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TRADITION, TRANSMISSION TRANSFORMATION

PROCEEDINGS OF TWO CONFERENCES ON PRE-MODERN SCIENCE
HELD AT THE UNIVERSITY OF OKLAHOMA

EDITED BY

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E.J. BRILL
LEIDEN · NEW YORK · KÖLN
1996

WAS THE SCIENTIFIC REVOLUTION REALLY A REVOLUTION IN SCIENCE?

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INTRODUCTION

Analysis of the Scientific Revolution of the seventeenth century long stood as the central achievement of the history of science as a discipline. Study of the Scientific Revolution defined the "core curriculum" for graduate study in the field, and it set the theme for many undergraduate textbooks.¹ According to a widely shared narrative, Copernicus's astronomical proposals, although compatible with Ptolemaic astronomical principles taken generally, contradicted Aristotelian physics. A crisis arose. Galileo sought, but only partially achieved, a new physics suited to a moving earth. Kepler added some new descriptive laws of planetary motion. Newton, taking inspiration from Galileo's physics and using Kepler's laws, synthesized a new physics that was at once incompatible with that of Aristotle and supportive of Copernicus's planetary ordering. Newton's eventual success depended on both observational evidence and the use of mathematically-expressed laws, marking a new combination of observation and mathematization that came to define modern physics and modern science more generally.

More recently, this once-shared interpretation has undergone scrutiny and reappraisal. Some wish to broaden the story, by attending to other seventeenth-century fields of inquiry, such as medicine or natural history, or to the contribution of "non-standard" discourses such as those of magic and alchemy.² These impulses are laudable, and

¹ Herbert Butterfield, *The Origins of Modern Science, 1300–1800* (London, 1950; rev. ed. New York, 1965); A. Rupert Hall, *The Scientific Revolution, 1500–1800: The Formation of the Modern Scientific Attitude* (London/New York, 1954; rev. ed., 1983); Richard S. Westfall, *The Construction of Modern Science: Mechanisms and Mechanics* (New York, 1971; repr. Cambridge/New York, 1977); for an overview, see Arnold Thackray, "History of Science," in *A Guide to the Culture of Science, Technology, and Medicine*, ed. Paul T. Durbin (New York, 1980), pp. 26–28.

² Phillip R. Sloan, "Natural History: 1670–1802," in *Companion to the History of Modern Science*, eds. R. C. Olby, G. N. Cantor, J. R. R. Christie, and M. J. S. Hodge

the inclusion of natural history is important especially for the eighteenth century, though it must also be admitted that the most significant changes in biology, chemistry, and medicine took place in later centuries, and that the effects of magic and alchemy on the experimental culture of the eighteenth and nineteenth centuries were not great (Newton's secret alchemical notes notwithstanding). The sternest questioning has come from those who deny that the Scientific Revolution actually occurred. Such questioning stems primarily from a reinvigorated "continuity thesis": there was no revolution because there was not a sufficiently radical, or sufficiently rapid, change to qualify as a *revolutionary* change; the developments in science during the seventeenth century are essentially continuous with medieval science.³

I want to challenge the notion that there was a scientific revolution in the seventeenth century, but on different grounds. While it is reasonable to label some part of the intellectual change in the seventeenth century a "revolution," it is doubtful whether it should be called a "scientific" revolution. Indeed, to call the revolution "scientific" is perhaps the most profound instance of the anachronistic imposition of nineteenth- and twentieth-century categories on a previous period in all of the history of science.

A variety of vocabularies and conceptual tools are available to historians of science and historians of philosophy for describing and analyzing past intellectual practices and their products. One might, for instance, use the vocabulary of recent science and philosophy to provide a description and account of past work, by "translating" its content using terms familiar today—a practice that must always occur to some extent, because one cannot remain wholly in the vocabulary of the past and hope to communicate with the present.

(London/New York, 1990), pp. 295–313; Frances A. Yates, *Giordano Bruno and the Hermetic Tradition* (London, 1964); Brian Easlea, *Witch Hunting, Magic, and the New Philosophy: An Introduction to Debates of the Scientific Revolution, 1450–1750* (Brighton, England and Atlantic Highlands, N.J., 1980); for a critical appraisal, see Brian P. Copenhaver, "Natural Magic, Hermeticism, and Occultism in Early Modern Science," in *Reappraisals of the Scientific Revolution*, eds. David C. Lindberg and Robert S. Westman (Cambridge/New York, 1990), pp. 261–301.

³ For a review of the continuity thesis, see Peter Barker and Roger Ariew, "Introduction," in *Revolution and Continuity: Essays in the History and Philosophy of Early Modern Science*, eds. P. Barker and R. Ariew (Washington, D.C., 1991), pp. 10–18.

This approach is, however, subject to the danger of distortion through naive anachronism, and historians of science have become acutely sensitive to this danger. Many historians therefore prefer to begin by using "actor's categories"—the categories used explicitly or implicitly by historical agents themselves—to describe the cognitive products of the past. Although the use of actor's categories is hardly the only analytical tool available to historians, who opportunistically adopt whatever terms of analysis might be useful (whether drawn from social and cultural history, literary criticism, philosophy, anthropology, or sociology), it provides a helpful starting point for attaining an initial sorting of past texts and practices, by permitting the investigator to develop a road map that fits the intellectual terrain as it was discerned at the time that the roads were originally laid down. Such a map, while in no way final, is preferable to a description that simply assimilates past intellectual products to present categories without raising the question of fit or attending to the dangers of distortion.

I am applying the historical strategy of beginning with actor's categories to the "Scientific Revolution" itself. In other words, I am posing questions about the existence and character of the Scientific Revolution by deriving my initial categories of analysis and my initial understanding of the intellectual scene from the writings of the seventeenth century, and by following the evolution of these initial categories in succeeding centuries. This project fits the theme of cross-cultural transmission and appropriation—a theme of the present volume—if one takes the notion of a culture broadly, so that, say, seventeenth- and eighteenth- or nineteenth-century European intellectual cultures are deemed sufficiently distinct that one can speak of the "transmission" of texts and ideas from the one to the other as cross-cultural.⁴ I maintain that a process of transforming and assimilating seventeenth-century achievements manifests itself in two distinct cultures of interpretation, one developed by historians of philosophy, the other by scientists and historians of science. The first, following actor's categories, interprets the revolution in the seventeenth century as a philosophical displacement, partly fomented

⁴ A. I. Sabra, "The Appropriation and Subsequent Naturalization of Greek Science in Medieval Islam: A Preliminary Statement," *History of Science* 25 (1987): 223–243.

by a radical change in astronomical theory; the second, retrospectively applying the post nineteenth-century sense of the term "science" to seventeenth-century events, finds a "scientific" revolution, or the birth of modern science. While the second interpretation has been dominant, the first approach must be followed if we are to understand the historical process by which modern science came into being—for the second approach simply finds "science" there all along. From this vantage, the rapid revolutions were philosophical and mathematical, inspired by Descartes' metaphysically based corpuscularianism and Newton's philosophical empiricism and invention of the calculus. The installation of classical physics as the paradigmatic natural science took much longer, and was completed only toward the end of the eighteenth century.

I. A SEVENTEENTH-CENTURY "REVOLUTION" IN THOUGHT?

I. B. Cohen has made an extended study of actor's uses of the concept—or at least the term—"revolution" as applied to seventeenth-century science. As he has documented in detail, during that century the primary meaning of the term "revolution" was a complete turn around a wheel or orb, a cyclical return. But he also finds the term used to mean a momentous change, and he finds it so used during the seventeenth century to describe the upheaval caused by Harvey in medical physiology, and in the early eighteenth century to describe the radical change in mathematics effected by Leibniz and Newton.⁵ Thus, the term "revolution" could have been used in the seventeenth century to describe a general break with Ptolemy in astronomy and with Aristotle in natural philosophy; but so far as we know it was not.

Nonetheless, a host of seventeenth-century authors claimed to effect radical change in various areas of intellectual pursuit, including logic or methodology, and natural and experimental philosophy. In order to illustrate a self-proclaimed revolution in the seventeenth century, Cohen quotes from Henry Power's *Experimental Philosophy* of 1664, which proclaimed that "all the old [Aristotelian] rubbish must be thrown away, and the rotten buildings be overthrown," to

⁵ I. B. Cohen, *Revolution in Science* (Cambridge, Mass., 1985), pp. 85–90.

prepare for "a new foundation of a more magnificent philosophy."⁶ He might have cited an earlier invocation of the image of abolishing the old in order to begin again in Francis Bacon's *Novum organum*, where Bacon set forth "resolutely to compel himself to sweep away [abolere] all theories and common notions, and to apply the understanding, thus made fair and even, to a fresh examination of particulars," an endeavor which, if carried out, would be worthy of comparison (he thought) to the deeds of Alexander the Great, for nothing less was contemplated than "a new birth of science."⁷ Or he might have quoted an even more widely read invocation of the image of overturning the old to make room for the new in Descartes' *Discours de la methode*, where Descartes compared his method of doubt to "razing the houses of a town" in order to build on better foundations, and to "pulling down" a house in order to build anew. Indeed, Descartes directly compared his project radically to reform his own opinions with what we would term a "political revolution," that is, with the attempt to "reform a state by changing all of its foundations, and overthrowing it in order to remake it." He prudently affirmed that while it is reasonable to engage in a complete overthrow of one's own opinions in order to effect cognitive reform, it would not be reasonable to overthrow the state. He also said that it would be unreasonable to seek a complete reform of the "entire body of the sciences, or the order established in the schools for teaching them."⁸ In the latter case he was dissimulating, for Descartes did intend the cognitive self-reform of the *Discours* to stand as a model for a more general cognitive reform, as became apparent when he recast the project of "overturning" (*evertere*) all of one's beliefs as the project of

⁶ *Ibid.*, p. 90.

