
>
> *Simp.:* Let me think a moment here, for I have not formed a picture of it in my mind.
>
> *Salv.:* Listen to that, Sagredo; here is the *quoddam reminisci* in action, sure enough.[76]

Salviati's response is openly ironic, but what does the irony reveal?

To begin with, we must ask where reminiscence is in action and what it is. A first glance suggests that it involves pausing to recall a specific instance of the type of phenomenon under examination ("data well known") and to imagine concretely or to picture the instance (in order to "see the solution"). Perusal of Salviati's previous arguments confirms both of these impressions. In the previous fifty pages, he has again and again offered (or accepted from Sagredo) concrete instances, based on experience shared by all three: rolling a ball down or up an incline, observing the inability of the wind to move a heavy object on a table, throwing a heavy ball and a wad of cotton, rolling a hoop, shooting an arrow, propelling a ship with oars, observing the flies that persistently follow a moving horse, and swinging a string with an object tied to one end. He had his conversants imagine numerous other concrete cases, such as the flight of arrows shot from a moving carriage, various cannon shots, and the motions of a menagerie traveling below deck on a ship. In some cases he specifically directs the group to imagine (*figurare*) a situation, and on some occasions he introduces a figure of his own to aid their comprehension.[77]

From these examples of Salviati's "deeds," together with the tone of his response to Simplicio's suggestion that he holds a key Platonic doctrine, it becomes apparent that Salviati has put considerable distance between himself and the Platonic doctrine of reminiscence, in which one recalls an earlier experience of directly apprehending the eternal Forms (perhaps before one's soul has become embodied). Even a less literal reading of Platonic reminiscence suggests something quite different from the reminders involved here, for Salviati's (and Sagredo's) reminders are of previous sensory experience or involve the exercise of the imagination on everyday sorts of objects and events,

which places them in direct opposition to the Platonic emphasis on pure intellectual intuition over the senses and imagination.[78]

While it is safe to conclude that the doctrine represented by Salviati is not Platonic, it is more difficult to give it a positive characterization. Clearly Galileo's conception of how one acquires knowledge (*scienza*) is not that one simply recalls various previous experiences or imagines objects with which one has had experience. He has Salviati *say* that he will cause Simplicio "to resolve the objection by merely recalling" some facts that Simplicio knows but has not been struck by. In practice, Salviati must not only get Simplicio to *recall* relevant instances; he must also get him to *see* their relevance and to *draw* the right conclusions. Salviati and Sagredo both emphasize that Simplicio must come to grasp their arguments for himself – an act that surely must involve something more than mere recollection, and regarding which they assure him that he has the needed ability.[79] One clear suggestion of the source of this ability comes early in the discussion of the mast experiment. Salviati plays devil's advocate against Simplicio, maintaining that a ball released on an inclined plane will remain stationary. When Simplicio repeats his assertion that the ball will roll, Salviati responds: "And you take this for granted not because I have taught it to you – indeed, I have tried to persuade you to the contrary – but all by yourself, by means of your own common sense [*giudizio naturale*]."[80] This interchange occurs just after Salviati has decided to draw a conclusion out of Simplicio by "interrogation." Hence *giudizio naturale* – natural discernment, natural judgment, or "common sense" – appears to be the means for achieving those conclusions that are based upon recollection of specific instances.

Yet this answer is by itself unsatisfying, for it does not seem to capture everything that is going on when Salviati extracts conclusions from the unwilling Simplicio, or even from the eager Sagredo. The conclusions seem too articulate, the reasoning too robust to be derived from unguided *giudizio naturale*. Salviati asks more than recollection and common sense from Simplicio; beyond asking him to consider the relevant instances, he requires him to think about them correctly, and this, in instance after instance, amounts to getting him to think about them geometrically. Salviati demands "common sense" that is guided by geometrical reasoning and applied to images, figures, or diagrams. And while these images or figures are not merely recalled, neither are they created ex nihilo by pure reason. Rather, they are constructed by fitting a geometrical figure to facts known from experience.

This point is illustrated by the continuation of the passage on casting stones. Simplicio's "picture" of the impelled stone, produced through "recollection," suggests a geometrical diagram. There need be no doubt that his picture is geometrical, for Salviati intervenes to teach him "the words" for "the truths" that he has discerned by himself, and these words are geometrical (e.g., "tangent," "arc").[81] Of course, Simplicio's ultimate conclusion that the stone leaves the notched stick along a tangent is a sophisticated achievement, and he gets considerable prompting from Salviati in forming this geometrical picture. Specifically, Salviati prompts him to fit a geometrical construction to the fact that the stone, in leaving the stick, flies away in a straight line that must be generated from the last portion of its circular path.[82] In this case, then, geometrical reasoning is employed to bring order to facts known through experience. And indeed, when Salviati reviews what Simplicio has been shown to know through reminiscence – the tangential path of the projectile and the curve in this path as the object falls to the ground – he remarks that the latter is known because "all heavy bodies tend that way,"[83] which is another appeal to shared experience. Hence, in this passage (to which numerous others could be added), Simplicio's "recollection" amounts to the application of the geometrically trained, empirically constrained imagination to various cases in which a crucial proposition might be exemplified or tested.

The notion of a geometrically *trained* imagination can bear emphasis. Part of the task that Galileo faced in gaining acceptance not only for the Copernican system but also for his own sciences of materials and of motion was a resistance to the mathematical approach to nature. In order to get a fair hearing from (at least part of) his audience, he needed to replace what he characterized as their philosophy of "words" with an appreciation of the force of arguments cast in the form of geometrical demonstration. For this reason, both the *Dialogue* and the *Two New Sciences* constitute attempts to propagandize on behalf of mathematical science. This "propaganda" ranges from the simple praise of "demonstrative science" over the terminologically based arguments presented by Simplicio, to the commendation of the study of mathematical works in exclusion of logical ones for the purpose of learning the art of demonstration, to repeated instances of showing, often by simple example, the usefulness of applying geometry to both practical and theoretical problems – instances that often evoke a laudatory outburst from Sagredo or Simplicio.[84] Although this repeated praise of geometry and emphasis on its pedagogical value might seem to reaffirm Galileo's alleged Platonism, it is interesting to note that the characterization of Plato as a supporter of geometry or mathematics is thrice put in the mouth of Simplicio, and once in the mouth of Sagredo, but never in the mouth of Salviati,

who simply defends the importance of geometry and geometrical demonstration, saving his praise for Euclid, Archimedes, and Copernicus.[85] Put together with his ironical attitude toward the Platonic doctrine of reminiscence, Salviati's remarks on geometry appear as the remarks of one who is teaching the value of the mathematical approach to nature through instances of its practice, rather than the remarks of one who has a Platonic appreciation of pure geometrical intuition.

Even if Galileo's appeal to reminiscence does not attest a Platonic theory of knowledge, there remains the problem of the actual basis of his "a priori" prediction of the outcome of the mast experiment. Examination of the subsequent discussion shows that Salviati does not purport to establish the result a priori in the modern philosophical sense – that is, independently of sensory experience. Rather, he claims merely to establish the result "a priori" as scientists today sometimes use that term – to mean "before the observation is made." His claim rests upon the application of general principles to the "experiment" (imagined event): the principle of indifference to motion about the center of the earth ("circular inertia"), and the notion of "impressed force," which together lead to the conclusion that when the stone is dropped from the mast, it will, by virtue of its shared motion with the ship, move along with the ship and, losing little or no ground because of air resistance, will fall at the foot of the mast. Salviati's claim, then, is based upon the application of two principles – the principle of indifference to horizontal motion and the principle of the conservation of impressed force – to the "mast experiment" prior to the event.

This conclusion immediately raises the question of how these principles are known. Salviati's arguments are in fact quite complex, for, as Paul Feyerabend and others have pointed out, he must not only establish the notions of "circular inertia" and impressed force but also the notion that impressed and "natural" (in this case, downward) motions can be compounded, which, along with the first two notions, was contrary to Aristotelian doctrine.[86] The arguments involve appeal to common experience, as well as to additional imagined outcomes. Some of the work is quite easy – as when Salviati seeks to establish the viability of the notion of "impressed force" by demolishing the Aristotelian doctrine that the medium is what causes a projectile to remain in motion once it has left the thrower's hand. The idea of the "indifference" to motion along the horizontal is established by interpolation from the fact that the least downward or upward tilt is sufficient to facilitate or hinder a ball's motion, to the conclusion that on the horizontal the ball is indifferent to motion. These arguments are not unproblematic, and they do involve additional suppositions.[87] But their presentation involves constant appeal to commonly observable events as evidence, and thus by no means takes place independently of appeals to sensory experience.

The style of argumentation employed by Galileo in his discussion of the mast experiment has been characterized by several authors as an argument *ex suppositione*, or from a supposition. As explicated by Jesuit philosophers and mathematicians at the Collegio Romano, such argumentation proceeds demonstratively (in either geometrical or syllogistic fashion), from a given supposition to a conclusion. The conclusion having been established as following with necessity from the supposition, the status of the supposition then becomes the focus of attention. In discussions of this type of argument, a variety of attitudes toward the supposition were regarded as appropriate, depending on the circumstances. Thus, in a didactic setting, the supposition might be proffered as capable of demonstration, but the student might be asked to accept it on faith. For the mathematical scientist who believed a supposition to be true, at least three attitudes were possible: He might regard the supposition as self-evident; he might regard it as demonstrable from other accepted principles; or he might regard it as something that could be established on the basis of experience.[88] The predicted outcome of the mast experiment was not advanced as self-evident; given the alternatives, it must therefore have been seen as following from suppositions which themselves had been established either by appeal to experience or by appeal to other accepted principles.

Those who seek to assimilate Galileo to Aristotelianism contend that argument *ex suppositione* formed the core of Galileo's conception of scientific method throughout his career, putting him in lifelong debt to the methodological discussions of the Jesuits at the Collegio Romano, and hence to Aristotelian philosophy.[89] In evaluating this contention, it is important to distinguish several points. To begin with, the attitude toward mathematical science that Galileo allegedly inherited from the Collegio must be distinguished from full-fledged Aristotelianism, as Wallace has been careful to observe.[90] The central features of Aristotelian philosophy are simply absent from Galileo's writings. Thus, although he sometimes adopts causal language, one does not find a systematic use of the Aristotelian four causes; his restriction of the investigation of motion to "local motion" ignores the Aristotelian investigation of motion as a principle of qualitative change; and his few remarks on the operation of the senses run counter to an Aristotelian account. Moreover, he explicitly rejects the Aristotelian logic, doctrine of motion, and concern with substances,

essences, and qualities.[91] There is, then, no question of attributing a full-fledged Aristotelian philosophical stance to Galileo.

Even so, the question remains of whether Galileo's attitude toward the demonstrative sciences was derived from sources at the Collegio. Here, it is important to distinguish the possibility that the Collegio was one of the sources of Galileo's understanding of the mathematical sciences from the claim that Galileo's understanding was the same as that of the Collegio. What seems to be an Aristotelian doctrine need not be. Thus, Galileo seems to echo the Aristotelian doctrine of abstraction by regularly distinguishing between what can be demonstrated "in the abstract" and what applies to actual material bodies; however, these references to mathematical results "in the abstract" are more plausibly interpreted in connection with the mathematical practice of assuming perfectly straight lines without breadth and absolutely flat planes without thickness. Indeed, as Wallace himself has argued, Galileo's attitude toward mathematical idealization is an advance beyond any position known to have been available at the Collegio and is perhaps best seen as an extension of Archimedes' approach to mathematical science.[92] If we now recall Galileo's frequent praise of practicing mathematical scientists and his early acquaintance with their writings, it seems natural to explain the fact that both Galileo and the Collegio used *ex suppositione* reasoning and its vocabulary by the fact that both he and a number of the Jesuits, particularly Christopher Clavius and his students, looked to the mathematical sciences themselves for examples of demonstrative reasoning. Galileo's use of *ex suppositione* reasoning need not be taken to reveal a particularly Aristotelian stance toward mathematical science; it may simply show that he was drawing upon the example of earlier mathematical science for his basic conception of scientific argumentation.

As a last attempt to link Galileo with Aristotle, one might argue that Galileo's emphasis on sensory observation should be read as his endorsement of Aristotle's sense-based epistemology over Plato's flights of rational intuition; indeed, Galileo himself insists that on this point he is in agreement with Aristotle's own intention and practice, as opposed to the submissive attitude of later Aristotelians, who quote the master on matters about which they should look and decide for themselves.[93] Hence, if we are forced to assimilate Galileo to either Plato or Aristotle, perhaps we should choose the latter. And yet we could tally roughly an equal number of passages praising reason over the senses and invoking Plato's mathematical approach in preference to Aristotle's qualitative one. Perhaps, then, Galileo should be assimilated to both; or since, if I am right, neither set of passages can be worked into a coherent Platonic or Aristotelian position, perhaps he should be assimilated to that ubiquitous type, the Renaissance eclectic.

It is true that Galileo offers no coherent body of doctrine on the relation of the human intellect to physical reality comparable to that of Descartes, or on the relation between the mind and God's geometrical plan for the universe comparable to that of Kepler. Despite his frequent appeal to geometrical demonstration as the standard of certainty, he develops no theory of geometrical demonstration. In fact, he presents no theory of knowledge at all, in the sense that he gives no systematic account of the knowing activity of the mind and of the mind's relation to the objects known. This aspect of his work has been commented upon often and has been described by saying that Galileo was not a "systematic philosopher" or that he "reads like a scientist" rather than like a philosopher.[94] Typically, this is taken to mean that he has simply absorbed a ready-made philosophical stance, which lies implicit in his work, and, on the basis of the type of evidence reviewed earlier, he is assimilated to a version of Platonism, Aristotelianism, or some combination thereof.