⁷ Francis Bacon, *Instauratio magna* (London, 1620), pt. 2, "Novum organum," bk. 1, sec. 97; English translation in *The Works of Francis Bacon*, eds. James Spedding, Robert L. Ellis, and Douglas D. Heath, new ed., vol. 4 (London, 1870), pp. 93–94. Charles Webster, *The Great Instauration: Science, Medicine and Reform, 1626–1660* (London, 1975), describes the atmosphere of rapid change and reformation in which Bacon wrote and in which his works were received. Cohen proclaims that Bacon "was not a scientist" and maintains that while Bacon may have "revolutionized the philosophy of science," he did not produce a revolution in science itself (*Revolution in Science*, pp. 149–150).

⁸ René Descartes (published anonymously), *Discours de la methode pour bien conduire sa raison, & chercher la verité dans les sciences* (Leiden, 1637), pp. 14–15; in his *Oeuvres*, ed. Charles Adam and Paul Tannery, 11 vols. in 13 (Paris, 1964–1974), vol. 6, p. 13. Descartes' *Oeuvres* will be cited as "AT."

an impersonal mediator in the *Meditationes de prima philosophia*,⁹ and presented the project and its consequences for natural philosophy in textbook form in the *Principia philosophiae*.¹⁰ Descartes, then, proposed an intellectual revolution as early as 1637. And Cohen provides many additional instances of seventeenth-century authors proclaiming to effect radical change in some or all of the disciplines that we now lump together as "the sciences."¹¹

For an intellectual revolution to occur it is not enough that someone proclaim that they have effected or will effect one; the change must be perceived and accepted by some significant number of the would-be revolutionary's contemporaries and successors. Again, Cohen has been able to document the widespread appreciation of the revolutionary (or radical, or fundamental) change effected by Descartes in natural philosophy, Harvey in physiology, Galileo in mechanics, and Newton in mathematical natural philosophy.¹² A general sampling of the literary output of the seventeenth century would show that the widest and most fundamental change completed during that century was effected by the work of Descartes. His numerous followers claimed to find in his work an across-the-board transformation of philosophy, a complete sweeping-away of the Aristotelian system. Not only were Descartes' own works frequently reprinted,¹³ but other writers, including Antoine Le Grand, Pierre Regis, and Jacques Rohault, developed general statements of his philosophy or his physics intended for public and pedagogical consumption.¹⁴ So if an intellectual revolution takes place when there is

⁹ René Descartes, *Meditationes de prima philosophia* (Paris, 1641), p. 8 (AT 7, p. 17).

¹⁰ René Descartes, *Principia philosophiae* (Amsterdam, 1644).

¹¹ Cohen, *Revolution in Science*, pt. III: beyond Bacon and Descartes, the figures who at least proclaimed a revolution by Cohen's criterion include Kepler, Gilbert, Galileo, Paracelsus, Harvey, and Newton.

¹² *Ibid.*

¹³ A.-J. Guibert, *Bibliographie des oeuvres de René Descartes publiées au XVII^e siècle* (Paris, 1976), lists eight seventeenth-century editions of the *Discours*, ten of its Latin translation as *Specimina philosophiae*, twelve Latin and four French editions of the *Meditationes*, twelve Latin and eleven French editions of the *Principia*, ten French and twelve Latin editions of the *Passions*, three French (with Latin) and two Latin editions of the three-volume *Lettres*, four French and six Latin editions of *L'Homme*, and ten editions of works entitled *Opera philosophica*.

¹⁴ Antoine Le Grand (d. 1699), *Institutio philosophiae secundum principia D. Renati Descartes*, new ed. (London, 1678); trans. Richard Blome, *An Entire Body of*

a self-conscious attempt to replace an established orthodoxy that succeeds relatively well by contemporary measures and that occurs reasonably quickly—to paraphrase Roy Porter's suggested criterion¹⁵—there was at least one general revolution in seventeenth-century thought, that set in motion by Descartes.

But was this revolution, or that of Galileo or Harvey or Newton, a "scientific" revolution? There is no study of the concept and the term "science" to set beside Cohen's investigation of the concept and the term "revolution."¹⁶ During the seventeenth century the term "science" and its Latin, French, and Italian cognates were used to mean simply knowledge, or, more rigorously, a systematic body of knowledge. As such, arithmetic and geometry were denominated sciences, as were theology and metaphysics. There was no implication that "scientific" knowledge need be empirically based or pertain to perceivable entities. Thus, theology, denominated "Divine Science" or the "Science of God," included two branches, one based on revelation and the other on natural reason; some considered the latter science to be unrelated to sense experience.¹⁷ So while seventeenth-century categories could allow that a revolution occurred within some "sciences" so denominated, e.g., astronomy and the newly created (or revived) science of motion, the term "science"

Philosophy, According to the Principles of the Famous Renate Des Cartes (London, 1694). Pierre Sylvain Regis (1632–1707), *Système de philosophie: contenant la logique, métaphysique, physique & morale*, 7 vols. (Lyon, 1691); Jacques Rohault (1618–1672), *Traité de physique*, 2 vols. in 1 (Amsterdam, 1676); trans. John Clarke (Samuel's brother), *System of Natural Philosophy*, 2nd ed., 2 vols. (London, 1728–1729; repr. New York, 1987). Although these authors presented their Cartesianism straightforwardly, in other contexts Cartesian or corpuscularian philosophy was presented in Aristotelian guise, e.g. by interpreting Aristotelian "form" as the arrangement of particles. René Le Bossu, *Parallèle des principes de la physique d'Aristote et de celle de René Des Cartes* (Paris, 1674; repr. Paris, 1981), is a notable reconciler; for further discussion, see Marjorie Grene, "Aristotelico-Cartesian Themes in Natural Philosophy: Some Seventeenth-Century Cases," *Perspectives on Science* 1 (1993): 66–87.

¹⁵ Roy Porter, "The Scientific Revolution: A Spoke in the Wheel?", in *Revolution in History*, eds. Roy Porter and Mikuláš Teich (Cambridge, 1986), p. 300.

¹⁶ For a survey of uses of the terms "science" (as well as "philosophy") since the seventeenth century, see George MacDonald Ross, "Science and Philosophy," in *Companion to the History of Modern Science*, eds. Olby et al., pp. 799–815; on the meanings of "science," see also David Lindberg, *Beginnings of Western Science* (Chicago, 1992), pp. 1–4.

¹⁷ Le Grand, *An Entire Body of Philosophy*, pp. 54b, 56–57.

remained much broader than our term, and so would not capture what was special about the changes that we now denominate by the "Scientific Revolution."

It is, of course, no news that the Scientific Revolution was not so denominated when it took place. The present question is whether there was a concept and perhaps a term available during the seventeenth century that picked out what we retrospectively call "seventeenth-century science," or if our concept of seventeenth-century science, when viewed through seventeenth-century categories, is like Frankenstein's monster, put together out of pieces taken from here and there.

II. "NATURAL PHILOSOPHY" AND "MATHEMATICAL SCIENCE" IN THE EARLY MODERN PERIOD

"Natural philosophy" suggests itself as an historical equivalent to what we call "science," and some authors use it in this way.¹⁸ But the correspondence is not sufficiently close for present purposes. During the seventeenth century (as before), "natural philosophy" was also termed "physics" or the science of nature. As with the term "science," we lack careful studies of these terms in their medieval and early modern employment. But their central meaning is clear: "physics" or "natural philosophy" was the branch of investigation, or the portion of the school curriculum, devoted to the study of nature as a whole, that is, the entire created world. "Philosophy" in this context had connotations similar to "science," of a systematic body of knowledge organized around first principles.

Given these glosses, the term "natural philosophy" might then be rendered as "systematic knowledge of nature," and this may seem quite close to what we now label as science. But consider some points of comparison. Seventeenth-century natural philosophy included the study of all corporeal being, from body in general, through the inanimate world, to plants and animals, including the human animal. Among terrestrial things, only the souls of humans were sometimes, though by no means always, excluded from physics and placed instead under the rubric of metaphysics.¹⁹ The term

¹⁸ Lindberg, *Beginnings of Western Science*, pp. 3-4.

¹⁹ One sign of the categorization of the sciences is provided in seventeenth-

"natural philosophy," then, had a broader extension than our term "science," because it included study of souls. But along other dimensions of comparison its extension is narrower. As commonly portrayed in textbooks, natural philosophy did not properly include the "mixed-mathematical" sciences of optics and astronomy, the latter being an area of knowledge at the center of the Scientific Revolution.²⁰ Among astronomical writers themselves, whether revolution-

century textbooks. Among Aristotelian textbooks, all natural beings, including the soul, fell within physics: Franco Burgersdijck (1590-1635), *Collegium physicum, disputationibus XXXII* (Oxford, 1664); Pierre Barbay (d. 1664), *In universam Aristotelis philosophiam introductio*, 6th ed. (Paris, 1700); Eustace of St. Paul (1573-1640), *Summa philosophiae quadripartita* (Cologne, 1638), pt. 3, "Physica." Authors of commentaries on the soul divided over whether the rational soul belonged to physics or metaphysics: Francisco Toledo (1532-1596), *Commentaria una cum quaestionibus in tres libros Aristotelis De anima* (Cologne, 1594), proem, q. 2 (fol. 4), subsumed the soul in all of its operations under physics; *Commentarii Collegii Conimbricensis ... In tres libros De anima*, 2nd ed. (Cologne, 1600), proem, q. 1, a. 2 (pp. 7-8) and Antonio Rubio (1548-1615), *Commentarii in libros Aristotelis De anima* (Lyon, 1620), proem, q. 1 (pp. 10-11), subsumed the study of embodied souls under physics, and of the soul separated from the body under metaphysics. Cartesian textbooks are discussed below.

²⁰ Franco Burgersdijck, *Idea philosophiae naturalis, sive methodus definitionum & controversiarum physicarum*, revised edition (Oxford, 1667), treats the substantial nature of the sky and celestial orbs as usual within Aristotelian physics, only mentioning the "astronomers" to indicate that they add two additional spheres to the eight acknowledged by philosophers (disp. 10, thes. 2, p. 24); Eustace of St. Paul, *Summa philosophiae quadripartita*, pt. 3, "Physica," discusses the heavens and mentions a "recent mathematical proposition" on the number of the spheres, increasing the number beyond eight in order to account for the observed motions, but he does not portray the mathematical models involved (pt. 2, tr. 1, disp. 2, q. 6, pp. 97-98); Pierre du Moulin (1568-1658), *Physicorum seu scientiae naturalis libri novem* (Amsterdam, 1645), distinguishes between astronomy and physics thusly: "De coelo aliter differit Astronomus, aliter Physicus. Astronomus agit de siderum vario motu, situ, magnitudine, intervalis, aspectus. Physicus agit de coelo quatenus est substantia simplex, rotunda, se movens in orbem, incorruptibilis, fulgens, diaphana, causa generationum & corruptionum" (bk. 2, ch. 4, p. 25). Charles François d'Abra de Raconis (1580-1646), *Tertia pars philosophiae, seu physica* (Lyon, 1651), contains in the section on the heavens a brief discussion of epicycles (Disp. de coelo & sphaerae, sec. 3, q. 1, a. 3, pp. 309-311), and adds a brief appendix on the spheres (pp. 312-326), following John of Sacrobosco. Pierre Barbay, Professor of Philosophy in Paris, in his *Commentarius in Aristotelis physicam*, 5th ed., 2 vols. (Paris, 1690) appends to his treatment of the usual topics in physics a separate treatise on the celestial spheres, which discusses eccentric circles and epicycles, and compares the Ptolemaic, Copernican, and Tychoic systems (vol. 1, pp. 402-513); in this treatise he subordinates "astrologia" to geometry (ch. 1, p. 403), and in the text of the physics proper, in the part on celestial bodies, he explains: "Corpora caelestia possunt considerari duobus modis. Primo, Physice, prout sunt quaedam

ary or not, some denominated astronomy as a mathematical science, some subsumed it under both mathematics and physics as a truly "mixed" mathematical science, while others sought to incorporate it within physics or natural philosophy;²¹ the inclusion of astronomy as a proper part of physics, or the division of astronomy into mathematical and physical branches, each became common during the eighteenth century.²² But in any case the term "natural philosophy" remains too broad to pick out our Scientific Revolution. In addition to the breadth of subject-matter already mentioned, there is the further point that many authors considered natural philosophy to have a dependent relation on metaphysics; Descartes and Leibniz agreed in

corpora naturalia, ex quibus proprietates quaedam naturales consequuntur. Secundo, Astrologice, habita ratione suorum motuum & periodorum, affectionumque mathematicarum cum motu connexarum. In hoc Tractatu ea primo modo considerabimus" (vol. 2, p. 3). Similar remarks are found in Bartholomew Keckermann, *Operum omnium ... tomus primus*, 2 vols. (Geneva, 1614), *Systema astronomiae compendium* (placed after logic and physics, and before geography and metaphysics), bk. 1, ch. 1, vol. 1, col. 1835. These late scholastic conceptions generally reflect the earlier Latin tradition, Edward Grant, *Planets, Stars, and Orbs: The Medieval Cosmos, 1200-1687* (Cambridge, 1994), pp. 36-39; they do not reflect the developed tradition within Arabic astronomy of introducing physical considerations into mathematical astronomy, F. J. Ragep, *Naṣīr al-Dīn al-Ṭūsī's Memoir on Astronomy*, vol. 1 (New York, 1993), pp. 24-29. Finally, Cartesian textbooks observed the division between "natural philosophy" and "astronomy," whether explicitly, Le Grand, *An Entire Body of Philosophy*, p. 146a, or implicitly, Regis, *Système de philosophie*, vol. 2, Physique, bk. 2.

²¹ Mathematical: Johannes Hevelius (1611-1687), *Machina coelestis*, 2 vols. (Gdańsk, 1673-1679), vol. 1, pp. 1, 6. Mixed mathematical: Giovanni Battista Riccioli (1598-1671), *Almagestum novum* (Bologna, 1651), bk. 1, ch. 1, p. 2. Physical: Johannes Kepler, *Astronomia nova aitiologetos, seu physica coelestis* (Heidelberg, 1609); Jean Baptiste Du Hamel (1624-1706), *Astronomia physica* (Paris, 1660), pp. v-vi, xvii-xviii; Giovanni Alfonso Borelli (1609-1679), *Theoricae medicorum planetarum ex causis physicis deductae* (Florence, 1666). On the rise of "physical" astronomy, see Alexandre Koyré, *The Astronomical Revolution*, trans. R. E. W. Maddison (Paris/Ithaca, 1973), and Nicholas Jardine, *The Birth of History and Philosophy of Science* (Cambridge, 1984), ch. 7, who argues that mathematical and physical astronomy remained distinct (though with increasing interaction in the late sixteenth century) prior to Kepler's bold proposal for a truly "physical" (or "metaphysical") astronomy.

²² David Gregory, *Astronomiae, physicae & geometricae elementa* (Oxford, 1702); Thomas Rutherford, *A System of Natural Philosophy, Being a Course of Lectures in Mechanics, Optics, Hydrostatics, and Astronomy*, 2 vols. (Cambridge, 1748). Nonetheless, Ephraim Chambers, *Cyclopaedia: or, an Universal Dictionary of Arts and Sciences*, 2nd ed., 2 vols. (London, 1738), vol. 1, "Astronomy," portrayed a division of opinion between those who considered astronomy a "mixed mathematical science" and those who considered it a branch of physics.

distinguishing physics from metaphysics, but also in using metaphysical arguments to provide the foundation or framework for physics.²³ Topics that we would now consider to be metaphysical rather than scientific, such as the essence of material substance or the relation between soul and body, were regularly discussed under the heading of natural philosophy. And these topics must be included in the revolutionary shifts of thought when those are viewed from a seventeenth-century perspective, even if no one metaphysics achieved sufficient acceptance to justify the claim that there was a "metaphysical revolution" in the seventeenth century (Descartes' coming the closest). Rather, there was persistent metaphysical agitation, both within natural philosophy and in metaphysics proper.

But what about the "mathematical sciences" themselves? Perhaps the Scientific Revolution was truly *scientific*, if not in genus, then in species, precisely because it was a revolution in a subset of the mathematical sciences—so denominated—of the sixteenth and seventeenth centuries. Optics and astronomy are the likely candidates. Together with arithmetic, geometry, and music, they were the paradigm "mathematical sciences" as the seventeenth century began, even if they were not then encompassed by the category of physics.²⁴ Optics was conceived as a general theory of vision; it was not simply what we might term the "physics of light," or even the geometrical description of the pathways taken by light under specified conditions.²⁵ Only parts of optics were mathematical science in our sense: the portions of optics proper pertaining to the analysis of light in the medium, and nearly the whole of the parts denominated as

²³ Descartes, preface to *Les Principes de la philosophie* (Paris, 1647) pp. 25-28 (AT 9B, pp. 14-16); Gottfried Wilhelm Leibniz, "On Body and Force, Against the Cartesians," in his *Philosophical Essays*, ed. and trans. Roger Ariew and Daniel Garber (Indianapolis, 1989), pp. 251-252, 255.

²⁴ Christoph Scheibler (1589-1653), in a widely used textbook at Oxford, the *Philosophia compendiosa*, 9th ed. (Oxford, 1671), divided philosophy into "superior" (metaphysics, physics, morals) and "inferior" parts, the latter including the traditional quadrivium; in the work itself he first treated logic, metaphysics, and physics, then geometry, astronomy, and optics, followed by ethics, politics, economics, and a compendium on method. On the common portrayal of the relation of astronomy to physics, see n. 20.

²⁵ David Lindberg, *Theories of Vision from al-Kindi to Kepler* (Chicago, 1976), p. x; A. I. Sabra, *The Optics of Ibn al-Haytham: Books I-III, On Direct Vision* (London, 1989), vol. 2, pp. liii-iv.