The fact that Galileo did not develop a systematic theory of knowledge or theory of method should not lead to the conclusion that he did not make his own distinctive contribution to the methodology of modern science. For, while he does not have an account of truth in the sciences, he does believe that he can recognize such truth when he sees it and that it will be found in assertions cast in the form of mathematical demonstration and brought sufficiently into agreement with experience. He does not try to convince us of this by a theory of intellectual intuition, sensory abstraction, or the like; rather, he shows it to us, by repeatedly having the characters in his dialogues remark on the usefulness and certainty of mathematical reasoning as they apply it (often with notable success) in their investigation of the Copernican system or the two new sciences. Like Descartes (and Plato and Aristotle), Galileo believes that everyone can and must see the truth for himself.[95] Descartes tries to give an account of this noetic power; Galileo suggests that readers who are not used to discerning things for themselves should read a few books in mathematics to get into shape. Galileo's contribution to the methodology of modern science is revealed in his attitude toward the application of mathematics to nature, an attitude that is made especially manifest in his dialogues, and one that we must explore further.

Galileo: Mathematics as metaphysics or as science?

In the preceding section, I hope to have established that Galileo neither espoused nor consistently followed a Platonic or an Aristotelian

conception of natural knowledge. Acceptance of this conclusion, however, does not put to rest the notion that Galileo adopted a "Platonic" or "mathematical" metaphysics, for the construction of a systematic account of the mind and its relation to the objects of knowledge does not exhaust the metaphysical possibilities for a figure such as Galileo. Perhaps his metaphysics consisted simply in the doctrine that nature is fundamentally mathematical, that is, in his adoption of a "mathematical ontology" reminiscent of the geometrical atomism of Plato's *Timaeus*. This would constitute a "first-order" metaphysics, in which one develops a substantive metaphysical doctrine without providing a "second-order" account of the relationships among God, nature, and the human mind as a framework for the doctrine.

Evidence for the ascription of a mathematical ontology to Galileo has seemed ready to hand: I have in mind the passage in the *Assayer* about the mathematical language of the "grand book" of the universe; the praise of the mathematical approach to nature, near the end of the Third Day of the *Dialogue;* and the numerous statements regarding the geometrical character of matter (found in several works). I wish to fit this evidence into an alternative picture of Galileo, one that denies that he subscribed to a mathematical ontology and, indeed, denies that he subscribed to any ontology (theory of being) in the metaphysical sense at all. Rather than revealing Galileo's mathematical ontology, these passages reveal his attitude toward the character of scientific knowledge, and toward the properties of material bodies that must be investigated if such bodies are to be objects of scientific knowledge. This attitude does not derive from, and is not proffered as, a theory of the essence of matter; rather, it reflects a conception of the kinds of properties that can be treated within the sciences, which means, for Galileo, within the demonstrative or mathematical sciences. The passages that convey this attitude do so by showing us Galileo's attempts to extend the paradigm of scientific knowledge provided in actual mathematical sciences (and practices) to new sciences, or to new approaches and conclusions within established sciences.

Evidence for my position is to be found in the passage that is perhaps most widely cited as establishing Galileo's geometrical ontology – the passage from the *Assayer* on the geometrical language of the book of nature. Considerable light is thrown on this passage by considering its context within the *Assayer*, as well as its context in the ongoing dispute between Galileo (or his student Mario Guiducci) and his opponent "Lotario Sarsi" (a pseudonym used by Horatio Grassi) over the positions and paths of the comets of 1618. Briefly, in an earlier work Guiducci (speaking for or with Galileo) attacks Grassi for "subscribing to Tycho's every statement," which Sarsi, in reply, first denies as a gloss on the earlier text and then in effect confirms, concluding that given Ptolemy's problems with the data on Mars and Copernicus's condemnation, "Tycho remains as the only one whom we may approve as our leader among the unknown courses of the stars."[96] It is toward the end of Galileo's response to this sentence and its surrounding paragraph that the passage on the book of nature occurs:

> It seems to me that I discern in Sarsi a firm belief that in philosophizing it is essential to support oneself upon the opinion of some celebrated author, as if when our minds are not wedded to the reasoning of some other person they ought to remain completely barren and sterile. Possibly he thinks that philosophy is a book of fiction created by some man, like the *Iliad* or *Orlando Furioso* – books in which the least important thing is whether what is written in them is true. Well, Sig. Sarsi, that is not the way matters stand. Philosophy is written in this grand book – I mean the universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth. Sarsi seems to think that our intellects should be enslaved to that of some other man . . . , and that in the contemplation of the celestial motions one should adhere to somebody else.[97]

Inspection of this passage in its entirety reveals that the oft-quoted portion was put forward in the context of another Galilean theme, the rejection of authority in favor of the use of one's own reasoning and observation. The immediate use of the book metaphor is to provide a contrast between treating "philosophy" (here, with the connotation "natural philosophy") as the fictional creation of an author or as the content of a nonfictional work, the universe itself. Galileo's point is that the true philosopher will learn to read the latter work for himself, which requires first learning the proper language. And that language is mathematical, which, for Galileo, means geometrical.[98]

But note that the passage is unclear about the precise status of this geometrical language. It has seemed to say that geometrical figures constitute the substantial alphabet of the universe itself, and yet it literally says that mathematics is the language, not of the universe, but of philosophy. Should we read it as saying that the universe itself is constituted by an exclusively geometrical alphabet, or that philosophical knowledge of the universe is exclusively geometrical, with the implication that such knowledge extends only to the geometrical properties of natural things? The passage does say that philosophy is written *in* the universe in mathematical language, but this need mean no more than that the objects of natural philosophical knowledge have determinate geometrical properties; that is, that there is a true geometrical shape to the orbits of Jupiter's moons, a true position and pathway for the three comets, or, on a broader scale, a true configuration for the entire solar system. On this reading, it is not the universe that is mathematical, but those of its properties that constitute the objects of scientific knowledge.

And yet, even this reading of the passage may seem to support the view that Galileo subscribed to a mathematical ontology. For if knowledge of nature is knowledge of geometrical properties, then natural bodies must possess geometrical properties, a conclusion that may seem in itself to show that Galileo embraced a geometrical ontology. There is, however, a world of difference between holding with the *Timaeus* that material bodies are constituted by geometrical figures, or with Descartes that the essence of matter is extension, and maintaining with Galileo that material objects possess a determinate size and shape and that the scientific knowledge we possess of such bodies is of those properties. The former amounts to saying what bodies are; the latter amounts to saying which of their properties can be the object of scientific knowledge. And while one might argue for a geometrical ontology in order to guarantee the applicability of geometry to nature, that is not the only strategy that one can adopt to justify the mathematical sciences. One might appeal to their prior success – in applications ranging from ordinary marketplace weights and measures to surveying and hydrostatics – thereby justifying their application through practice.

Comparison of the different ways in which Galileo and Descartes justified a geometrical approach to nature is particularly revealing of the nonmetaphysical character of Galileo's arguments, for, although the two authors faced similar opponents and had similar aims, they adopted quite different strategies. They both wished to overthrow the Aristotelian approach to nature, with its emphasis on "natures" or "essences" as principles of qualitative change. We have seen that Descartes fought metaphysics with metaphysics, replacing the active essences of the Aristotelians with his own passive essence, extension, thereby offering a new mathematical ontology. Galileo rejected the search for essences altogether and, instead of providing an alternative ontology or general theory of being, focused attention on the properties of celestial and terrestrial bodies that admit of mathematical handling.

Although the difference between Descartes's attempt to establish a mathematical ontology and Galileo's attempt to enlarge the boundaries of mathematical science is one that must ultimately be appreciated by characterizing the body of each author's work as a whole, Galileo has aided the characterization of his work by explicitly contrasting his own aims with the search for essences. In the *Letters on Sunspots* he describes two approaches to theorizing about the heavens: "In our speculating we either seek to penetrate the true and intrinsic essence [*essenza*] of natural substances, or content ourselves with a knowledge of some of their properties [*affezioni*]."[99] He despairs of the former approach, holding it to be "as impossible an undertaking with regard to the closest elemental substances as with more remote celestial things." After illustrating the futility of asking even what terrestrial things *are*, he proceeds to sketch the second of the theoretician's options: "If what we wish to fix in our minds is the apprehension of some properties of things, then it seems to me that we need not despair of our ability to acquire this respecting distant bodies just as those close at hand." We know the *periods* of the planets, the *shape* of the moon, and so forth. Therefore, even if we cannot know the "true substance" of the sunspots, "still it does not follow that we cannot know some properties of them, such as their location, motion, shape, size, opacity, mutability, generation, and dissolution."[100] (Lest it seem that Aristotelian philosophical categories have reappeared, under the guise of mutability, generation, and dissolution, let us recall that in Galileo's examination of the sunspots these properties amount to changes in size and shape.) In sum, then, Galileo's advice is to forsake essences and focus on geometrical properties. He does not present these latter as defining material substance but as the type of property about which we can obtain scientific knowledge.

This passage must not be made to support more weight than it can bear. For even if Galileo officially forsakes the search for essences, it may still be that he effectively made a metaphysics of his method by treating matter as if it must be geometrical, and only geometrical. And indeed, he certainly did not restrict his attribution of geometrical properties to observable phenomena such as sunspots; he attributed geometrical properties to subvisible matter, and geometrical regularity to motions that he could not directly measure.[101] In order to decide if these attributions amount to a mathematical metaphysics, we need to examine his mode of arguing for them.

Galileo produced passages about the geometrical character of subvisible matter that sound very much like metaphysics. Indeed, his most metaphysical-sounding argument for treating matter mathematically is again to be found in the *Assayer*. Here we find a version of the distinction – familiar from the works of Descartes and Locke – between "primary" and "secondary" qualities: "I do not believe that for exciting in us tastes, odors, and sounds there are required in external bodies anything but sizes, shapes, numbers, and slow or fast movement; and I think that if ears, tongues, and noses were taken away, shapes and numbers and motions would remain but not odors or tastes or sounds." We also find what seems a familiar justification for this distinction: "Therefore I say that upon conceiving a material or corporeal substance, I immediately feel the need to conceive simultaneously that it is bounded and has this or that shape," and so on for size, position, and number; "but that it must be white or red, bitter or sweet, noisy or silent, of sweet or foul odor my mind feels no compulsion to understand as necessary accompaniments; indeed, without the senses to guide us, reason or imagination would perhaps never arrive at such qualities," so that the latter should be treated as mere "names," by comparison with the former "primary and real" attributes (*accidenti*).[102] These passages are strongly evocative of Descartes's argument for the distinction, which he based on an appeal to what is known in bodies by the intellect or understanding as opposed to the senses. But in order to determine the extent of the similarity, we need to know whence Galileo means to derive the force of his appeal to conceivability. In telling us that in order to account for the production of sensations in us, we need suppose only size, shape, number, and motion in external bodies, is he telling us what type of scientific account we should aim to give to all material interactions, including those between external objects and the sense organs, and then remarking that the sensory qualities as experienced are dependent upon characteristics of the sentient organism, or is he appealing to a purely rational intuition that matter has only mathematical properties? That is, should we read these passages as a sketch of a theory of the senses along mechanistic lines, or as a metaphysical argument for a metaphysical distinction? If the former, then the theory need be no more metaphysical than Newton's theory of refrangible rays or than more recent electromagnetic theories of light and color. If the latter, then Galileo may be deemed a metaphysician, though a spotty and uneven one, since, unlike Descartes, he provides no framing theory of the relationship between conceivability and ontology to bolster his argument.

I prefer the former interpretation. In arguing for it, I can do no better than to fit these passages into a broader picture of Galileo as a mathematical scientist. (And perhaps no better is possible, since to establish Galileo as a nonmetaphysician is to provide a positive characterization of a nonmetaphysical attitude that runs throughout his significant works.) This broader picture of Galileo has been adumbrated in my previous allusions to Galileo as a mathematical practitioner who saw himself as extending the approach of earlier mathematical scientists – and above all, Archimedes – into new domains. It is time to bring the strands of these allusions together into a positive characterization of Galileo's "Archimedean" attitude.[103]

What, then, characterizes Galileo's "Archimedean" approach to science? First, there is his acceptance of the Euclidean paradigm of demonstration, in which propositions are derived from axioms, definitions, and postulates. In formulating a science of, say, motion, the Archimedean demands the same rigorous demonstrative argumentation from axioms and postulates as is found in geometry proper; this is part of what Galileo has in mind when he reiterates his preference for "necessary demonstrations." But, as we have seen, it was commonly remarked that not all of the propositions in a science can be demonstrated; hence, the need for axioms and postulates from which to begin.[104] And so once again the question arises of how these are known. Within arithmetic and geometry themselves, they were generally taken as self-evident or as commonly accepted. Galileo put forward some of the propositions of his science of motion as having this status, such as the axiom that "the space traversed with greater speed is greater than the space traversed in the same time with lesser speed."[105] Presumably, this axiom *would* be granted by all; Galileo simply proposes it, without offering a justification or explaining why none is required. Other propositions are more problematic and must be established through controlled observation. Thus, in the case of free fall as discussed in the *Two New Sciences*, he has Sagredo agree that Salviati's definition of uniformly accelerated motion may make perfect sense as an abstract proposition (which may enter into demonstrative arguments); but Sagredo wants to know whether "this definition, conceived and assumed in the abstract, is adapted to, suitable for, and verified in the kind of accelerated motion that heavy bodies in fact employ in falling naturally."[106] Salviati responds by reporting various observations in support of the conformity of the definition with actual cases of bodies in descent. Of course, once the definition has been established by seeing that it fits actual cases, Galileo feels free to use it to establish further demonstrative conclusions, which he accepts as true without further appeal to experience. Nonetheless, while it is true that to characterize a science as "mathematical" or "demonstrative" implies that its propositions follow demonstratively from axioms and postulates, it need not imply that these

axioms and postulates are already known with certainty to hold true of nature, even if the attainment of such certainty is a sought-after goal.