"dioptrics" and "catoptrics." In the other parts of optics which dealt with the anatomy, physiology, and psychology of vision, mathematics was sometimes found—as in descriptions of the anatomy and physiology of the lens and of the binocular correspondences between the two eyes, and of the conditions for the perception of size, shape, and distance—though not always (e.g., much of the anatomy and physiology was not mathematical). But in any case, the "mathematical science" of optics cannot be the standard bearer for the Scientific Revolution, because it did not undergo a revolution in the seventeenth or any nearby century. While there was significant change in parts of optics, including a change in the physiological theory of visual reception (on the retina instead of in the crystalline), and an advancement of the study of the physics of light in Newton, these are more accurately seen as advances in a continuously developing line of inquiry than as revolutionary displacements.²⁶

There was, it is agreed, a revolution in astronomy, which is usually said to have begun with Copernicus and been brought to completion by Kepler and Galileo. Astronomy as a mathematical science was brought to a high state of refinement in the ancient and medieval worlds. Copernicus's proposals set off a controversy that was not truly resolved until Newton's *Principia*. This resolution, however, created a new bond between mechanics and mathematical astronomy, yielding the new field of "physical astronomy." If we regard astronomy as a traditional "mathematical science," its "revolution" was as complete as ever with Galileo and Kepler (though wide-spread acceptance took longer); for what happened afterwards (and was already present in Kepler) was a transformation

²⁶ Cohen concludes that Newton's work in optics was not revolutionary (*The Newtonian Revolution* (Cambridge, 1980), p. 11); the only revolution in optics he names is that of Faraday and Maxwell (*Revolution in Science*, pp. 303, 440). G. N. Cantor, "Physical Optics," in *Companion to the History of Modern Science*, eds. Olby et al., pp. 634–636, ascribes "the optical revolution" to the early nineteenth century, emphasizing the work of Thomas Young and Augustin Fresnel. Lindberg, *Theories of Vision from al-Kindi to Kepler*, p. 207, denies that Kepler was a revolutionary theorist, while suggesting that his theory had (unspecified) "revolutionary implications." In seventeenth-century works on vision, Kepler's discovery was much discussed, and it perhaps produced a revolution in visual physiology, but not in the theory of vision proper (including its psychological aspects). If there was an earlier revolution in the whole of visual theory, it was that effected by Alhazen (Lindberg, *ibid.*, ch. 4), even if the recognition of his revolutionary achievements was slow (Sabra, *Optics of Ibn al-Haytham*, vol. 2, p. xi).

of astronomy from a traditional mathematical science that eschewed the search for physical causes, to a branch of physical science that took its explanatory principles from Newtonian mechanics.

We have now come full circle, to a slightly elaborated version of the traditional narrative recounted at the start of this chapter: the Scientific Revolution was constituted precisely through the development of our modern notion of science—or, more precisely, of physics, taken as the paradigm science—when the old physics or natural philosophy was transformed as it incorporated the mathematical sciences, and especially astronomy and the new mechanics, and sundered its relations with metaphysics.²⁷ Descartes and Newton unified celestial and terrestrial physics, thereby incorporating astronomy into natural philosophy, and Galileo and Newton eschewed metaphysics. Indeed, these are the very reasons these authors are taken to be the Revolutionaries—especially Galileo and Newton, who showed the way to a mathematical physics. But from the perspective of asking whether the Scientific Revolution can be understood to have been such when framed in actor's categories, we must ask whether this story of the transformation of physics into an experimental mathematical science captures the reasons that the authors in question were considered revolutionaries in the seventeenth century. For the danger remains that in telling the story that culminates in Newton in just this way, we are unwittingly applying our term "science" retrospectively so as to gerrymander the boundary of a past historical episode.

In the case of Descartes, his description of a unified terrestrial and celestial physics was only part of his achievement when measured by a seventeenth-century metric. Moreover, he did not truly incorporate mathematical astronomy into his physics or theory of nature. In seventeenth-century terms, Descartes was recognized as propounding a new system of philosophy to replace the Aristotelian one, a system of which his corpuscularian theory of the heavens was only one part. Metaphysics filled the entire first part of the *Principia philosophiae*, Descartes' systematic statement of his new philosophy. The "phys-

²⁷ John L. Heilbron, *Elements of Early Modern Physics* (Berkeley/Los Angeles/London, 1982), ch. 1, contends that the old physics was replaced by the new when mathematical science replaced the old qualitative science and forced a shrinking of subject-matter, and when experiment became the basis for establishing claims (implying, but not explicitly stating, a rejection of a priori metaphysics).

ics" of the remaining parts included not only the basic properties of matter, the laws of motion, and the explanation of inorganic phenomena, both celestial and terrestrial, but also the phenomena of living things (plant, animal, and human) and the production of sensations in the human mind (though the treatment of living things was excluded for lack of time).²⁸ Descartes' followers filled out his "new philosophy" by producing textbooks that covered the usual fourfold division of philosophy into logic, physics, metaphysics, and morals. Le Grand and Regis each wrote comprehensive works in which metaphysics was placed before physics as its foundation and source of first principles (reversing the usual Aristotelian order). Le Grand included the full range of natural phenomena, from basic matter to plants, animals, human physiology, mental substance, and the mind-body union, under the rubric of natural philosophy;²⁹ Regis differed in treating the mind itself under metaphysics.³⁰ Rohault's *System of Natural Philosophy*, by contrast, was restricted to physics or natural philosophy. His book differed from its Aristotelian counterparts in the content of its general physical concepts, in ascribing one type of corporeal substance and one set of explanatory concepts to the earth and heavens alike, and in its counterpart to the treatment of ensouled beings: Rohault moved the treatment of the sensory qualities up front and explained them in accordance with corpuscular mechanisms, he gave a mechanistic treatment of human physiology, and he merely touched on the rational soul and its relation to the body.³¹ His book also differed in teaching that the essence of matter is extension and is known to be so through reason alone, independently of the senses and of the contemplation of any created thing. In accordance with Descartes' grounding of physics in a meta-

²⁸ Descartes, *Principia philosophiae*, pt. IV, art. 188 (AT 8A, p. 315); and preface to *Principes de la philosophie*, pp. 28–29 (AT 9B, pp. 16–17).

²⁹ Le Grand, *Institutio philosophiae*, praecognoscenda, arts. 7, 15, 16; trans. Blome, preface, sec. 3.

³⁰ Regis, *Système de philosophie*, vol. 1, Métaphysique, bk. 1.

³¹ Jacques Rohault, *System of Natural Philosophy*, pt. 1, chs. 18, 22–35. Aristotelian textbooks of physics typically included discussion of the general concepts of physics, such as matter, form, privation, cause, and substance, more particular concepts such as the four elements, and special physical topics, including the heavens (treated "physically"), meteorological phenomena, and the phenomena of "ensouled" beings, including plants, animals, and humans (see the physics books cited in notes 19 and 20).

physics discovered via the "light of nature," Rohault derived the first principles of physics, including the impossibility of a vacuum, from this insight.³² The Cartesian revolution was an attempt to alter natural philosophy by means of metaphysics.

Galileo is usually accorded a more central role than Descartes in effecting the Scientific Revolution, so perhaps we should look to his work for the founding of a new mathematical physics. It is certainly the case that Galileo was concerned to remove objections to the earth's motion by ridiculing the Aristotelian theory of motion, and, for the case of free fall near the earth, by providing an alternative account. But he did not explicitly link either natural philosophy or mechanics with astronomical explanation. He did propagandize for the application of mathematics to problems in natural philosophy whenever possible,³³ and it is indeed likely that he believed the mathematical sciences of nature to be the ones most worth pursuing. But he seems never to have conceived of the project of replacing the old physics with a unified, comprehensive mathematical natural philosophy, of the sort that resulted from Newton's work; rather, he saw himself as contributing to various mathematical *sciences* already in existence, and as adding two new ones of his own.³⁴ I have found no instance in which he claimed to find in the second of his new sciences, the science of motion, the basis for a comprehensive theory of nature. In the strict (seventeenth-century) sense of the term, Galileo did not propound a physics, even if he did apply mathematics to natural philosophical questions.

Newton's case is more difficult. His *Principia* and *Optics* largely fit our conception of physical science, especially since the more obviously metaphysical discussions in those works are separated off

³² *Ibid.*, pt. 1, ch. 7, arts. 1–10; ch. 8. He concluded "from that Knowledge which we have by Reason, that the *Essence* of Matter consists in *Extension*, because that is what we first perceive in it," and continued: "that we may carry our Knowledge as far as the Light of Nature will permit; let us consider that the Idea of Extension is so far from depending upon any created Thing, that we can scarce get it out of our Minds, when we try to imagine Nothing, which we believe was before the Creation of the World; which shows that it does not depend upon created Things, ..." (ch. 7, arts. 9–10). Rohault drew upon Descartes' metaphysics without extending its practice.

³³ Galileo Galilei, *Dialogue Concerning the Two Chief World Systems, Ptolemaic & Copernican*, trans. Stillman Drake, 2nd ed. (Berkeley/Los Angeles/London, 1967), pp. 14, 200.