Galileo's commitment to an Archimedean approach required not only that he establish the axioms and postulates of particular mathematical sciences; as one who sought to extend the Archimedean approach into new domains, he needed to justify his expansion of the boundaries of mathematical science, or of the domain in which geometry is considered to "fit" nature. I have suggested earlier that it was not his strategy to attempt an across-the-board justification. Galileo took a variety of attitudes toward this problem, depending upon the specifics of the case. These attitudes range from the outright assertion, without further argument, that mathematical structures fit material objects, to the view that the fit is "close enough," to the view that the actual fit must be determined empirically. We can best understand these attitudes by seeing them in action in particular cases.

Sometimes Galileo admitted that the results of demonstration do not perfectly fit what is observed. He explained deviations from what is demonstrated "in the abstract" by an appeal to "material hindrances" or the "imperfections of matter." This attitude, which has been taken as an instance of the Platonic distinction between the ideal world of Forms and its imperfect reflection in the world of the senses, is perhaps better seen in relation to what Galileo termed Archimedean "geometrical license."[107] Basically, this "license" allows the geometer (or staticist, or mechanician, etc.) to treat results demonstrated from "ideal" axioms as fitting the material world, when the fit is "close enough." Galileo cites the classical example of Archimedes' willingness to treat the various portions of the horizontal arm of a balance as equidistant from the center of gravity, even though that center is a point at the center of the earth. Some sixteenth-century mathematicians, such as Giovanni Battista Benedetti and his pupil Guidobaldo del Monte, had seen this as grounds for rejecting portions of Archimedean statics as lacking in rigor. Others, such as Tartaglia, overlooked such deviations as too small to be of consequence.[108] Significantly, in the *Two New Sciences* Galileo upholds the rigor of the demonstration, while at the same time admitting that when applied to actual cases there are small deviations that must be overlooked. In the case of the balance arm, he defends Archimedes' demonstration as correct by recalling that Archimedes had specified the balance to be an infinite distance from the center of gravity, but Galileo also admits that for actual balances the distance is finite. He has Salviati reason as follows:

> Here I add that we may say that Archimedes and others imagined themselves, in their theorizing, to be situated at infinite distance from the center. In that case their assumptions would not be false, and hence their conclusions were drawn with absolute proof. Then if we wish later to put to use, for a finite distance, these conclusions proved by supposing immense remoteness, we must remove from the demonstrated truth whatever is significant in [the fact that] our distance is not really infinite, though it is such that it can be called immense in comparison with the smallness of the devices employed by us. . . . We must find and demonstrate conclusions abstracted from the impediments, in order to make use of them in practice under those limitations that experience will teach us.[109]

The workmanlike tone of this response echoes the celebrated passage from the *Dialogue* in which Salviati compares the "geometrical philosopher" with the tradesman in the marketplace and admonishes that, just as the latter must subtract the packaging in arriving at the weight of goods sold, so the former, "when he wants to recognize in the concrete the effects which he has proved in the abstract, must deduct the material hindrances." The upshot is that with respect to the application of geometry to material objects and events, "the errors lie not in the abstractness or concreteness, not in geometry or physics, but in a calculator who does not know how to make a true accounting."[110] In determining whether a given demonstrative result accords with nature, there is a knack of knowing what to discount and what to treat as a disconfirmation. Galileo does not specify how this is to be done in general, but argues in particular cases that, for example, air resistance or friction may be discounted and gives advice about how such "hindrances" may be reduced. The appeal to "know-how" in making a true accounting suggests that, at least in part, this knack is learned in the actual course of collecting measurements, an attitude that accords well with reconstructions of Galileo's experimental practice.[111]

On other occasions, Galileo claimed that material objects are exactly described by the propositions of geometry. The most striking instance of this sort occurs in the *Dialogue*, where Salviati at first claims that a "material sphere" – if actually spherical – would touch a "material plane" – if actually planar – in a single point, but then is forced to admit that perfect material spheres and planes do not exist. This has been taken as an admission by Galileo that geometry does not describe actual matter but applies only to a counterfactually "ideal" set of objects.[112] I think the principal point of the argument is, rather, that the actual, nonspherical, material globe is, as regards shape, in perfect

conformity with geometry. In a case in which a "globe" is slightly out of round and a surface is not truly planar, geometry predicts that the "globe" will touch the "plane" "over a part of its surface." Galileo's point here is that insofar as matter has a determinate shape, its shape is just as "geometrical" as a perfect shape considered in the abstract. He was willing to push this point very far, for in the same passage he argues that if two irregular, jagged-edged bodies "were well scoured and both were placed upon a table so that one could not bear down upon the other, and then if one were gently pushed toward the other, . . . [they] could be brought into simple contact at a single point."[113] Here Galileo has Salviati present a picture of subvisible matter as "clean" – as having a perfectly determinate shape, which, even if it is irregular, nonetheless conforms fully to geometrical descriptions of such irregular shapes.

This willingness to push mathematical or geometrical science so far as to suppose that subvisible matter has a "clean" geometrical shape may seem to reveal Galileo as a man who, despite his failure to develop a systematic metaphysics, was nonetheless gripped by the metaphysical picture of geometrized matter. But consider again the context of this "push." Galileo may be seen here as teaching his contemporaries what may have seemed to them a counterintuitive result. For us, the suspect part of his claim is the geometrical definiteness of Galileo's subvisible matter, but then we have become accommodated to the *unanschaulich* character of subatomic physics. For Galileo, the important point was that even imperfect shapes are nonetheless geometrical. So this example may be seen as one in which Galileo has a particular point to teach about the application of geometry to nature. And in the most important of the other contexts in which he pushes a geometrical picture of matter in general – specifically, in the First Day of the *Two New Sciences* – I would argue that he is teaching the application of a particular science (in this case, the science of materials) and that it is the needs of this particular science that lead to the assumption that matter in general can be treated geometrically.[114] These examples show Galileo making various claims about the geometrical character of matter in particular contexts, but they neither reveal nor suggest a general argument for the conclusion that matter is essentially or exclusively geometrical in character.

While Galileo's approach to mathematical science was not metaphysical, it was philosophical, for in examining and teaching a variety of specifics regarding the application of geometry to nature, Galileo revealed himself to have been more than Archimedean. Archimedes simply produced treatises on mathematical subjects, many "pure" and some "applied" (such as the treatises on hydrostatics or the lever). Galileo produced treatises of the latter sort, such as the Latin treatise on motion embedded in the *Two New Sciences*. In so doing, he of course extended the Archimedean approach to a new subject matter. But he went beyond Archimedes, not only in conquering new domains; of greater significance, he provided a type of reflection on the practice of mathematical science not found in Archimedes. Galileo sought to teach the intellectual skills and attitudes required for the development and application of the mathematical sciences. This involved reflecting upon the cognitive claims of these sciences in various contexts.[115] In the course of these reflections, he performed some of the same type of justificatory work that Aristotle and Descartes attempted in their metaphysical and methodological treatises. But he performed this work in his own way. Rather than offering a treatise on method or a theory of being, he offered examples of a method and of the types of properties to which it can be applied.[116]

The distinctive features of Galileo's attitude toward mathematics and nature may be summed up by returning to the comparison with Kepler and Descartes. We have seen that Galileo eschewed the development of a general account of the mind and its relation to nature. Although he looked to mathematics as a model of knowledge, he neither sought an a priori insight into the plan of a geometrizing deity nor extended this model into a rational, intellectualist account of knowledge in general. While adopting the demonstrative form of presentation, he embedded it within a discussion of a complex group of practices pertaining to the application of demonstrative results in concrete cases. His mathematical approach was taught through the examination of instances of its application, not through the presentation of a codified set of precepts. Galileo sought to expose the reader to occurrences of the appropriate type of thought, by exposing him to occurrences of good and bad judgment. For this the dialogue form was especially well suited, because it allowed him to work through numerous cases in which concrete judgments were rendered, praising the good and criticizing the bad. He could present objections to a mathematical approach and then show that they did not apply in specific instances, without having to present a blanket justification for the approach. In the presentation of the proper attitude toward the application of mathematics to nature, Galileo spoke as a reflective practitioner teaching his practice, where he might have spoken as a metaphysician.

This aspect of Galileo's achievement is difficult to characterize, because there is no single term that aptly describes it. Some have sought to capture Galileo's emphasis on specific problems and results by characterizing his attitude as that of the pragmatic engineer. While it is certain that there is something of the hands-on attitude of the engineer in many of Galileo's writings, this will not serve as a general

characterization, for Galileo's aims were not exclusively applied or practical. He was a theoretician who engaged in the enterprise of developing general sciences – for example, a general science of motion – without keying these sciences to specific practical applications. Others have attempted to characterize Galileo as a typical modern physicist, who demands both mathematical rigor and experimental confirmation. This too fails, for Galileo was not a physicist in the sense of one who provides a single, unified theory for all of nature; he engaged in various mathematical sciences, none of which show the scope and unity of the post-Newtonian conception of general physical theory. Moreover, Galileo was not exclusively engaged in "basic science"; he aimed to show that basic science of a certain type was a workable alternative to the other conceptions of natural philosophy with which he was forced to compete. In defending Copernicus and developing a science of motion, he came directly into conflict with, and needed to provide an alternative to, the metaphysical and methodological conceptions of Aristotelian physics. He was faced with the problem of providing a viable alternative conception of natural science, not merely with the problem of establishing his own scientific theories against others of the same type. Galileo did not meet this philosophical challenge by developing a new metaphysics and theory of knowledge; rather, he proceeded to establish, in case after case, the appropriateness of the Archimedean style of science for each domain of natural phenomena that he examined.

Galileo's most significant contribution to the development of scientific and philosophical thought may well lie in his attitude toward mathematical science and its justification. At a time when many of Europe's most powerful minds were trying to find a justification for the new science in a flash of insight into the divine mind, or in a general theory of the human mind, or in a specification of the natures of matter and motion, Galileo exemplified an alternative approach, and he did so with elegance and force. His achievement was to show how a mathematical approach to nature could be justified by its success in practice, and specifically how it might be sufficiently justified by numerous local instances of application. He revealed by example that one did not need a general theory showing the possibility of scientific knowledge and giving its first principles in order to defend the truth of specific scientific claims or to extend the application of a particular type of scientific approach into new domains.

Galileo's realism: Metaphysical or scientific?

Having reached this point in my argument, I wish to conclude my discussion of Galileo with a brief examination of yet another way in which he has been characterized as a metaphysician: that which arises from his "realism." This characterization stems from Pierre Duhem's classification of attitudes throughout the history of astronomy and physics into two types, "instrumentalist" and "realist." The former term denotes the doctrine that scientific theories merely provide convenient calculating devices for "saving the phenomena"; the latter is used to suggest that scientific theories satisfy the metaphysical impulse to know "the nature of reality." According to this distinction, which has become widely accepted and extended, Galileo (like Copernicus) was a realist – and therefore, according to Duhem, a metaphysician – because he claimed to have discovered the true configuration of the solar system.[117]

Against the characterization of Galileo as a metaphysician by virtue of his "realism," I contend that Galileo (like Copernicus) was a realist but not a metaphysician. The notion of metaphysical realism employed by Duhem and others conflates the claim to know the truth about some aspects of nature with the metaphysical claim to know the essence or nature of reality. Although there can be no doubt that Galileo was a "realist" with respect to heliocentrism and numerous other doctrines in natural philosophy,[118] this does not make him a *metaphysical* realist. As we have seen, neither Galileo's pronouncements nor his practice support the claim that he sought to determine the "essence" or "nature" of material substance or of particular natural bodies in the manner of traditional metaphysicians such as Aristotle or Descartes. I propose instead that he was an "astronomical realist" or, more generally, a "scientific realist," whose realism was constituted by the belief that he had adopted a true description of the paths of the planets and of other natural phenomena. One might construe Galileo's arguments for the reality of heliocentrism in much the same manner as Kepler construed Copernicus's: as "mathematical" arguments tendered a posteriori for a particular structure of the solar system. Although eschewing metaphysical insights of the Keplerian sort, Galileo, like Copernicus, claimed to know how the configuration of the planets would appear to an appropriately situated observer. In some notes to himself Galileo explicated the truth of the Copernican system in just this way: "If we could stand now on the earth and again on the sun or some other star, we might gain positive and sensory knowledge as to which revolved."[119] In arguing for the Copernican system, he aimed to show no more than that certain configural properties of the solar system are known, just as in the science of motion he attempted to show no more than that a certain relation between speed and time of travel holds for falling bodies.

On the face of it, then, Galileo's claim to have discovered the true

description of certain parts of nature seems no more metaphysical than the claim to know the true number of bricks in a pile or the true area of a farmer's field. Indeed, Galileo himself assimilated the determination of the position and trajectory of a heavenly body to the surveying of fields on the earth, in a delightful, pseudonymously published dialogue on the "new star" of 1604. The speakers are two rustics, Matteo and Natale. After opening pleasantries, Natale tells Matteo about a book on the "new star" by a professor at Padua. Matteo scoffs at Paduan academe, and then he engages Natale in the following exchange on the distance to the star:

> *Natale:* Far? Nuts. It's not even as far as the moon, from what the book said.
>
> *Matteo:* What is this fellow that wrote the book? Is he a land-surveyor?
>
> *Natale:* No, he is a Philosopher.
>
> *Matteo:* A Philosopher, is he? What has philosophy got to do with measuring? You know that a cobbler's helper can't figure out buckles. It's the Mathematicians you've got to believe. They are surveyors of empty air, just like I survey fields and can rightly tell you how long they are, and how wide. Just so can they.
>
> *Natale:* He said there in that book that the Mathematicians put it way too high, because they don't understand.
>
> *Matteo:* How don't they understand? Are you just singing to me, or making love?
>
> *Natale:* He says they imagine that sky can be destroyed or created a bit at a time, though not all at once. How should I know?
>
> *Matteo:* Now, where do Mathematicians talk that kind of reasons? If they just stick to measuring, what do they care whether or not something can be created? If it was made of polenta, couldn't they still see it all right? That wouldn't make it any bigger, or smaller, would it? These boners of his make me laugh.[120]

Although Galileo was later to claim the title of Philosopher for himself, he here contrasts philosopher and mathematician, in order to separate arguments that appeal to the essential nature of a thing (for example, the immutability of the heavens) from arguments that appeal to a thing's geometrical properties as determined through measurement. This distinction accords well with an early statement by Galileo, distinguishing philosophical questions pertaining to the qualities of things from configural questions in cosmology (questions pertaining to shape, size, distance, and motion).[121] According to my interpretation, the distinction marks a divide between metaphysical and nonmetaphysical arguments and modes of inquiry.

Against the characterization of Galileo's realism as "nonmetaphysical," with its seemingly blithe contrast between the metaphysics of substance and the nonmetaphysics of measurement, it might be argued that the very claim to determine the configuration of the solar system involves the metaphysical presupposition of an absolute spatial framework. One might classify this supposition as metaphysical on the grounds that it makes no *observational* sense to assign the sun a location at the center of the solar system prior to specifying the inertial frame of the observer, and that putting the sun in the middle has no *physical* content prior to the specification of the sun as the center of gravity of the solar system. Since, before Newton, neither of these specifications could be made, any attempt to give content to heliocentrism may seem, of necessity, to have been pure metaphysics.

In one sense this argument is obviously anachronistic, since the very notions of inertial frame of reference and center of gravity, as applied celestially, are Newtonian. Yet the objection does bring into relief a deep presupposition shared by both Galileo and Copernicus: that the solar system has a true configuration, that it makes sense to seek to locate the sun and the earth with respect to the stars. This supposition was, on the one hand, hardly metaphysical in Galileo's time: The idea that the sun has a determinate spatial location makes perfect sense on the assumption that the axis of the sphere of fixed stars is itself "fixed." This supposition was therefore a realist supposition about the spatial framework of the universe. Although this supposition ultimately was called into question, that need not make it metaphysical. The idea that one can determine the locations of bodies relative to the framework of the stars can be seen as the extension, into a new domain, of a set of measuring techniques that had a reasonable realistic interpretation in their primary domain – even if the distances involved in the new domain are immense and even if the instruments for detecting parallax were relatively inaccurate. The needed supposition only seems like metaphysics with hindsight, because it turned out that the treatment of the stars as a fixed frame of reference was not as straightforward as was supposed.

On the other hand, it is a long way from bricks and fields to the spatial structure of the universe. To say that in the context of the Copernican or Galilean enterprises the supposition of determinate locations for the stars, sun, and planets makes sense is to locate those enterprises firmly within the presumed correctness of Euclid's geometry as a description of physical space. Insofar as the latter forms a deep presupposition for both Copernicus and Galileo, one might

wish to label it a "metaphysical" presupposition. But here we must acknowledge the positivist conditioning behind this modern usage of the term "metaphysics." Within a context in which metaphysics is no longer considered a distinctive type of philosophical activity – a context perhaps colored by a view of science that regards the superseded assumptions of old theories as obstacles in the path of progress – it may seem appropriate to regard unargued presuppositions as metaphysics. But this sense of the word is quite other than the historically situated sense that I have developed in this paper, and to ascribe a "metaphysical presupposition" of this type to Copernicus and Galileo does not at all negate my distinction between authors who did, and did not, argue metaphysically. Moreover, although the extension of a set of measuring techniques to a larger domain (or the supposition that the types of properties measured also have determinate values subvisibly) can become "metaphysical" if it is done blindly and relentlessly, it must certainly be incorrect to view every speculative extension of an approach into new domains as inherently "metaphysical," in a pejorative sense. Whether it is metaphysical in any sense at all is another matter, to which I will return.

Metaphysics as presupposition and as argument

Kepler and Descartes each argued metaphysically for some aspects of their general approaches to and specific conclusions within astronomy and physics; Copernicus and Galileo did not. Copernicus simply pursued mathematical astronomy, whereas Galileo sought to justify and to extend a mathematical approach to nature. In his critical reflections on an Archimedean style of mathematical science, Galileo was led to evaluate its success and to parry challenges. Inasmuch as his justification did not appeal to a general theory either of nature or of the knowing mind and his evaluation did not seek its criteria outside the domain of practice, Galileo's reflections were not metaphysical. Yet they were philosophical, in that they constituted critical reflection on the cognitive claims of his particular assertions about nature and on various features of his methods and procedures.

If this picture is correct, then Galileo provides an example of a type of philosophical voice that has not been adequately recognized in the early modern period.[122] It is an inquiring voice, which pursues philosophy without engaging metaphysics. Galileo provides a model for a type of philosophical activity that undertakes the criticism of ongoing cognitive practices without seeking to establish a general metaphysics and without concluding that, in the absence of a general framework for criticism, philosophy is impotent. And while the model he provides is that of the reflective practitioner – as in the presentation and examination of his own new sciences in his *Two New Sciences* – he was also willing to extend his reflections to pursuits about which he was knowledgeable but in which he was not a working participant, as in his discussion of planetary astronomy in the Third Day of the *Dialogue*.

If the taxonomy of mathematical scientist, philosopher, and metaphysician that has resulted from our examination of the authors discussed in this chapter were extended to other figures in early modern science and philosophy, some adjustments might result in our perception of them. Huygens and Newton would count as *mathematical scientists*. Leibniz would figure as a *metaphysician*, who posited a sharp boundary between metaphysics and physics but regularly argued across that border. Locke's project would be set apart from the efforts of Descartes and Leibniz to establish a metaphysics for the new science; Locke would be seen as attempting to work out a conception of knowledge in the spirit of a new, *nonmetaphysical* approach to nature.

It may be of interest to explore further this classification of Newton as a mathematical scientist, for here I find myself in direct opposition to Burtt, whose aim was to show that science cannot escape from metaphysics by revealing that even the great Newton could not do so. Burtt described Newton as a first-rate scientist but a second-rate philosopher. He held the latter view partly because he believed that Newton accepted the philosophical implications of his work in natural philosophy unconsciously, and therefore uncritically.[123] But it may be that Newton was not a philosopher at all, in one sense – in the sense that a philosopher is a *first* philosopher – and perhaps this is the key to his philosophical achievement vis-à-vis science. Newton kept his cards close to his vest in the *Principia*, displaying his winning hand but only rarely revealing his gambler's appetite. He offered certain mathematically formulated laws of dynamics, which he contrasted with metaphysical – or, indeed, physical – hypotheses. His claim to "feign no hypotheses" amounted to a declaration that he would not offer speculations on the nature or essence of gravity or of matter. And yet on the very page in which he banished metaphysical and physical hypotheses from "experimental philosophy," he invoked just such a hypothesis in his mention of a "certain most subtle spirit" that he supposed to pervade the universe and to account for electrical and other phenomena.[124] This, however, may be seen as a violation of the model of scientific reasoning set by the *Principia*. Indeed, Newton himself was sensitive to a division between such speculations and the proper body of works such as the *Principia* or the *Optics*, and he

signaled this sensitivity by collecting such topics in "scholia" to the former work and "queries" to the latter, thereby setting them apart from properly established "propositions." *Principia*-style mathematical science is an extension of Galilean-style mathematical science, applied on a grander scale. The force of the *Principia* comes from the fitting of a unified mathematical structure to a broad range of phenomena, illuminating previously established laws of planetary motion and providing a stunning example of comparative unity and simplicity in the description of nature. And within the *Principia*, Newton claims no other force than this. In this sense, he continued and extended the Galilean attitude toward the fundamental tenets of natural philosophy.[125]

One may feel, nonetheless, that Newton's commitment to absolute space and time must be characterized as metaphysics. In one sense, I agree. Newtonian science provided a set of basic categories, such as mass, force, and absolute space and time, that conditioned scientific and philosophical thought for the next two hundred years. Beyond setting a framework for two centuries of activity in physical science, the Newtonian account of nature informed the core of metaphysical thought in philosophers such as Kant and in the movement toward materialism that formed the goad to Burtt's historical-philosophical essay. It may thus be seen to have yielded metaphysical implications, and so its author may be seen as a metaphysician. In this sense, each singularly great theoretician is a metaphysician, for such persons change the fundamental categories with which we think. Such changes may be "hidden" to the thinker and may therefore need to be "teased out" *à la* Burtt. Upon reflection, then, it may be said that although metaphysics is not to be equated with assumption or presupposition in general, when one's assumptions are, as in the case of Newton, incorporated into a stunning theoretical and empirical achievement, one may thereby earn the title of metaphysician.

Indeed, the singularity of Newton's achievement may itself have been instrumental in the development of the conception of metaphysics as presupposition. Given the ubiquity of Newtonian science by the second half of the eighteenth century, one might well have been tempted to see in its "presuppositions" answers to traditional metaphysical questions regarding the "nature of reality." In a way, Kant can be seen as having treated Newtonian science in this manner, though of course the metaphysical results he might thereby achieve were altered by his denial of the old goal of discovering the nature of "things in themselves" and his substitution for it of the conception of metaphysical principles as those which can be expected to hold for all possible experience. A century later, Cassirer endeavored to imitate

Kant's attempt to systematize the knowledge of his time, but now with the proviso that the systematization must be regarded as historically relative, and hence likely to be superseded.[126]

Newton's achievement was also instrumental in the development of a second tendency toward the equation of metaphysics with presupposition, insofar as it funded the old positivist ideal of a "purely factual" science. Once science is viewed as a matter of straightforwardly building theory from fact (as Newton sometimes characterized his procedure, and as his procedure was often characterized by others), it may seem to make sense to imagine a presuppositionless science and pejoratively to label those tenets that are no longer deemed factual as "metaphysical presuppositions." Burtt was seeking to turn this conception of metaphysics back against positivism by showing that even the greatest scientists made presuppositions or assumptions that could not be derived directly from the facts. In any event, with the decline of the positivist conception of science, this equation of metaphysics with presupposition must surely fade.

It is important to note that my arguments against the equation of metaphysics with presupposition are not intended to vitiate the philosophical projects of Burtt, Cassirer, Whitehead, and Koyré. The tendency of these authors to treat metaphysics as presupposition must be understood in the context of each author's specific aims. Cassirer regarded the problem of the historical development of science as a philosophical problem in the criticism of knowledge and sought to carry out a historical analysis of that development from a neo-Kantian point of view. This involved extracting various attitudes toward the relation of being and knowledge from the theory and practice of scientists and philosophers.[127] Burtt wrote to expose the metaphysical presuppositions of modern science, so that he could show their historical contingency and hold them up for criticism. Although he cast his approach as historical, he tended to search for the implications that could be drawn from Galilean or Newtonian science, rather than for the historically actual presuppositions involved in its development. According to Burtt's analysis, the mathematization of nature led to both the antiteleological view of nature as a machine and the distinction between primary and secondary qualities; the latter doctrine, in turn, was the opening wedge of a more encompassing distinction between object and subject, fact and value. This emphasis on implications was appropriate to his program of responding to what he regarded as his contemporaries' overly complacent acceptance of materialism.[128] Whitehead, too, sought to use his historical analysis to criticize the scientific materialism of his day, which he hoped to replace with his own philosophy of "organism." Koyré, by contrast, sought to vindicate Platonist metaphysics by showing that it lay behind the achievements of Galileo.[129] In each case, the search for presuppositions – whether these were characterized as having a historical origin in Platonism or not – had a significant role to play in the philosophical endeavor of the author (even if the endeavor itself now seems questionable on a variety of grounds).

My objection to these authors is not that they had philosophical axes to grind, but that they did not use the wheel of history to best advantage. Contemporary historians of science are often leery of engaging the history of science philosophically, perhaps fearing that their historical interpretations will thereby be tainted. And so they might. But this danger does not justify a blanket supposition that the interpretation of history is inevitably prejudiced by philosophical aims and that it is impossible for the philosophically minded reader to learn from past texts. Moreover, interpretation also can be undermined by insufficient philosophy. The analyses of Burtt, Koyré, and others are open to criticism, not on the grounds that their search for presuppositions was philosophically motivated, but rather because they failed to appreciate sufficiently the philosophical aspects of the texts in which they sought to discover presuppositions.[130] I am suggesting that their treatment of metaphysics as presupposition created a certain blindness to the distinct types of metaphysical and nonmetaphysical argumentation that I have attempted to uncover. The consequences of such blindness have been amply illustrated in the case of Galileo. Koyré and others went astray by mistaking the tone and attitude that go with Galileo's "Platonic" pronouncements. In so doing, they failed to see the character of his arguments and to appreciate the subtlety of his attitude toward the basic propositions of a demonstrative science. Thus, my claim is that Koyré was wrong about Galileo's Platonism and that this undercut Koyré's philosophical use of Galileo to bolster Platonism, whereas Burtt and Whitehead, in getting Galileo wrong, failed to derive the full philosophical benefit from him in their own campaign against metaphysics of a certain type. I do not see that these inadequacies of interpretation differ in kind from the inadequacies of Wallace's and Crombie's ostensibly purely historical, but nonetheless philosophically inadequate, reading of Galileo's method as Aristotelian.

There is a more general point to be made about the dangers of treating metaphysics as presupposition. The treatment of past texts as repositories of presuppositions can divert attention from the integrity of their argumentative structure. It invites one to consider the individual psychologies of the various authors: to ask whether a particular metaphysical position such as Platonism, as expressed in various books known or conjectured to have been in their libraries, might have been in their thoughts but only indirectly or elliptically expressed in their works. It encourages the search for hidden influences behind the text, and often takes a biographical approach. By contrast, to examine metaphysics as it was historically conceived is to examine it as argument: as something put forward with conviction, in order to evoke conviction. Such an approach cannot be satisfied with the charting of influence; it requires seeing how a text hangs together and develops its force. Extended beyond metaphysical texts, it seeks to be sensitive to the distinctive styles of argument that philosophers and scientists have employed, whether metaphysical or not.