³⁴ Galileo Galilei, *Two New Sciences*, trans. Stillman Drake (Madison, 1974).

into scholia and queries. But did Newton consider himself to have produced a new natural philosophy, or a new, general, experimental mathematical physics? The title of his *Philosophiae naturalis principia mathematica*, which is translated as the *Mathematical Principles of Natural Philosophy*, may be glossed in at least three different ways: as "the principles of a general natural philosophy that is wholly mathematical"; as "some mathematical principles in natural philosophy, the whole of which need not be mathematical"; or as "those mathematical principles in natural philosophy that have thus far been discovered, with suggestions on how to look for more, so that natural philosophy might become completely mathematical." Newton's stated wish in the preface to "derive the rest of the phenomena of nature by the same kind of reasoning from mechanical principles," and his acknowledgement that the needed principles remain unknown, suggest the third gloss.³⁵ That Newton considered the *Principia* and *Optics* to touch upon only a portion of natural philosophy is also suggested by his inclusion of physiological (e.g., Qu. 24–25) and chemical (Qu. 31) topics in the Queries to the *Optics*, and by his stated desire that the "method of analysis" should be pursued in "natural Philosophy in all its Parts."³⁶ In order to assess the revolutionary character of Newton's own achievements, we must follow the fortunes of the concepts and terms "natural philosophy" and "experimental mathematical physics" into the eighteenth century.

III. FROM "NATURAL PHILOSOPHY" TO "EXPERIMENTAL MATHEMATICAL PHYSICS"

We know there was a Cartesian revolution in natural philosophy in the seventeenth century, and that when viewed through actor's categories, it was not simply a revolution in what we now call science. In searching for a genuinely and specifically "scientific"

³⁵ Isaac Newton, *Mathematical Principles of Natural Philosophy*, trans. Andrew Motte and revised by Florian Cajori, vol. 1 (Berkeley, 1966), p. 13. See Chambers, *Cyclopaedia*, vol. 2, "Newtonian Philosophy," for an appreciation of the variety of senses in which a "Newtonian" approach to natural philosophy might be understood.

³⁶ Isaac Newton, *Opticks, or, A treatise of the Reflections, Refractions, Inflections & Colours of Light*, based on the 4th ed., London, 1730 (New York, 1952), Qu. 31, p. 405.

revolution, we must now ask whether there was a Newtonian Revolution. By the criteria proposed above, that for a revolution to occur it must be perceived and acknowledged to be successful by a reasonable number of contemporaries, it is clear that there was no Newtonian Revolution in the seventeenth century, but only several decades into the eighteenth,³⁷ if at all. In seeking a Newtonian culmination to the Scientific Revolution, we shall be looking for the transition from "natural philosophy" and distinct "mathematical sciences" to a unified "experimental mathematical physics."

We should distinguish among various ways in which experimental mathematical physics could be (and was) related to the earlier practice of natural philosophy. First, experimental mathematical physics could be a sub-practice within a more comprehensive natural philosophy, as it would be if one took natural philosophy to be the science of nature in general, including living things, and yet placed optics, mechanics, and astronomy among the sub-areas of this comprehensive natural philosophy. This "special sciences" view of experimental mathematical physics can be found in the seventeenth century—indeed, I have suggested that it was the conception held by Newton himself. Second, experimental mathematical physics might be taken to define physics itself, where the latter is a narrower discipline than the science of nature in general, one that is rooted in mechanics and that might extend to electricity, magnetism, and heat, but that excludes both chemistry and the science of living things. This view of physics as mechanics and allied disciplines can be found in the eighteenth century ('sGravesande, Nicholson), and it was firmly entrenched by the beginning of the nineteenth (Biot, Playfair).³⁸ Finally, experimental mathematical physics, rooted in

³⁷ William R. Shea, "The Unfinished Revolution: Johann Bernoulli (1667–1748) and the Debate between the Cartesians and the Newtonians," in *Revolutions in Science: Their Meaning and Relevance*, ed. William R. Shea (Canton, Mass., 1988), pp. 70–92.

³⁸ Willem Jacob van 'sGravesande (1688–1742), *Mathematical Elements of Natural Philosophy, Confirm'd by Experiments, or an Introduction to Sir Isaac Newton's Philosophy*, trans. J. T. Desaguliers, 6th ed., 2 vols. (London, 1747); William Nicholson (1753–1815), *An Introduction to Natural Philosophy*, 2 vols. (London, 1782); Jean Baptiste Biot (1774–1862), *Traité de physique expérimentale et mathématique*, 4 vols. (Paris, 1816); John Playfair (1748–1819), *Outlines of Natural Philosophy*, 2 vols. (Edinburgh/London, 1812–1814). See P. M. Harman, *Energy, Force, and Matter: The Conceptual Development of Nineteenth-Century Physics* (Cambridge, 1982), ch. 1.

mechanics, might be considered to be a replacement version of a general theory of nature, and hence as providing the explanatory framework for all of the branches of natural science, including chemistry and living things. This reductionist vision of mechanistic physics as the comprehensive science of nature had its nineteenth-century adherents (Huxley).³⁹ The transition from the first view to the second view marks the rise of physics as a narrowly defined discipline, and the transition from the second to the third marks an attempt to reclaim for physics its place as the general science of nature.

For the purposes of evaluating the character of the alleged "Newtonian Revolution" in science we may attend to the first transition. John Heilbron has examined the course of this change. He finds that in the generation formed during the lifetime of Newton, including the Dutch scholars 'sGravesande and Musschenbroek and the German systematist Wolff, a transition was effected from a general natural philosophy to a specialized physics, as expressed in the textbooks of these authors. Heilbron analyzes this change as the rejection of an Aristotelian bookish, qualitative physics and a Cartesian rational, corpuscular physics of vortices in favor of a Newtonian experimental mathematical physics restricted to mechanics, celestial mechanics, optics, electricity, magnetism, and heat.⁴⁰

In evaluating Heilbron's claims, we can at once allow that Newton changed the course of (what we now call) natural science by his stunning achievements in mathematization. The development of the calculus was soon recognized as of "revolutionary" significance, and it stimulated a new "school" of mathematical work especially among the French.⁴¹ More generally, Newton's unification of terrestrial and celestial mechanics in a book written in the spare Archimedian style of the *Principia*—definitions, axioms, theorems, and problems, with methodological and metaphysical remarks segregated into the Rules of Reasoning and the General Scholium—demonstrated the plausibility of subsuming parts of physics under mixed mathematics, or of developing a mathematical physics. The idea of a mathematical physics presented straightaway, without elaborate philosophical

³⁹ Thomas H. Huxley, "The Progress of Science," in his *Method and Results* (New York, 1896), pp. 42–129 at 60.

⁴⁰ Heilbron, *Elements of Early Modern Physics*, pp. 1–11.

⁴¹ Cohen documents the rapid recognition of Newton's new mathematical techniques, *Newtonian Revolution*, pp. 43–44.

preparation and discussion, was soon emulated, and especially by 'sGravesande, even if he softened the spare Newtonian presentation.⁴² Newton's own geometrical presentation was later replaced by the more flowing style of algebraic and analytic formulae surrounded by discursive text, which became an established norm for physics texts in the late eighteenth and early nineteenth centuries.⁴³

Nonetheless, there is much to challenge in Heilbron's thesis that Newton's work was quickly followed by the creation of a new, experimental mathematical physics. Heilbron under-emphasizes the extent to which Newton's science was, and was perceived by his contemporaries to be, a continuation of the corpuscular philosophy shared by Descartes, Gassendi, and Boyle (abstracting from their differences over atomism).⁴⁴ He emphasizes especially the appeal to experiment and pedagogical demonstration in characterizing the new physics, as well as to mathematical analysis. Against this view, one might observe that the "bookishness" of the Aristotelians was a pedagogical tendency of teachers in the schools, not a part of the principled core of Aristotelian philosophy. More importantly, as Ruestow's careful scholarship has shown, the use of pedagogical demonstrations in the teaching of physics was already entrenched at Leiden in the lecture hall of the Cartesian de Volder, who set up a special auditorium for demonstrations in 1675, more than forty years before the coming of the Newtonians 'sGravesande and Musschenbroek.⁴⁵ Cartesian physics was of course intended as a general theory of nature, and it is therefore evident that one could advocate experiment without adopting the narrowed view of physics. Moreover, not only is it the case that Rohault's version of Cartesian physics was still being taught at Cambridge in the 1740s, but the Abbé Nollet, in his *Leçons de physique expérimentale*, which went through numerous editions from 1743 until after his death in 1770, effected to stay neutral among the physics of Descartes, Newton, and Leibniz,

⁴² 'sGravesande, *Mathematical Elements of Natural Philosophy*.

⁴³ Nicholson, *Introduction to Natural Philosophy*; Pierre Simon, marquis de Laplace (1749–1827), *Traité de mécanique céleste*, 5 vols. (Paris, 1798–1825); Biot, *Traité de physique expérimentale et mathématique*.

⁴⁴ E.g. Pieter van Musschenbroek, *Introductio ad philosophiam naturalem*, 2 vols. (Leiden, 1762), ch. 2.