I do not wish to deny that intellectual biography, the charting of influence, and the excavation of presuppositions are useful and important for understanding philosophical and scientific texts. Nor do I claim that the rise of modern science took place independently of, or despite, Neoplatonic mysticism, hermeticism, and other "nonscientific" influences. In the case of Kepler, and many lesser figures, the motivational influence and theoretical usefulness of such modes of thought is beyond question. Moreover, I will gladly admit that there may have been a secret Platonic Copernicus, just as there has been discovered a secret alchemical Newton. Understanding such actual or possible interests can and does aid in the understanding of the texts of our authors at various points. But there is a danger in relying too heavily on such an approach, one to which I think Burtt succumbed: the danger of dissolving text and author into a set of background influences. The charting of influence and the search for presuppositions tends to conceal the fact that the writers we have been discussing were *authors:* originators of their own lines of influence, if you like. If we overlook the arguments and styles of argumentation that these authors chose to employ in their texts, we risk failing to appreciate the achievements embodied in their works, and so failing to learn from these works as we might. For, beyond their obvious uses as historical documents, these texts stand as instances and models of argumentation, in which case they must surely be understood as arguments, if they are to be understood at all (whether or not they are emulated). To learn from such texts, we must engage them. And it is, I take it, because we can learn from these texts – not only the history of our culture, as a means to self-understanding, but also the norms of good judgment embodied in the achievements of our culture – that we continually return to them. Why else bother?

Notes

1 Ernst Cassirer, *Das Erkenntnisproblem in der Philosophie und Wissenschaft der neueren Zeit*, 2nd ed., 2 vols. (Berlin: Cassirer, 1911), vol. 1; some of the topics of this work are covered (albeit more briefly) in Cassirer's *The Individual and the Cosmos in Renaissance Philosophy*, trans. M. Domandi (New York: Harper, 1963). E. A. Burtt, *The Metaphysical Foundations of Modern Physical Science: A Historical and Critical Essay*, rev. ed. (London: Routledge & Kegan Paul, 1932). A. N. Whitehead, *Science and the Modern World* (New York: Macmillan, 1925), esp. Chaps. 1–3. Alexandre Koyré, *Galileo Studies*, trans. John Mepham (Atlantic Highlands, N.J.: Humanities Press, 1978); *Metaphysics and Measurement: Essays in Scientific Revolution* (Cambridge, Mass.: Harvard University Press, 1968).

2 Burtt emphasizes the role of Neoplatonism in the rise of modern science: *Metaphysical Foundations*, pp. 40–4, 47, 71–3. See also Cassirer, *Erkenntnisproblem*, pp. 32, 329–30, and *Individual and Cosmos*, pp. 162–9; Whitehead, *Science and the Modern World*, pp. 41–6; and Koyré, *Galileo Studies*, pp. 159 and 201–9, and *Metaphysics and Measurement*, Chap. 2. Of course, these authors did not always agree; for example, Koyré, whose writings contain by far the most detailed and sensitive readings of the scientific texts in question, criticized both Cassirer's and Burtt's conceptions of Galileo's Platonism, complaining that the former turned Platonism into Kantianism, while the latter failed to distinguish mystical Neoplatonism from Galileo's mathematical Platonism (*Galileo Studies*, p. 222, n. 121, and p. 223, n. 123). Although I will treat Burtt as representative, where relevant I will indicate differences from the other authors and from more recent scholarship.

3 This standard picture is presented in Richard S. Westfall, *The Construction of Modern Science: Mechanisms and Mechanics* (New York: Wiley, 1971), esp. pp. 1, 120, and in a qualified form in A. Rupert Hall, *The Revolution in Science: 1500–1750* (London: Longman, 1983), esp. pp. 10–12, 285–7. Although individual investigators have challenged or ignored portions of this picture, I know of no alternative comprehensive reading of the relationship between science and philosophy in the Scientific Revolution.

4 R. G. Collingwood, *An Essay on Metaphysics* (1939; Chicago: Regnery, 1972), Chap. 5. Collingwood conceived "absolute presuppositions" as nonempirical in the sense that they were never called into question and hence were not subject to empirical test (he gives the example of the law of causality); he did not view them as nonempirical in the sense of lacking content: They could be characterized as "synthetic," rather than "analytic," in Kant's sense. For Burtt on assumptions and presuppositions, see *Metaphysical Foundations*, esp. pp. 14–16, 226. Whitehead described the philosophy of an epoch as the "fundamental assumptions which adherents of all of the variant systems within the epoch unconsciously presuppose" (*Science and the Modern World*, p. 71). Cassirer was in part looking for presuppositions, but given his neo-Kantian orientation he was more concerned with epistemological presuppositions (*Erkenntnisproblem*, pp. v, 5–18).

Koyré did not explicitly equate metaphysics with presupposition, but he treated metaphysics as background presupposition in his ascription of metaphysical positions to various authors (especially to Galileo). Interestingly, recent readings of the first book of Aristotle's *Physics*, and also of his *Metaphysics*, have emphasized the extent to which their dialectical character reveals that Aristotle's method was often one of searching for the presuppositions in a given area of thought (whether first philosophy itself or one of the special sciences); see G. E. L. Owen, "'Tithenai ta Phainomena,'" in *Articles on Aristotle*, ed. J. Barnes, M. Schofield, and R. Sorabji, 4 vols. (London: Duckworth, 1975–1979), 1:113–26; W. Wieland, "Aristotle's Physics and the Problem of Inquiry into Principles," in ibid., pp. 127–40; and Martha C. Nussbaum, "Saving Aristotle's Appearances," in *Language and Logos: Studies in Ancient Greek Philosophy*, ed. Malcolm Schofield and Martha C. Nussbaum (Cambridge: Cambridge University Press, 1982), pp. 267–93. However, such a view of Aristotle's method seems not to have had currency in the early modern period.

5 For the flavor of Burtt's biographical approach, see *Metaphysical Foundations*, pp. 26–43, 44–7, 71–3, 97–102. I am not, of course, questioning the usefulness of biography in general but only the part it plays in a certain attitude toward metaphysics.

6 For a characteristic statement that this tenet is inherently metaphysical, see Hall, *Revolution in Science*, pp. 285–7.

7 On the interpretation given to the term "metaphysics" by ancient authors, together with the origin and reception of the Andronicus story, see Hans Reiner, "Die Entstehung und ursprungliche Bedeutung des Namens Metaphysik," *Zeitschrift für philosophische Forschung*, 8 (1954):210–37, and "Die Entstehung der Lehre vom bibliothekarischen Ursprung des Namens Metaphysik," *Zeitschrift für philosophische Forschung*, 9 (1955):77–99. Reiner convincingly argues that the two senses of "metaphysics" distinguished in the following paragraphs of this chapter were accepted and discussed by Hellenistic commentators; his speculation that the term was of early Peripatetic origin rests on weaker ground. Reiner's argument is briefly presented in Takatura Ando, *Metaphysics: A Critical Survey of Its Meaning*, 2nd ed. (The Hague: Nijhoff, 1974), pp. 3–6. Kant's remarks occur in his "Vorlesungen über Metaphysik," in *Kants gesammelte Schriften* (Berlin: Akademie der Wissenschaften, 1900–), vol. 28, Pt. 1, p. 174.

8 The two senses of "metaphysics" just described are not incompatible, and they were closely related in Aristotle, who found the focus of the science of being qua being in the transphysical "prime mover"; on this, see G. Patzig, "Theology and Ontology in Aristotle's Metaphysics," in Barnes et al., *Articles on Aristotle*, 3:33–49. Both senses are found in Aquinas, although he emphasized the transcendent and divine character of the object of the science: Thomas Aquinas, *Commentary on the Metaphysics of Aristotle*, trans. J. P. Rowan, 2 vols. (Chicago: Regnery, 1961), 1:2.

9 Aristotle, *Physics*, I. 1–2; *Metaphysics*, III. 2.

10 See Edith Sylla, "The A Posteriori Foundations of Natural Science," *Synthese*, 40 (1979):147–87, which focuses on thirteenth- and fourteenth-century Oxford commentaries on Aristotle's *Physics*. The development of Aristotelian metaphysics in late medieval and early modern thought has been too little studied. Astrik Gabriel, "Metaphysics in the Curriculum of Studies of the Medieval Universities," in *Die Metaphysik im Mittelalter*, ed. Paul Wilpert (Berlin: de Gruyter, 1963), pp. 92–102, has done the service of charting its presence in university curricula; William J. Costello, *The Scholastic Curriculum at Seventeenth-century Cambridge* (Cambridge, Mass.: Harvard University Press, 1958), places metaphysics within the curriculum and gives some entry into its content (see esp. pp. 71–80). Descartes's claims that metaphysics can ground physics are well known (see, e.g., the Author's Letter to his *Principles of Philosophy*); Francis Bacon expresses this conception in various isolated remarks, for which see Lisa Jardine, *Francis Bacon: Discovery and the Art of Discourse* (Cambridge: Cambridge University Press, 1974), pp. 100–1.

11 Burtt rightly emphasizes that Platonic and Neoplatonic strains were woven into Christian thought in late antiquity and the early Middle Ages, especially through the influence of Plato's *Timaeus*. Although the absorption of Aristotle by the Latin West in the twelfth and thirteenth centuries led to Plato's partial eclipse, the recovery of virtually the entire Platonic corpus in the fifteenth century led to a renewed interest in Plato that extended throughout the sixteenth century. On these topics, see Raymond Klibansky, *The Continuity of the Platonic Tradition during the Middle Ages*, new ed. (Millwood, N.Y.: Kraus International, 1982), and A. C. Crombie, "Mathematics and Platonism in the Sixteenth-Century Italian Universities and in Jesuit Educational Policy," in Y. Maeyama and G. Saltzer, eds., *PRISMATA: Naturwissenschaftsgeschichtliche Studien* (Wiesbaden: Steiner, 1977), pp. 63–94. The "Platonism" of the Renaissance was deeply influenced by Neoplatonic commentary and, of course, may differ from what we today consider to be a good interpretation of the Platonic corpus.

12 In connection with the doctrine of subalternation, see Aristotle, *Physics*, II.2.194a7–11 and *Posterior Analytics*, I.7., esp. 75b14–20; geometrical constructions occur in *Meteorology*, III.3–5, and throughout the pseudo-Aristotelian *Mechanics*. For discussion, see Thomas Heath, *Mathematics in Aristotle* (Oxford: Oxford University Press [Clarendon Press], 1949). It has been suggested that the account of "demonstration" in the *Posterior Analytics* was intended to describe mathematical demonstration; at any rate, this thesis was under discussion at Galileo's Padua in the late sixteenth century (Crombie, "Mathematics and Platonism," p. 74). The doctrine of the "mixed" or "intermediate" sciences is discussed by Aquinas in questions V and VI of his commentary on Boethius's *De trinitate*, translated by A. Maurer under the title *The Division and Method of the Sciences* (Toronto: Pontifical Institute of Medieval Studies, 1963).

13 On the doctrine of abstraction, see Aquinas, *Division and Method*. Later scholastic discussions of this doctrine in connection with the relations among the sciences may be found in Eustace of St. Paul, *Summa philosophiae* (Cologne, 1620), Pt. I, pp. 155–7; Pt. III, pp. 1–4, and Pt. IV, pp. 1–3, and in the University of Coimbra, *Commentariorum . . . in octo libris Physicorum Aristotelis Stagiritae* (Cologne, 1599), col. 6. On the Italian front, see the

discussion of Blancanus in William A. Wallace, *Galileo and His Sources: The Heritage of the Collegio Romano in Galileo's Science* (Princeton: Princeton University Press, 1984), pp. 142–3, 207. Relevant passages from Aristotle include *Physics*, II.2.194a7–11; *Metaphysics*, XI.3.1061a28–b7; and *On the Soul*, III.7.431b12–16. Of course, it is not clear that either the doctrine of subalternation or the notion of "intelligible matter" provides the best interpretation of Aristotle's thought, but our interest here is in the versions of Aristotelian thought available during the late medieval and early modern period.

14 For a general treatment of the "mathematical renaissance," focused primarily on Italy, see Paul L. Rose, *The Italian Renaissance of Mathematics: Studies on Humanists and Mathematicians from Petrarch to Galileo* (Geneva: Droz, 1975); for the Middle Ages, see the chapters on mathematics and the various mathematical sciences in *Science in the Middle Ages*, ed. David C. Lindberg (Chicago: University of Chicago Press, 1978).

15 On the development of a full-blooded astronomy in Islam, see John W. Livingston, "Nasir al-Din al-Tusi's *al-Tadhkirah:* A Category of Islamic Astronomical Literature," *Centaurus*, 17 (1972–1973):260–75, and the helpful discussion of Jamil Ragep, "Cosmography in the *Tadhira* of Nasir al-Din al-Tusi," 2 vols., Ph.D. diss., Harvard University, 1982, vol. 1, sec. 2. On the "discipline" of astronomy in early modern Western Europe, see Robert S. Westman, "The Astronomer's Role in the Sixteenth Century: A Preliminary Study," *History of Science*, 18 (1980):105–47. See also David C. Lindberg, *Theories of Vision from al-Kindi to Kepler* (Chicago: University of Chicago Press, 1976), p. 100, on the disciplinary autonomy of optics in the late medieval period.

16 E. W. Strong, *Procedures and Metaphysics: A Study of the Philosophy of Mathematical-Physical Science in the Sixteenth and Seventeenth Centuries* (Berkeley and Los Angeles: University of California Press, 1936); the distinction between the two traditions is set out in Chap. 1. Strong originally had envisioned his work as substantiating and extending Burtt's.

17 Ibid., p. 13.

18 Ibid., pp. 68–90 and Chap. 7.

19 Ibid., Chap. 7 and pp. 215–16.

20 Ptolemy appeals to the "indisputable methods" of mathematics, *Ptolemy's Almagest*, trans. G. J. Toomer (New York: Springer-Verlag, 1984), p. 36. Tartaglia maintains that the certainty of mathematics stems from the fact that mathematicians "imagine" the objects of their constructions apart from matter, a factor that had led "the wise" to consider the mathematical disciplines "not only to be more certain than the physical, but even to have the highest degree of certainty": Niccolò Tartaglia, *Various Questions and Inventions* (Venice, 1546), in *Mechanics in Sixteenth-century Italy: Selections from Tartaglia, Benedetti, Guido Ubaldo, and Galileo*, trans. Stillman Drake and I. E. Drabkin (Madison: University of Wisconsin Press, 1969), pp. 106–7. (On the apparently "philosophical" character of the appeal to abstraction, see the following paragraphs.)

21 On the development of the idea that geometry describes space in something like the modern sense, see Roberto Torretti, *Philosophy of Geometry from Riemann to Poincaré* (Dordrecht: Reidel, 1978), Chap. 1, and the literature cited there. On the development of optics as a theory of vision based on the rectilinear "visual ray," see Albert Lejeune, *Euclide et Ptolémée: Deux stades de l'optique géométrique grecque* (Louvain: Bibliothèque de l'Université, 1948), pp. 77–80, 92–6. On the reality of the spherical constructions of ancient and medieval astronomy, see Ragep, "Cosmography in the *Takhkira.*" The doctrine that mathematical objects are realized in natural objects is reminiscent of Aristotle, although, in the Aristotelian context, it was embedded in the metaphysics of "intelligible matter" and the methodology of intellectual abstraction (see note 13, this chapter).

22 The quotation is from Book 3 of the *Almagest* (pp. 140–1); the metaphysical justification occurs in Book 9 (p. 420): "Now it is our purpose to demonstrate for the five planets, just as we did for the sun and moon, that all their apparent anomalies can be represented by uniform circular motions, since these are proper to the nature of divine beings, while disorder and non-uniformity are alien [to such beings]." "Divine perfection" was hardly the only justification available for the astronomical practice of using uniform circular motion. As Aristotle maintains, in *On the Heavens* (I.2), if the basic motion of the heavens were other than circular, "it would be remarkable and indeed quite inconceivable that this movement should be continuous and eternal" (269b7–9); even if the planets "wander," they do so periodically.

23 I do not mean to underplay the difficulty of doing this. An author may assume a philosophical position without making it explicit. Silence need not imply absence, and phrases and allusions may be the only overt evidence. But philosophical positions should not be too easy to come by. A judgment must be rendered about whether a given author is proceeding in accordance with a specific philosophical position by seeing whether his or her various pronouncements "hang together" in an appropriate manner.

24 Tartaglia writes as follows: "The physicist considers, judges, and determines things according to the senses and material appearances, while the mathematician considers and determines them not according to the senses, but according to reason, all matter being abstracted – as your Excellency knows that Euclid was accustomed to do" (*Various Questions*, in Drake and Drabkin, *Mechanics*, pp. 105–6). This initial appeal to "reason" is followed by a phrase describing mathematical objects as being "imagined apart from matter," a phrase that might suggest an Aristotelian conception of mathematical knowledge. However, three pages later Tartaglia may seem to be expressing a Platonic attitude: "And thus I say in conclusion that the more the parts or members of a material scale or balance resemble or approach the parts or members of an immaterial one (which is the original or ideal of all material ones), so much the more agile and responsive will it be than those which less resemble or approach this, the sizes being the same" (ibid., p. 109). Rather than holding that Tartaglia

could not make up his mind or that he was a typical eclectic, I suggest that, although he was eclectic in phraseology, the key to his attitude lies in the initial appeal to Euclidean practice to make sense of ideal mathematical objects.

25 Ptolemy, *Almagest*, p. 36. Ptolemy's preface is sometimes labeled "Aristotelian" on the basis of his division of theoretical philosophy into three branches: theology, mathematics, and physics. While the division is Aristotelian, Ptolemy invokes it in his preface only to undercut it by asserting the autonomy and precedence of mathematics.

26 On the rejection of syllogistic logic by Peter Ramus, see Cassirer, *Erkenntnisproblem*, pp. 130–5. Galileo and Descartes also attack syllogistic logic and contend that logical thinking is best displayed in mathematical works; it is unknown whether these attacks show the influence of Ramus.

27 Burtt, *Metaphysical Foundations*, p. 23. See also Westfall, *Construction of Modern Science*, pp. 12, 24; Hall, *Revolution in Science*, p. 118.

28 Burtt, *Metaphysical Foundations*, pp. 40–4. See also Hall, *Revolution in Science*, p. 70, where he labels the core of Copernicus's argument "aesthetic"; however, he dissociates Copernicus from Platonism and helio-mysticism, ibid., pp. 33–4, 67. The contemporary locus classicus of the interpretation described in this paragraph is Thomas S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Cambridge, Mass.: Harvard University Press, 1957). For an interesting response to Kuhn and others, see Imre Lakatos and Elie Zahar, "Why Did Copernicus' Research Program Supersede Ptolemy's?", in *The Copernican Achievement*, ed. Robert S. Westman (Berkeley and Los Angeles: University of California Press, 1975), pp. 354–83. Rose, *Renaissance of Mathematics*, pp. 122–130, reviews various lines of evidence for Platonic and other philosophical influences on Copernicus.

29 Nicholas Copernicus, *On the Revolutions*, ed. Jerzy Dobrzycki, trans. Edward Rosen (Baltimore: Johns Hopkins University Press, 1978), pp. 4, 7. In the *Narratio prima* of Copernicus's disciple, Rheticus, one finds a paean to the number six, in justification of counting the earth among the other planets (Mercury, Venus, Mars, Jupiter, and Saturn); references to a (questionably) Platonic treatise, the *Epinomis*, to the effect that astronomy was discovered with divine guidance; and quotation of the phrase attributed to Plato, "God ever geometizes," as something that Rheticus has learned to appreciate through the example of his teacher: *Narratio prima*, in *Three Copernican Treatises*, trans. Edward Rosen, 2nd ed. (New York: Dover, 1959), pp. 147, 163, 168. Of course, Rheticus need not be expressing Copernicus's own views; moreover, even in the *Narratio* these phrases are overshadowed by arguments concerning the precession of the equinox and the "order" of the planetary spheres (*Narratio prima*, esp. pp. 136–8).

30 Copernicus, *On the Revolutions*, p. 22.

31 Copernicus sets out his general argument in the preface to *On the Revolutions*, p. 4, and makes or reviews the crucial points on pp. 18, 20–1, 25, 120–3, 227, 240; the removal of common objections occurs primarily in Bk. 1, Chaps. 5–8. Although on some occasions he claims that he will "demonstrate" his new position (e.g., p. 5), his local claims for his arguments

show that he did not attribute to them the certainty of geometrical demonstration (see the latter part of the present section).

32 The metaphysical justification of uniform circular motion is couched in terms of the sphere expressing "its form as the simplest body"; the astronomical justification comes in a discussion of irregularities in the motion of the sun, moon, and planets: "We must acknowledge, nevertheless, that their motions are circular or compounded of several circles, because these nonuniformities recur regularly according to a constant law. This could not happen unless the motions were circular, since only the circle can bring back the past. Thus, for example, by a composite motion of circles the sun restores to us the inequality of days and nights as well as the four seasons of the year" (Copernicus, *On the Revolutions*, pp. 10, 11; see also p. 123, on grasping nonuniform motion through uniform mean motion).

33 This does not mean that the "scandal of the equant" could not have motivated the search for alternatives to Ptolemy, including the heliocentric alternative, as Copernicus maintains in the *Commentariolus* (in Rosen, *Three Copernican Treatises*, p. 57) and in *On the Revolutions* (p. 240), and as Curtis Wilson maintains in his "Rheticus, Ravetz, and the 'Necessity' of Copernicus' Innovation," in Westman, *Copernican Achievement*, pp. 17–39. Copernicus's remarks on motivation and Wilson's historical investigation pertain to what started Copernicus on the path to his new position; we are focusing on the arguments that Copernicus presented to his reader in support of heliocentrism.

34 *On the Revolutions*, pp. 17, 21, 25, 120, 122. The "simplicity" or "economy" stems from moving the smaller, enclosed body, rather than the larger, framing body, and in accounting for precession by the relations between the second and third of the motions already ascribed to the earth.

35 Ibid., pp. 4, 18, 20, and 22.

36 Copernicus described his book as written for astronomers and said that his aim was to gain their considered approval (ibid., pp. 5, 21).

37 Pierre Duhem, *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo*, trans. Edmund Doland and Chaninah Maschler (Chicago: University of Chicago Press, 1969), p. 27. Much mischief has been caused by the acceptance of Duhem's characterization of Ptolemaic astronomy as inherently "instrumental" (ibid., pp. 16–18). Duhem's case was aided by the fact that the more "physical" portions of Ptolemy's *Planetary Hypotheses*, trans. Bernard Goldstein, Transactions of the American Philosophical Society, n.s., vol. 57, no. 4 (Philadelphia: American Philosophical Society, 1967), were until recently available only in Arabic and Hebrew. But it was overdrawn from the outset, and one of the very passages that he cited (p. 18) in its support – in which Ptolemy portrays the heavenly medium as "yielding" to the complex motions of his circular constructions – seems to argue for, rather than against, their physical reality (*Almagest*, pp. 600–1). On mathematical constructions as descriptions of physical reality in Islamic astronomy, see Ragep, "Cosmography in the *Takhkira*." On Copernicus and the Latin West, see Noel M. Swerdlow, "Pseudodoxia Copernicana," *Archives internationale d'histoire des sci-*

ences, 26 (1976):108–58. E. J. Aiton, "Celestial Spheres and Circles," *History of Science*, 19 (1981):75–114, surveys Greek, Arabic, and Latin authors and establishes connections among them.

38 In interpreting this criterion of "physical plausibility," one must avoid seeking an analogy for the Newtonian conception of forces producing orbits; given the tendency of astronomers to avoid questions about the substantial composition and motive force of the celestial spheres, "physical plausibility" amounts to mechanical and kinematic coherence. On the separation of physical astronomy from natural philosophy or physics proper, see Swerdlow, "Pseudodoxia Copernicana," pp. 143–8; Westman, "Astronomer's Role"; and Nicholas Jardine, *The Birth of History and Philosophy of Science: Kepler's "A Defence of Tycho against Ursus" with Essays on its Provenance and Significance* (Cambridge: Cambridge University Press, 1984), Chap. 7.

39 The promise occurs in *On the Revolutions*, p. 4; the phrases quoted earlier appeared in the Introduction to Book 1 (pp. 7–8), which was not included in any sixteenth- or seventeenth-century edition of the work.

40 The quoted phrases are from *On the Revolutions*, pp. 227, 307, 25, 4; see also Bk. 1, Chaps. 9–10. For reconstructions of Copernicus's arguments, see Lakatos and Zahar, "Copernicus' Research Program," with comments by Stephen Toulmin (in Westman, *Copernican Achievement*, pp. 384–91), and Clark Glymour, *Theory and Evidence* (Princeton: Princeton University Press, 1980), pp. 178–203.

41 *De revolutionibus orbium coelestium* (Nurnberg, 1543; reprint edition, Brussels: Culture and Civilization, 1966), p. 7r; *On the Revolutions*, p. 17.

42 On the mathematical sufficiency of Ptolemy, see Copernicus, *Commentariolus*, trans. Rosen, p. 57, and *On the Revolutions*, p. 4. Copernicus discusses the relativity of observed celestial motion in *On the Revolutions*, pp. 11–12, from which it follows that either the earth or the heavens might be in motion, and he mentions the "reversible agreement" of the opposing hypotheses on diurnal rotation on p. 51. He admits the equivalence of constructions for the yearly earth/sun motions on p. 155, lines 33–4 (Rosen says that this sentence was intended for deletion and, in any case, was inserted in the wrong place, but it does make sense in the position in which it was printed. That Copernicus recognized the point can be seen from another bit of the manuscript that actually was deleted: p. 25, lines 19–20). He discusses the equivalence of epicyclic and eccentric models within his own system on pp. 156, 164, 169–70.

43 *On the Revolutions*, p. 122, lines 38–9, and p. 17, lines 30–2; see also p. 120, lines 11–16.

44 Burtt, *Metaphysical Foundations*, p. 50. See also Cassirer, *Erkenntnisproblem*, pp. 328–77, and Koyré, *Galileo Studies*, pp. 144–53.

45 See especially Johannes Kepler, *Mysterium cosmographicum / The Secret of the Universe*, trans. A. M. Duncan (New York: Abaris, 1981), greeting to the reader, original dedication and preface, and Chap. 14. E. J. Aiton's introduction (ibid., pp. 17–31) summarizes the main themes of the work and provides helpful explication, drawing upon Kepler's correspondence.

46 Kepler, *Harmonice mundi*, in *Gesammelte Werke*, ed. Walther von Dyck and Max Caspar, 18 vols. (Munich: Beck, 1937–1959), vol. 6. The discussion of Plato and the doctrine of innate archetypes occurs in Chap. 1, esp. pp. 220–1. Book 4 is presented as an explanation of astrological phenomena, and particularly as an account of how the "aspects" of the stars might (through their harmonious proportions) affect events on earth, given the supposition that earthly souls are naturally responsive to harmonies; the discussion in the first four chapters is, however, quite general, and the book is listed on the title page as "Metaphysical, Psychological, and Astrological" (p. 9). Kepler later applied the doctrine that the "Ideas of quantities . . . are like a pattern in souls made in the image of God" in connection with his cosmographic hypothesis pertaining to the five solids (*Mysterium*, p. 73). He characterized the creation of the universe in accordance with geometrical structures as the product of God's play and suggested that in emulating this play, he (Kepler) did so in accordance with a natural tendency (Jardine, *Birth of History and Philosophy of Science*, p. 252).

47 The quoted phrases are from *Mysterium*, pp. 63, 77–9, 97–9; Kepler characterizes Copernicus's "a posteriori" arguments as "established by observation" (pp. 77–9, 97–9; Kepler knew that reasoning from observation involves the application of standards for selection among hypotheses, and hence he here implies that such standards are not metaphysical). Whereas Kepler saw Copernicus as carrying on the work of Ptolemy, he saw himself (in part) as continuing the sublime speculations of Pythagoras and Plato on the five solids (pp. 49, 53, and 63). It should be noted that Kepler is probably using "a priori" to mean "from cause to effect," and "a posteriori" to mean "from effects to cause"; so understood, a priori reasoning proceeds independently of the senses only if the causes are so known.