⁴⁵ Edward G. Ruestow, *Physics at Seventeenth and Eighteenth-Century Leiden: Philosophy and the New Science in the University* (The Hague, 1973), pp. 96–106.

refusing, for one thing, to choose sides on the "vis viva" controversy.⁴⁶

The most serious flaw in Heilbron's thesis lies in his claim that the Newtonians 'sGravesande and Musschenbroek, and the systematist Wolff, all adopted the narrowed view of physics. The claim comes closest with 'sGravesande, who made the radical proposal that physics should be deemed a branch of mixed mathematics, thus reversing the dominance relation that held among the Aristotelians. He restricted the domain of physics to laws of motion governing bodies, and to a narrowed list of subfields including hydrostatics, hydrodynamics, pneumatics, physical optics, and celestial mechanics.⁴⁷ But he made himself special in doing so.⁴⁸ Musschenbroek, 'sGravesande's contemporary and colleague at Leiden, retained the broad notion of physics. His book gave detailed treatment only to the general theory of body and the laws of motion, mechanics, electricity, magnetism, hydrostatics, fire, optics (including the theory of vision), acoustics, and meteorology. But he left no doubt that physics proper extends to the whole domain of nature, including fossils, plants, and animals. Further, he located physics, or natural philosophy, among the traditional four philosophical disciplines, to which he added a fifth branch entitled "teleology," citing Wolff as precedent.⁴⁹ His examples of natural laws included the reproductive law that like produces like, and he illustrated the law of cause with the example of a nervous excitation causing muscular

⁴⁶ Jean Antoine Nollet (1700–1770), *Leçons de physique expérimentale*, 8th ed. vol. 1 (Paris, 1775), p. xx; and lesson 3, sec. 1. On Rohault in Cambridge, Heilbron, *Elements of Early Modern Physics*, pp. 3–4.

⁴⁷ 'sGravesande, *Mathematical Elements of Natural Philosophy*, preface, p. ii.

⁴⁸ Among the early English Newtonians, whose work was less widely circulated than 'sGravesande's and Musschenbroek's, John Keill (1671–1721) entitled his work *Introduction to Natural Philosophy* (London, 1720), and earlier, in Latin, *Introductio ad veram physicam* (Oxford, 1702), and seems to have intended thereby to forward the narrowed view of physics; J. T. Desaguliers (1683–1744), *A Course of Experimental Philosophy*, 2 vols. (London, 1734–1744), spoke of "mix'd Mathematics, where we reason mathematically upon Physical Subjects" (p. 2); and Andrew Moite (d. 1730), *A Treatise of the Mechanical Powers* (London, 1733), considered his subject-matter to fall within mathematics (his book grew out of his lectures in geometry at Gresham College), though he hoped that his work would be useful to those "entering the study of Natural Philosophy" (preface).

⁴⁹ Musschenbroek, *Introductio ad philosophiam naturalem*, ch. 1.

contraction.⁵⁰ In Germany, Wolff and his school also held to the broad definition of physics. Wolff divided physics into "general physics," treating of body in general, and the various parts of physics, which included cosmology, meteorology, oryctology (the science of fossils), hydrology, phytology, physiology, and anthropology.⁵¹

More generally, the disciplinary structure of physics conveyed by eighteenth-century encyclopedists did not favor the narrow view of physics. Ephraim Chambers held to the wide view, defining "natural philosophy" as "that science which considers the powers of nature, the properties of *Natural Bodies*, and their mutual action on one another: otherwise called *Physics*."⁵² He placed the narrow-view physical disciplines under "mixed mathematics," which included mechanics, hydrostatics, pneumatics, hydraulics, optics, geography, hydrography, chronology, gnomics, pyrotechny, military architecture, civil architecture, and music.⁵³ Diderot and d'Alembert, in the "Système Figuré" of the *Encyclopédie*, divided the "science of nature" into three branches: the "metaphysics of bodies," or "general physics"; "mathematics," including arithmetic and geometry, mechanics, geometrical astronomy, and optics (among others); and "particular physics," including zoology, physical astronomy, meteorology, cosmology, botany, mineralogy, and chemistry.⁵⁴ Near the end of the century, Johann Gehler, in his *Physikalisches Wörterbuch*, defined physics as "the entire theory of the nature of the corporeal world, or of the properties, powers, and effects of bodies."⁵⁵ While allowing that the "applied mathematical" sciences, including mechanics, optics, and astronomy, are an important part of physics or the theory of nature (*Naturlehre*), he maintained that the latter cannot be limited to mathematical sciences, for it at least must include chemistry. In the end, he urged that physics should comprise

⁵⁰ *Ibid.*, secs. 19, 30 (pp. 5, 12).

⁵¹ Christian Wolff, *Philosophia rationalis sive logica* (Frankfurt/Leipzig, 1740), secs. 75–84 (pp. 35–37).

⁵² Chambers, *Cyclopaedia*, vol. 2, "Natural Philosophy." He defines "Physicks" as the "doctrine of natural bodies, their phenomena, causes, and effects."

⁵³ *Ibid.*, "Mathematics."

⁵⁴ Denis Diderot and Jean Le Rond d'Alembert, *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*, 35 vols. (Paris, 1751–1780; repr. Stuttgart-Bad Cannstatt, 1966), vol. 1, p. liii.

⁵⁵ Johann Samuel Traugott Gehler (1751–1795), *Physikalisches Wörterbuch*, new ed., 6 vols. (Leipzig, 1798–1801), "Physik," vol. 3, p. 488.

natural history, chemistry, and the mathematical sciences as its three main branches, which was in effect to retain the conception of physics as the theory of nature in general.⁵⁶

In any case, examination of the scope of application of the term "physics" is not decisive either for determining the shift from natural philosophy to narrow physics or for evaluating the presence of a Newtonian Revolution. The name "natural philosophy" contains two terms, and the broad/narrow issue pertains only to the first of them. We have not yet confronted the problem of what was "philosophical" about natural philosophy. On a bland reading, the word "philosophy" here just means "scientific" or "systematic" knowledge of all and any things. But in fact, "philosophy" explicitly suggested (a) thinking for one's self, and (b) providing "reasons" for facts or claims; in practice, it also included (c) reflecting on the grounds of human knowledge, and (d) systematically analyzing the fundamental concepts of a given area of knowledge, their inter-relations, and (often) their relations to previously used concepts. Narrow-sense "physicists" held auto-cognition in high esteem and sought theoretical principles that served as "reasons," so points (a) and (b) do not distinguish their enterprise from philosophy. But concern with the epistemic basis of one's cognitive claims, e.g. in sense or in reason or in both, was a characteristically philosophical aspect of early natural philosophy, and one that continued to characterize some narrow physics before physics finally "became separate" (in many eyes) from philosophy. Such concerns are now retrospectively characterized as either "epistemological" or "methodological," depending on whether one wants to ally them less or more closely with science in the recent sense of that term.⁵⁷ Newton's followers represented him as effecting a change in method. One of the most rapidly accepted aspects of Newton's natural philosophy was his empiricism and his alleged rejection of speculative hypotheses. There was, then, a rapid Newtonian Revolution, but it was philosophical: it was the

⁵⁶ Ibid., "Mathematik," vol. 3, p. 160; "Physik," vol. 3, pp. 490–493.

⁵⁷ Shea, "Unfinished Revolution," p. 75, labels Johann Bernoulli's objection to Newtonian physics on the grounds that the action of gravity is unintelligible an "epistemological" objection owing to Bernoulli's Cartesian heritage. But might not the preference for intelligible explanatory concepts equally be labeled "methodological," and hence allied with the proper practice of science (taken to include methodological remarks)? In either case, it is a "philosophical" consideration.

change from Cartesian rationalism to Newtonian empiricism. It was advanced in the prefaces and introductions to the works of Newtonians such as 'sGravesande and Musschenbroek, as they rejected Cartesian claims to perceive the essence of matter a priori for the position that bodies can be known only with the aid of the senses.⁵⁸

We have been following the separation of experimental mathematical physics from natural philosophy. This separation was consolidated only in the second half of the eighteenth century,⁵⁹ lending some justice to the title of Hall's *The Scientific Revolution, 1500–1800*. If the Scientific Revolution is taken to mean the instauration of classical physics, it took more than 150 years, from the first half of the seventeenth century to the second half of the eighteenth, and hence was not sufficiently abrupt to be a revolution at all. The reasonably swift revolutions were philosophical and mathematical: Descartes' rationally-based corpuscularianism, Newton's empiricism, and Newton's science of fluxions.

Leaving aside these variations, we may observe a more profound sense in which "natural philosophy" or "science" remained "philosophical" throughout the eighteenth century and into the nineteenth: by continuing to include in the opening chapter the dialectical philosophical practice of reflecting on, criticizing, and analyzing the history of the central concepts used in the conceptualization, analysis, and explanation of nature. This dialectical method can be traced back to Aristotle, and variants of it are found in the discursive, critical portions of Galileo's *Dialogues* and *Discourses*, and in the metaphysical portions of Descartes' works. Among the major Newtonians, 'sGravesande was the least philosophical in this sense; philosophical analysis is shot through large chunks of Musschenbroek's works, and nearly all of Wolff's. I do not know when this sort of preliminary conceptual criticism and philosophical analysis became suspect in physics, or at least became something reserved primarily for night thoughts and popular monographs. But that will

⁵⁸ 'sGravesande, *Mathematical Elements of Natural Philosophy*, preface, "Oration Concerning Evidence"; Musschenbroek, *Introductio ad philosophiam naturalem*, ch. 1.