48 One such discussion occurs in *Mysterium*, Chap. 1. On Kepler's attitude toward and understanding of Copernicus's arguments, see Robert S. Westman, "Kepler's Theory of Hypothesis and the 'Realist Dilemma,'" *Studies in History and Philosophy of Science*, 3 (1972):233–64, and Jardine, *Birth of History and Philosophy of Science*, Chap. 7.

49 In the original preface to the *Mysterium*, Kepler reports his eagerness to "see whether the proposition which I had conceived in words [regarding the five solids] would agree with the circles of Copernicus, or whether my joy would be scattered to the winds" (p. 69). In the same work, he emphasizes that he had guessed the structure of the universe by considering that it must be good and beautiful (esp. pp. 53–5, 93–5), which led him to five solids and six planetary orbits. In subsequent letters he affirms the need to check his a priori reasoning against the observed positions of the planets, and in the second edition of the *Mysterium* he paraphrases Brahe's letter asking him to "hold in abeyance my speculations which were derived a priori, and apply my mind instead to considerations of the observations which he was simultaneously offering" (p. 59).

50 Burtt, *Metaphysical Foundations*, Chap. 4, esp. pp. 96–102.

51 For recent discussions of Descartes's philosophy in general, see Margaret D. Wilson, *Descartes* (London: Routledge & Kegan Paul, 1978), and E. M.

Curley, *Descartes against the Skeptics* (Cambridge, Mass.: Harvard University Press, 1978). Desmond M. Clarke, *Descartes' Philosophy of Science* (University Park: Pennsylvania State University Press, 1982), examines the relationship between Descartes's metaphysics and physics (Chap. 4). To my mind, the most philosophically satisfying discussion of this relationship remains that by Gerd Buchdahl, in his *Metaphysics and the Philosophy of Science: The Classical Origins, Descartes to Kant* (Oxford: Blackwell, 1969); see also Bernard Williams's balanced discussion in his *Descartes: The Project of Pure Enquiry* (New York: Penguin Books, 1978), Chaps. 8–9.

52 Descartes's "derivation" of the three laws (in the *Principles of Philosophy*, Pt. II, esp. articles 24–44) may not seem metaphysical (in a historical sense); Descartes, however, characterized it as such: See his *Philosophical Letters*, ed. Anthony Kenny (Oxford: Oxford University Press [Clarendon Press], 1970), p. 136.

53 For Descartes's discussion of the derivation of his "principles," see the Author's Letter preceding the *Principles*.

54 Since the doctrine of clear and distinct perception may be viewed as a methodological doctrine, Burtt's remark that important thinkers tend to make a metaphysics of their method is apt, in this case (*Metaphysical Foundations*, p. 226): Descartes did make a metaphysics of his method. But he did it explicitly, as one engaged in metaphysics, and not as one who unwittingly succumbed to temptation. I have examined the interplay between Descartes's method and metaphysics in "The Senses and the Fleshless Eye: The *Meditations* as Cognitive Exercises," in *Essays on Descartes' Meditations*, ed. Amèlie O. Rorty (Berkeley and Los Angeles: University of California Press, 1986), pp. 45–79, esp. sec. 5.

55 As with many thinkers in the Renaissance and early modern period, Descartes has been claimed for both Plato and Aristotle, or at least certain of his central tenets have been held to be in a Platonic tradition (Etienne Gilson, "L'innéisme Cartésien et la théologie," in his *Études sur le rôle de la pensée mediévale dans la formation du système Cartésien*, 4th ed. [Paris: Vrin, 1975], pp. 9–50) and in an Aristotelian one (Clarke, *Descartes' Philosophy of Science*, Chap. 8).

56 Examples of Descartes's use of scholastic terminology are evident in the *Principles*, e.g., Pt. I, articles 51–3 and 56–65, in the Third Meditation, and in the *Objections and Replies*, replies 1, 2 (appendix), and 4. While some instances of such terminology may be explained as Descartes's attempt to co-opt the scholastics, the concepts of substance and essence are too deeply embedded for the terminology to be explained away in this fashion.

57 Descartes also violated Aristotelian doctrine by regarding mind and body as each constituting a "complete being" (another scholastic notion; see *Objections and Replies*, replies 2 and 4), thus denying the fundamental Aristotelian doctrine that the mind is the "form" of the human body. I have discussed Descartes's creative violations of Aristotelian metaphysics in "First Philosophy and Natural Philosophy in Descartes," in *Philosophy, Its History and Historiography*, ed. A. J. Holland (Dordrecht: Reidel, 1985), pp. 149–64.

58 For Descartes's statement of his doctrine that extension is known by pure intellection, see the second half of the Second Meditation and the first few paragraphs of the Sixth. I have explicated Descartes's position in contrast with an Aristotelian one in "The Senses and the Fleshless Eye." An exception to the strict abstractionism of Thomas and others is provided by Albertus Magnus and his followers, on which see Katharine Park, "Albert's Influence on Late Medieval Psychology," in *Albertus Magnus and the Sciences*, ed. James A. Weisheipl (Toronto: Pontifical Institute of Medieval Studies, 1980), pp. 501–35, esp. sec. A.

59 Descartes put forth his doctrine of the creation of the eternal truths in letters to Marin Mersenne of 15 April and of 6 and 27 May 1630 (*Letters*, pp. 11–12, 13–14, 15); he affirmed it in print in the fifth set of *Objections and Replies*, in reply to objections to the Fifth Meditation. The letters themselves were first published in *Lettres de M. Descartes*, ed. Claude Clerselier, 3 vols. (Paris, 1657–1667), vols. 1–2. On the place of this doctrine in Descartes's thought, see Jean-Luc Marion, *Sur la théologie blanche de Descartes: Analogie, création des vérités eternelles et fondement* (Paris: Presses Universitaires de France, 1981).

60 On the foundation of physics upon metaphysics, see the Author's Letter to the *Principles* and the letters to Mersenne of 11 November 1640 and 28 January 1641 (in *Letters*, pp. 82, 94); on the relation between physics and geometry, see the *Principles*, Pt. II, article 64, and the letter to Mersenne of 27 July 1618, in *Oeuvres de Descartes*, ed. C. Adam and P. Tannery, 11 vols. (hereafter, *AT*), new ed. (Paris: Vrin, 1964–1974), 3:268.

61 In a letter of 1637, Descartes wrote of his philosophy that "like Mechanics, it considers shapes and sizes and motions" (*Letters*, p. 38). It is interesting to note that in the earlier *Rules for the Direction of the Mind*, Descartes had seemed to conceive the natural philosopher as seeking proportional relations among fundamental magnitudes (see esp. rules VIII, XIII, and XIV), a conception much akin to the search for quantitative laws of nature. For a helpful account of the project of the *Rules*, and its breakdown, see John A. Schuster, "Descartes' *Mathesis universalis*: 1619–1628," in *Descartes: Philosophy, Mathematics and Physics*, ed. Stephen Gaukroger (Sussex: Harvester Press, 1980), pp. 41–96, and his 1977 Princeton Ph.D. dissertation, "Descartes and the Scientific Revolution, 1618–1634: An Interpretation," 2 vols. (Ann Arbor: University Microfilms International, 1977).

62 On the metaphysical function of the deity in providing a conceptual home for causal agency, see my "Force (God) in Descartes' Physics," *Studies in History and Philosophy of Science*, 10 (1979):113–40, and "First Philosophy and Natural Philosophy." See also Clarke, *Descartes' Philosophy of Science*, Chap. 4.

63 Descartes dismisses Galileo's law of fall in his letter to Mersenne of 11 October 1638 (*AT*, 2:386–7); I accept the suggestion in the annotation (p. 415) that Descartes rejected the law because his plenum-physics told him that such precise laws would not be realized in actual cases (see also *Principles*, Pt. II, article 53). On Descartes and Galileo, see William R. Shea, "Descartes as a Critic of Galileo," in *New Perspectives on Galileo*, ed. Robert

E. Butts and Joseph C. Pitt (Dordrecht: Reidel, 1978), pp. 139–59.

64 Descartes's methodological remarks bearing on the need for experiment occur in the *Discourse on Method*, Pt. VI, and in *Principles*, Pt. IV, articles 203–6. For discussions of Descartes's systematic recognition of the need for experiment, see Williams, *Descartes*, Chap. 9, and Clarke, *Descartes' Philosophy of Science*, Chaps. 2 and 6, and the literature cited therein. While recognizing a strong role for experience and experiment in Descartes's natural philosophy, I consider him less of an "empiricist" than does Clarke (see my "First Philosophy and Natural Philosophy").

65 *Meteors*, First Discourse; Descartes to Vatier, 22 February 1638, and to Morin, 13 July 1638 (in *Letters*, pp. 48–9, 57–9); *The World*, Chaps. 1–5; see also the letters to Plempius of 3 October and 20 December 1637 (in *Letters*, pp. 35–40, 43–4) and to Mersenne of 17 May 1638 (*Letters*, pp. 55–6). The *Meteors* was published in 1637 and the letters in the *Lettres* of 1657–1667; *Le monde* was composed by 1633 and published in 1664.

66 While "simplicity" may seem to be an inherently "metaphysical" criterion, Descartes explicitly sets it off from the a priori metaphysical arguments he was later to publish in the *Meditations* and *Principles* (Descartes to Vatier, in *Letters*, p. 48). He seems rather to include it within an a posteriori type of reasoning, perhaps because it is a criterion (even if a "conceptual" one) applied to hypotheses on the basis of their relative merits in accounting for a set of phenomena, rather than a criterion for reasoning independently of sensory experience.

67 It might seem that Descartes would simply refuse to believe evidence contrary to his physics (see, e.g., *Le monde*, in *AT*, 9:43); the contention that his denial of the vacuum had the force of "logical necessity" would seem a case in point (Descartes to Mersenne, 9 January 1639, in *Letters*, p. 63). Yet he was willing to grant the (remote) possibility that his assertion of the instantaneous velocity of light was false, even though this assertion was central to his physics (Descartes to Mersenne, 17 May 1638, in *Letters*, p. 56), and to discuss the details of various empirical tests (Descartes to Beeckman, 22 August 1634, *AT*, 1:307–12).

68 Scholars have long debated the question of whether Galileo was a philosopher and, if so, of what type. See Peter Machamer, "Galileo and the Causes," in Butts and Pitt, *New Perspectives*, pp. 161–80; Robert E. Butts, "Some Tactics in Galileo's Propaganda for the Mathematization of Scientific Experience," in ibid., pp. 59–85; Paul K. Feyerabend, *Against Method* (1975; London: Verso, 1978), Chaps. 6–13; A. C. Crombie, "Sources of Galileo's Early Natural Philosophy," in *Reason, Experiment, and Mysticism in the Scientific Revolution*, ed. M. L. Righini Bonelli and William R. Shea (New York: Science History, 1975), pp. 157–75; and Dudley Shapere, *Galileo: A Philosophical Study* (Chicago: University of Chicago Press, 1974), esp. pp. 143–5. My own position on the sense in which Galileo was a philosopher shares some features with that of Maurice A. Finocchiaro, *Galileo and the Art of Reasoning: Rhetorical Foundations of Logic and Scientific Method* (Dordrecht: Reidel, 1980), esp. Chap. 6, although I question whether Galileo may significantly be characterized as "a counterinductivist, *and* an Aristotelian, *and* a Platonist, *and* an empiricist, *and* a rationalist" (p. 159).

I agree with Strong's denial that Galileo was a metaphysician (*Procedures and Metaphysics*, Chap. 6), but I believe that Strong did not see the non-metaphysical philosophical dimension to Galileo's work.

69 Burtt, *Metaphysical Foundations*, pp. 71–6, 83, and 197–8; Koyré, *Galileo Studies*, pp. 159 and 201–9, and *Metaphysics and Measurement*, Chap. 2 (but see this chapter, Note 3); and Cassirer, *Erkenntnisproblem*, pp. 32 and 329–30, and *Individual and Cosmos*, pp. 162–9. Although Cassirer maintained that Galileo was a Platonist in his mathematical outlook on nature, he was careful to show ways in which Galileo avoided a deep commitment to metaphysics: *Erkenntnisproblem*, pp. 383 and 404, and "Galileo's Platonism," in *Studies and Essays in the History of Science and Learning*, ed. M. F. Ashley Montagu (New York: Schuman, 1946), pp. 277–97.

70 These lines of evidence are presented by Burtt, *Metaphysical Foundations*, pp. 64–72, and Koyré, *Galileo Studies*, pp. 159, 166–7, 204–9.

71 Crombie, "Sources," and A. Carugo and A. C. Crombie, "The Jesuits and Galileo's Ideas of Science and of Nature," *Annali dell'Instituto e museo di storia della scienza di Firenze*, 8 (1983):3–68; Wallace, *Galileo and His Sources*, esp. pp. 91–6, 219–20, 338–49.

72 Galileo, *Dialogo sopra i due massimi sistemi del mondo* (Florence, 1632), in *Le opere di Galileo Galilei*, National Edition (hereafter, *EN*), ed. Antonio Favaro, 20 vols. (Florence: Ministry of Public Instruction, 1890–1909), 7:129; translation adapted from *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican* (hereafter, *TCWS*), trans. Stillman Drake (Berkeley and Los Angeles: University of California Press, 1953), p. 103.

73 *TCWS*, p. 145; *EN*, 7:171.

74 Koyré, *Metaphysics and Measurement*, pp. 12–15, and *Galileo Studies*, pp. 164–7.

75 *TCWS*, pp. 190–1; *EN*, 7:217. Drake glosses this as a Socratic and Platonic doctrine (*TCWS*, note to p. 191); other commentators have asserted that it is a straightforward endorsement of a Platonic doctrine: e.g., Koyré, *Metaphysics and Measurement*, pp. 41–3, and Cassirer, *Individual and Cosmos*, pp. 168–9. Shapere suggests that although Galileo was not a Platonist, he may have *thought* that he was (*Galileo*, pp. 131–3, 142).

76 *TCWS*, p. 191; *EN*, 7:217–18. Sagredo, the third interlocutor, is the spokesman for educated "common sense."

77 These examples occur in *TCWS*, pp. 145–90.

78 On Plato's doctrine, see the *Meno*, 81–86b, *Phaedo*, 72e–76e, and *Phaedrus*, 247c–250a; see also *Republic*, Book VII, 518b6–d1. In the *Meno* and *Phaedo* the discussion alludes to drawings or other sensory examples; in all of the passages except the *Meno* the discussion makes clear that the knowledge is attained by intellectual apprehension, independently of the senses. Contrast this with Salviati's subsequent literal usage of *ricordare* (the Italian word used to gloss *reminisci*) and related terms (*TCWS*, p. 193; *EN*, 7:219–20.

79 Contrary to Feyerabend (*Against Method*, p. 81), the arguments in favor of diurnal rotation are not portrayed by Galileo as "known and conceded by all"; Simplicio is portrayed as being able to grasp them for himself, but often only with considerable prompting and after he has paused to

think (e.g., *TCWS*, pp. 89–97, 147, 157–61, 191–93).

80 *TCWS*, p. 146; EN, 7:172.

81 Simplicio introduces some of them himself ("circumference," "angle"), after which Salviati praises him and goes on to supply the remaining words, such as "tangent" and "arc." Simplicio confirms Salviati's geometrical construal of his meaning: "I understand perfectly, and this is just what I meant" (*TCWS*, p. 192).

82 Ibid.

83 Ibid., p. 194.

84 Ibid., pp. 9–11, 35, 197, 200, 203, 397; *Discourses and Mathematical Demonstrations Concerning Two New Sciences* (hereafter, *TNS*), trans. Stillman Drake (Madison: University of Wisconsin Press, 1974), pp. 59–60, 119–20, 133. Brian Vickers discusses the use of praise and blame in "Epideictic Rhetoric in Galileo's *Dialogo*," *Annali dell'Instituto e museo di storia della scienza di Firenze*, 8 (1983):69–102, although in my view he portrays Simplicio as too uniformly a simpleton: Simplicio is rebuked for not knowing his geometry (*TCWS*, pp. 30, 281, 337), but he also shows the ability to gain geometrical skills, for which he is praised (*TCWS*, pp. 192, 288–9).

85 *TCWS*, pp. 203, 289, 397; *TNS*, pp. 93, 123, 223. An early biographer remarked that Galileo appreciated Plato for his use of dialogue, and Pythagoras for his "way of philosophizing, but in genius he said that Archimedes surpassed all, and he called him his master" (*EN*, 19:645; translation from Crombie, "Sources," p. 157).

86 Feyerabend's discussion (*Against Method*, Chaps. 6–8) of the Aristotelian doctrines that Galileo had to overcome is helpful. See also Shapere, *Galileo*, Chaps. 2–4.

87 *TCWS*, pp. 149–54 and 145–8. In order to establish the "indifference" of bodies to horizontal motion, Galileo must assume that impetus is not self-corrupting, as he himself had earlier held it to be (Shapere, *Galileo*, pp. 75–6). In this context it will be helpful to remember that in order to counter objections against the theory of the motion of the earth based on the behavior of falling bodies, Galileo needed only to show that a theory of motion could be provided that was consistent with the earth's rotation – not that such a theory was true.

88 Carugo and Crombie, "Jesuits and Galileo"; Wallace, *Galileo and His Sources*, pp. 101–16 and Chap. 6. Galileo's attitude is not that he must always demonstrate from self-evident or previously known propositions: Sometimes basic propositions must be determined through measurement. In such cases his approach is not particularly hypothetico-deductive; he is seeking to determine a basic definition by experience, after which he will treat it as known with certainty for the purposes of further demonstration. Although Galileo at times took the attitude of testing through consequences, he did not take it systematically, nor did he reflect upon it, as he did upon other aspects of his practice. It is, then, quite correct to say that his model of science was based on an older conception of demonstrative science and should not straightforwardly be equated with the familiar hypothetico-deductive model (see Ernan McMullin, "The Conception of Science in Galileo's Work," in Butts and Pitt, *New Perspectives*, pp. 209–57; on Galileo and method, see also Winifred Lovell Wisan, "Galileo's Scientific Method: A Reexamination," in ibid., pp. 1–57).

89 Carugo and Crombie, "Jesuits and Galileo"; Wallace, *Galileo and His Sources*. The evidence presented by these authors, based upon their examinations of Galileo's early notebooks, shows that Galileo was well acquainted with the methodological discussions at the Collegio, and Wallace's examination of his correspondence shows that he enjoyed amiable relations with certain Jesuits throughout his life (ibid, Chap. 6). But they present little evidence to show that Galileo *adopted* the positions of the textbooks or manuscripts he copied. Indeed, Wallace's comparison of Galileo's notebooks with Collegio texts (*Galileo and His Sources*, Chap. 2) shows that at times Galileo did not really understand the material he was copying (pp. 71–2); Wallace's arguments to show that Galileo subscribed to the copied material are virtually nonexistent, and in Chap. 3 he simply shifts to the device of labeling the material reconstructed from the notebooks as "Galileo's views" or "Galileo's position."

90 Wallace limits his ascription of Aristotelianism to Galileo's methodology (*Galileo and His Sources*, p. 99 and chap. 6, sec. 4), while acknowledging Galileo's non-Aristotelian positions on other matters (pp. 233–5, 237–8); at the same time, he locates the sources of some of Galileo's criticisms of Aristotle in scholastic writers (pp. 277, 303–4).

91 Galileo's remarks on the operation of the senses occur in the *Assayer*, in *The Controversy of the Comets of 1618*, trans. Stillman Drake and C. D. O'Malley (Philadelphia: University of Pennsylvania Press, 1960), pp. 308–13. On logic and motion, see *TCWS*, pp. 35, 130–54; *TNS*, pp. 133, 65–71. On the search for essences, see the *Letters on Sunspots*, in *Discoveries and Opinions of Galileo*, trans. Stillman Drake (Garden City, N.Y.: Doubleday, 1957), pp. 123–4, and *TCWS*, pp. 39, 234.

92 On mathematics as treating of matters "in the abstract," see *TCWS*, pp. 203–8, and *TNS*, pp. 12–13, 58, 112–13, 223–7. Galileo's extant notebooks contain no treatment of Aristotelian doctrines regarding the mathematical sciences; the position that Wallace attributes to him is based upon Christopher Clavius and Clavius's student Josephus Blancanus (*Galileo and His Sources*, pp. 136–48).

93 *TCWS*, pp. 51, 110–13.

94 Butts, "Galileo's Propaganda," p. 60; Machamer, "Galileo and the Causes," p. 161; and McMullin, "Conception of Science," pp. 217–19.

95 There is a tendency to characterize the active, inquiring approach of the characters in Galileo's dialogues as Socratic, but their attitude of seeking to discern things for themselves is equally Aristotelian and, for that matter, is characteristic of a wide spectrum of authors whom we characterize as "philosophical" (e.g., see the Author's Letter to Descartes's *Principles*).

96 The quotations are from Drake and O'Malley, *Controversy on the Comets*, pp. 36, 71.

97 Galileo, *Assayer*, pp. 183–4; *EN*, 6:232.

98 Three pages earlier (in the same section of reply), Galileo disparaged Sarsi's claim that Grassi had followed Tycho's method of determining the distance of the comet from the earth, since "Tycho, in his manner

of investigating the distance of a comet by observations made from two different places on the earth, shows himself needful of attention to the very first elements of mathematics" (ibid., p. 181; *EN*, 6:229).

99 Galileo, *Letters on Sunspots*, p. 123; *EN*, 5:187.

100 Galileo, *Letters on Sunspots*, p. 124. In his Latin treatise "On Local Motion," embedded in *TNS*, Galileo rhetorically asks whether his definition of accelerated motion agrees with the *essentia* of naturally accelerated motion; this use of the word need not be given the sense of an Aristotelian "nature," or principle of change, but may be understood in its general connection with definition.

101 On the move to the subvisible, see *TNS*, pp. 58, 64; one motion that he could not measure was motion in a void (*TNS*, p. 76).

102 Galileo, *Assayer*, pp. 311, 309; *EN*, 6:350, 347–48.

103 Galileo's connection with Archimedes has, of course, been discussed before; typically, the "Archimedean" side of Galileo has been assimilated to Platonism: see, e.g., Koyré, *Metaphysics and Measurement*, pp. 14, 38, and William R. Shea, *Galileo's Intellectual Revolution: Middle Period, 1610–1632*, 2nd ed. (New York: Science History. 1977), Chaps. 1–2. Although the work of Archimedes and other mathematical authors often was found suffixed to a Neoplatonic preface, this was not universally the case; Tartaglia, for example, avoided Neoplatonism in both his edition of Archimedes and his own mathematical treatises: *Archimedes, His Tract De Incidentibus Humido, or the Natation of Bodies Upon, or Submersion In, the Water or Other Liquids*, trans. Thomas Salusbury, in *Mathematical Collections and Translations*, 2 vols. (London, 1661–1662), vol. 2, Pt. 1 (note especially the opening dialogue); see also the Letters of Dedication to Tartaglia's *New Science* and *Various Questions*, in Drake and Drabkin, *Mechanics*, pp. 63–9, 98–100.

104 See Tartaglia, *Bodies in Water*, p. 334, and *Various Questions*, pp. 111–112.

105 *TNS*, pp. 148–9.

106 Ibid., p. 155.

107 On material hindrances, see *TCWS*, pp. 207 and 232–3; on geometrical license, see *TNS*, pp. 223–5.

108 Benedetti, *Book of Various Mathematical and Physical Ideas* (Turin, 1585), in Drake and Drabkin, *Mechanics*, pp. 176–8; Guidobaldo, *The Book of Mechanics* (Pesaro, 1587), in ibid., pp. 259–65; Tartaglia, *Various Questions*, in ibid., pp. 128–32. See also Drake's introduction, pp. 46–7.

109 *TNS*, pp. 224–5.

110 *TCWS*, pp. 207–8; see also the appeal to the notion of a "good accounting," in *TNS*, p. 225. See *TNS*, pp. 12–13, for an interesting case in which Salviati rejects Sagredo's appeal to "material hindrances" and the "imperfections of matter."

111 Stillman Drake, *Galileo at Work: His Scientific Biography* (Chicago: University of Chicago Press, 1978), Chaps. 5–6.

112 Butts, "Galileo's Propaganda," pp. 71–4.

113 The quotations are from *TCWS*, pp. 203–8. For a helpful discussion of Galileo's use of the imagination in connection with the subvisible, see Lorraine J. Daston, "Galilean Analogies: Imagination at the Bounds of Sense," *Isis*, 75 (1984):302–10.

114 *TNS*, First Day, esp. pp. 11–13, 58–61.

115 Tartaglia may be seen as providing an earlier example of this type of questioning, as in his remarks on the status of axioms and definitions (see this chapter, Note 104).

116 Descartes criticized Galileo for the digressions in his writing and for his failure to provide a unified set of first principles (letter to Mersenne of 11 October 1638); Galileo spoke of the appropriateness of his style of writing in a letter of 1640 (to Leopold of Toscana; both letters are quoted in Feyerabend, *Against Method*, p. 69).

117 Duhem, *To Save the Phenomena*, Introduction; Chap. 1 (esp. pp. 5–11); Chap. 5; Chap. 7 (esp. pp. 104–12); and Conclusion.

118 *TCWS*, pp. 39 and 234; *Letters*, pp. 123–4. In the *Letters on Sunspots*, Galileo asserts that there exists a "true constitution of the universe," which is "unique, true, real, and could not possibly be otherwise," and which he later makes clear is Copernican (*Discoveries and Opinions*, p. 97). Throughout the *Letter to the Grand Duchess Christina* he repeatedly affirms this "realist" position and even suggests that Copernicus's astronomical findings might be used as a basis for interpreting Scripture (ibid., pp. 173–210). While his tone is more circumspect in the *Dialogues*, he does suggest three arguments that he believes establish the earth's annual revolution with a degree of certainty nearly equal to that of geometrical demonstration: (1) He argues, on the basis of telescopic observations, that Mercury, Venus, Mars, Jupiter, and Saturn revolve about the sun, from which he concludes (in accordance with a supposition of the continuity of nature) that the earth, located between Venus and Mars, must revolve as well, a hypothesis that also explains the retrograde motions of the other planets with an "ease and simplicity" missing in the Ptolemaic system (*TCWS*, pp. 318–45). (2) He offers an argument that the observed paths of the sunspots are best explained by a combination of solar rotation and terrestrial revolution (*TCWS*, pp. 345–56). (3) He presents his prized argument that the tides can best be explained through postulating a "sloshing" effect, created by compounding the daily and annual motions assigned to the earth (*TCWS*, Fourth Day).

119 Galileo, unpublished notes, quoted in Drake, *Discoveries and Opinions*, p. 170.

120 Galileo, *Dialogue Concerning the New Star*, originally published pseudonymously as *Dialogo de Cecco di Ronchitti in perpuosito de la stella nova* (Padua, 1605), trans. Stillman Drake, in *Galileo against the Philosophers* (Los Angeles: Zeitlin & Ver Brugge, 1976), pp. 33–53, quotation from p. 38. Some reviewers have questioned the attribution of the dialogue to Galileo, without firmly rejecting it (e.g., Ernan McMullin, "*Galileo against the Philosophers:* An Essay Review," *Centaurus*, 23 (1980):302–11). I have accepted the attribution of Favaro (*EN*, 2:269–73) and Drake (in his translation).

121 Drake, *Galileo at Work*, p. 52.