⁵⁹ Thomas L. Hankins, *Science and the Enlightenment* (Cambridge, 1985), ch. 3; Harman, *Energy, Force, and Matter*, ch. 1; Simon Schaffer, "Natural Philosophy," in *The Ferment of Knowledge: Studies in the Historiography of Eighteenth-Century Science*, eds. G. S. Rousseau and Roy Porter (Cambridge, 1980), pp. 55–91.

be the story of the real separation of physics, and of science more generally, from philosophy, and the reversal of such proscriptions, as has occurred recently in evolutionary biology and in cognitive psychology, marks the re-acceptance and acknowledgement of philosophical reflection as proper to the practice of science.

IV. "SCIENCE" AND THE HISTORY OF SCIENCE

In approaching the seventeenth and eighteenth centuries as historians of science, we have tended to focus on the rise of scientific institutions, the beginning of experimentation, the development of individual sciences and the procurement of important results, the incorporation of the revolutionary findings such as those of Copernicus and Galileo into the curriculum, and on the influence of nonscientific pursuits such as magic and alchemy on the development of science itself. Understandably enough, the unifying theme has been the institutional and intellectual developments that are recognizable as "scientific" to us now. Pursuit of such a focus provides a fairly tight and economical narrative to explain "how science arose" out of the mathematical and philosophical disciplines extant as the modern period began. Whatever may be its defects as contextual history, this approach has much to recommend it to practitioners of the discipline called "the history of science" who want to keep the "scientific" parts their story firmly in focus.⁶⁰

Yet in learning to focus on the "scientific" facets of seventeenth-century natural philosophy and mathematical science, we learn to slice away the parts of the texts we read or the institutions we study that do not constitute a proper part of the development of science as we now understand it. Sometimes we are uncomfortably aware of the process of surgery, as in the case of Kepler, where we feel the need to acknowledge that the search for cosmic harmony was the fundamental motive of his astronomy. Even so, scant attention has been paid to Kepler's own categories for describing his work, as when he described himself as pursuing a "metaphysical astronomy" by contrast with the mathematical astronomy of Copernicus.⁶¹

⁶⁰ Institutional factors pertaining to the publicly offered motivations for teaching the history of science, including its role in science education per se, must certainly play a role here.

⁶¹ Johannes Kepler, *The Secret of the Universe: Mysterium cosmographicum*,

Similarly, in the case of Galileo we long focused on questions pertaining to whether he did experiments. Wallace and Crombie have recently given prominence to his early relation to Aristotelian philosophy.⁶² But what of the philosophical character of his own mature writings, in both the *Dialogue* and the *Discourses*? By picking out what we consider to be the "scientific" content of those works, we ignore much of his philosophical argumentation against Aristotelianism and the philosophical qualities of his presentation of his own attitude toward astronomy and the sciences of materials and motion.⁶³ This stripping away of the philosophical and metaphysical content and contexts of seventeenth-century works effectively masks the historical problem of how modern science—conceived as the empirical investigation of nature in a manner (apparently) independent of explicit philosophical commitments—came into being. By finding "science" present from the start, one avoids the need to explain how the self-consciously pursued enterprise of modern science, so firmly entrenched during the present century, actually arose. Historians of science thereby become blind to a central problem in the history of science, viz., the origin and development of the modern practice of science itself.

Further, in focusing on the rise of "science" and "scientific" institutions in the seventeenth century we may overlook the institutional structures already in place. In particular, we may downplay the traditional curricular structures that provided the framework for teaching the material that we call science. Recent research has shown that there was more of the new science incorporated into the traditional curriculum than had been suspected.⁶⁴ But in straining to

trans. A. M. Duncan (New York, 1981), p. 63; see also Jardine, *Birth of History and Philosophy of Science*, pp. 250–251.

⁶² William A. Wallace, *Galileo and His Sources* (Princeton, 1984); A. Carugo and A. C. Crombie, "The Jesuits and Galileo's Ideas of Science and of Nature," *Annali dell'istituto e museo di storia della scienza di Firenze* 8 (1983): 3–68.

⁶³ These philosophical aspects of Galileo's texts are discussed in Maurice A. Finocchiaro, *Galileo and the Art of Reasoning* (Dordrecht, 1980), and Gary Hatfield, "Metaphysics and the New Science," in *Reappraisals*, eds. Lindberg and Westman, pp. 117–139.

⁶⁴ John Gascoigne, "The Universities and the Scientific Revolution: The Case of Newton and Restoration Cambridge," *History of Science* 23 (1985): 391–434; Mordechai Feingold, "The Universities and the Scientific Revolution: The Case of England," in *New Trends in the History of Science*, eds. R. P. W. Visser, H. J. M. Bos, L. C. Palm, and H. A. M. Snelders (Amsterdam/Atlanta, 1989), pp. 29–48.

detect incorporations of this sort, we may overlook the continuing effect of traditional curricular structures on the textual and cognitive structures of natural philosophy throughout the eighteenth and into the nineteenth centuries. In Germany, for example, the Wolffian system of the sciences retained a basically Aristotelian structure which served to organize textbooks and learning, even if the content of Wolff's system owed much to Leibniz and Newton. In the Wolffian curriculum, natural philosophy was considered a branch of philosophy that was conditioned by metaphysical subjects such as ontology.⁶⁵ If Newtonian science entails a rejection of the Aristotelian and Cartesian notions that metaphysics conditions physics, then the Newtonian Revolution is only complete once the notion of metaphysical foundations has been excised from the main literature of science, including its major presentations in textbook and lecture. In the meantime, a quite different conception of the relation of natural philosophy to the other branches of philosophy was embedded in institutional structures, and thus conditioned the prevailing conception of "physics," even as Newton's mathematical natural philosophy and its continuing development slowly changed the predominant conception of physics. At the same time, if we include among the "actors" in the development of modern science those who were engaged in university studies, then the relation between what we call science and what they called philosophy remained problematic well into the nineteenth century.

V. THE SEVENTEENTH-CENTURY REVOLUTIONS IN SUBSEQUENT HISTORIOGRAPHY

These reflections on actor's categories have implications for the historiography of the "Scientific Revolution." The use of the term "the scientific revolution" may belong exclusively to the twentieth century (although the term "philosophical revolution" was in earlier use).⁶⁶ But the idea that there was a reasonably rapid and successful

overturning of the Aristotelian orthodoxy during the seventeenth century has a much longer history. Cohen has traced this history in the portion of the older literature that we retrospectively associate with science.⁶⁷ The history can be fully appreciated, however, only by expanding our historiographical conceptions in accordance with our investigation into "actor's categories." For indeed, many of the earlier works that discuss the overthrow of Aristotelian philosophy in the seventeenth century and the subsequent rise of a new natural philosophy are histories of philosophy, produced in the eighteenth and nineteenth centuries.⁶⁸ If we are looking specifically for discussions of a "scientific" revolution these histories will seem irrelevant. But if we accept that the contextually sensitive historian should realize that what we now call the Scientific Revolution would earlier have been considered a "philosophical revolution," the relevant bibliography becomes multiplied by a middling digit.

The earliest history of philosophy I have found that implies there was a revolution in the seventeenth century and devotes considerable attention to natural (and mathematical) philosophy as part of that revolution is *Historia critica philosophiae* of 1742–1744, by the evangelical theologian and schoolmaster Johann Jakob Brucker (1696–1770).⁶⁹ Brucker's history of philosophy attended not only to the individuals who contributed to the alteration of philosophy in general, among whom he included Bruno, Cardan, Bacon, Campanella, Hobbes, Descartes, and Leibniz, but also to those who effected changes in the particular branches of philosophy, including logic, natural philosophy, morals, and politics. In natural philosophy, he considered both those who sought the reform of natural philoso-

"la révolution philosophique" led by Bacon and Descartes; each included the contributions to natural philosophy in their discussions of the revolutionaries.

⁶⁷ Cohen, *Revolution in Science*, chs. 5–13; Cohen includes some literature pertaining to learning in general on occasion, as in his reference to William Temple's works (Cohen, pp. 86–87).

⁶⁸ John Christie, "The Development of the Historiography of Science," in *Companion to the History of Modern Science*, eds. Olby et al., pp. 5–22, draws attention to Jean d'Alembert's, Adam Smith's, and Joseph Priestley's contributions to the historiography of the Scientific Revolution (at pp. 7–10), and in connection with Smith he acknowledges a "complex intertwining of history of science with philosophical concerns" (p. 9), but he does not note the discussions found in contemporary histories of philosophy.

⁶⁹ Johann Jakob Brucker, *Historia critica philosophiae*, 4 vols. (Leipzig, 1742–1744).

⁶⁵ Wolff, *Philosophia rationalis*, secs. 94–95 (pp. 42–43).

⁶⁶ Application of the term "revolution" (or the equivalent) to the seventeenth-century changes in philosophy is old: Johann Gottlieb Buhle (1763–1821), *Geschichte der neuern Philosophie*, 6 vols. (Göttingen, 1800–1805), vol. 3, p. iv, spoke of "die philosophische Revolution" led by Descartes, and Victor Cousin, *Cours de l'histoire de la philosophie*, new ed., vol. 1 (Paris, 1841), p. 58, spoke of

phy in general, among whom he included Bacon, Gilbert, Gassendi, and Descartes, and those who contributed specifically to the mathematical branch of natural philosophy, including Copernicus, Tycho, Kepler, Galileo, and Newton. He thus placed natural philosophy in the context of the other branches of philosophy, while devoting attention to the very developments that would later be picked out as constituting the Scientific Revolution.

Brucker did not call the events he described a "revolution," but he used language that indicated he considered them to be equivalent to a revolution. He divided the history of philosophy into three periods, ancient, middle, and modern, as was common. He ended the ancient period at the beginning of the Roman Empire; he began the modern period in the fourteenth century, with the "rebirth" of letters. As regards what he termed the "reform" or "restoration" of philosophy, he considered the revival of letters itself to be merely a preparatory stage, like the twilight before the dawn.⁷⁰ He described the actual reform in language that suggests political revolution, or at least revolt. He spoke specifically of the initiation of the reform through throwing off the "yoke" of authority and ancient prejudice. He saw two threats to free philosophizing: a prejudice in favor of ancient sects, and the authority of the church on the side of Aristotelianism. Once human reason was free of ancient authority, it was guided by its own light, refusing to admit anything as true that it did not see by rational judgment, evident truth, or certain demonstration.⁷¹ Brucker attributed the initial attempts at philosophical restoration to Bruno and Cardan; he credited Bacon with being the first to actually succeed in the reform and improvement of philosophy, followed by Campanella, Hobbes, and Descartes.⁷² Finally, he emphasized both the speed and the scope of the change: he maintained that philosophy

⁷⁰ Brucker, *Historia critica philosophiae*, vol. 4.1, p. 4.

⁷¹ *Ibid.*, vol. 4.2, pp. 5, 7. Brucker's protestantism no doubt should be taken into account in evaluating the oppressive role he assigned to the Catholic Church (and the liberating influence to Melancthon and Luther); but it cannot explain away his perception of a discontinuity in the seventeenth century, which was shared by Catholic thinkers on both sides of the question (revolutionaries and indexers alike). Similarly, the anti-clerical attitude of a Condorcet or d'Alembert might explain some aspects of their histories of human thought and their perceptions of discontinuity in the seventeenth century; nonetheless, the perception of that discontinuity is not merely a social construction.

⁷² *Ibid.*, vol. 4.2, pp. 12, 62, 90, 107, 145, 200.

had changed more during the hundred years since Bacon than it had in the previous thousand years, and he characterized the reform as extending to the "whole body" of philosophy.⁷³

Brucker considered the reform in natural science to have begun prior to the reform of philosophy in general, and specifically to have started with Telesio in the case of natural philosophy in general, and Copernicus in the case of the mathematical branch. Interestingly, he contended that there were fewer hindrances to this part of the reform—the Galileo affair notwithstanding—because changes in natural philosophy were less threatening to authority than changes in other parts of philosophy. His account of the development of natural philosophy in general stresses that it was an assault on Aristotelian orthodoxy, and emphasizes the important goad to the use of "experiment," or experience, provided by Bacon. In his discussion of natural philosophy, he highlighted Nathaniel Carpenter, William Gilbert, Daniel Sennert, Kinelm Digby, Robert Boyle, and William Harvey (among others), having already touched on the contributions of Bruno, Cardan, Campanella, Hobbes, Descartes, Leibniz, and Thomasius.⁷⁴ In treating mathematical philosophy, he portrayed Copernicus as being driven to reform Ptolemy's system because of the latter's mismatch with observation, and he asserted that Copernicus had demonstrated the phenomena "geometrically." He mentioned Kepler for his elliptical orbits, his three laws, his awareness of gravitational attraction, and his unfortunate attribution of souls to planets. Galileo's importance consisted mainly in the usual list: his telescopic discoveries, his *Dialogues*, his recantation, his geometrical treatment of the laws of moving bodies; Brucker also mentioned Galileo's project for measuring longitudinal distances using the moons of Jupiter. He devoted the most space to Newton, mentioning his work in optics, his *Principia*, and his work on the *Chronology of Ancient Kingdoms*. He provided a synopsis of the *Principia*, emphasizing the laws of motion and their application to both terrestrial and celestial phenomena. He extracted several Queries from the *Optics*, and statements of Newton's method. And

⁷³ *Ibid.*, vol. 1, p. 44.

⁷⁴ *Ibid.*, vol. 4.2, pp. 612–627. In the German history he singled out Bacon, Sennert, Digby, Gilbert, Gassendi, and Descartes as responsible for the renewal and reform of natural philosophy: *Erste Anfangsgründe der philosophischen Geschichte*, 2nd ed. (Ulm, 1751), p. 513.

he paraphrased Newton's disclaimer from assigning a cause to explain the force of attraction, quoting from Cotes' preface.⁷⁵ Here we find the older historiography of the Scientific Revolution pretty well developed, but told as the subplot in a larger story of philosophical reform.

VI. THE HISTORY OF PHILOSOPHY AND SCIENCE IN CONTEXT

The contextual approach to the seventeenth century and to an early history of philosophy suggests that there is a need for more study of the connection between the history of what we call science and what we call philosophy; for many of the actors tended to see both as interconnected parts of philosophy. In many cases, what we call science was taught as part of a coherent philosophy curriculum. This conclusion is at odds with Porter's recent portrayal of the relation between modern science and philosophy. He sees the connection between science and philosophy as part of an ideology imposed on the past by "philosophical" interpreters of the Scientific Revolution writing in the twentieth century, including Koyré, Butterfield, the Halls, and Gillispie. He sees the, in his terms, less than blissful marriage of history of science with philosophy of science as resulting from a retrospective interpretation of science as ultimately philosophical.⁷⁶

Porter's charge that Koyré and others artificially tried to make science into philosophy could make sense only for someone who had already accepted the nineteenth- and twentieth-century division between philosophy and science and had read it back onto previous figures. My own view is that we should make the relation between what we call "philosophy" and what we call "science," prior, say, to 1950, into an explicit object of investigation. This should be done not only for scientific writings, but for historical writings that portray previous natural philosophy and what came to be called natural science. I would conjecture that a controlling variable in whether historical accounts talk of or imply a "Scientific Revolution" will

⁷⁵ Brucker, *Historia critica philosophiae*, vol. 4.2, pp. 627–628, 632–638, 627–655. In the German history he singled out Copernicus, Brahe, Kepler, Galileo, Huygens, and Newton in mathematical philosophy: *Anfangsgründe der philosophischen Geschichte*, pp. 514–515, 517.

⁷⁶ Porter, "The Scientific Revolution," in *Revolution in History*, eds. Porter and Teich, pp. 295–296.

depend on whether the historian in question took the division between philosophy and science to be obvious or evident. There is no sharp boundary determining when the division became evident: some histories of philosophy in eighteenth- and early nineteenth-century Germany virtually omit natural philosophy from discussion, and treat mostly figures that we would now unproblematically categorize as philosophers.⁷⁷ But some late nineteenth-century histories devoted a major section to the new science, placing Galileo and Newton on the same footing with Descartes and Locke.⁷⁸

Part of the history of the separation of science and philosophy is known: nineteenth- and twentieth-century positivists alike taught that science came into its own only when it freed itself from metaphysics. Given the strong positivist streak found in historians of science during the early and mid-twentieth century, it is not surprising that this conception of science should serve as a commonplace in our field. One even sees the split between science and philosophy portrayed teleologically, as if it were what science had been striving for all along, as when one says that "science was still considered part of philosophy" in the eighteenth century. The division seems to be treated as if it were unproblematic and permanent, as if the positivistic distinction between science and metaphysics revealed the timeless essence of science, and showed it to be truly separate from philosophy.⁷⁹

⁷⁷ Buhle, *Geschichte der neuern Philosophie*, vols. 3–4, treated as major figures Descartes, Gassendi, Hobbes, Grotius, Malebranche, Spinoza, Leibniz, and Locke; he did not devote a section to the new science (though he discussed it in connection with the figures mentioned), and he granted a scant 13 pages to Newton, compared with 120 and 200 to Leibniz and Locke.

⁷⁸ Harald Höffding, *History of Modern Philosophy*, trans. B. E. Meyer, 2 vols. (New York, 1950; German edition, 1895–1896).

⁷⁹ Cohen helps himself to an unexamined distinction between "science" and other pursuits, including "philosophy" (*Revolution in Science*, esp. ch. 9). Porter implies a clear distinction between science and philosophical pursuits such as metaphysics, while allowing that such pursuits continued to play a role within "science," even after Newton ("Scientific Revolution," p. 303). Joseph Ben-David's discussion in *The Scientist's Role in Society* (Englewood Cliffs, N.J., 1971) takes the concepts of "science" and "scientist" as being applicable from ancient times onward, with an implied contrast to "philosophy" and "philosophers"; he implicitly defines the scientist as a person with "a burning desire to understand nature in its own terms," and acknowledges that such persons might be found among "philosophers" in earlier times while enforcing a contrast between the scientist and the "traditional philosopher" (pp. 28–29).

However, the positivist influence on the origins of our discipline does not explain why historians of science who are trained to be contextually sensitive—sensitive to the categories of their historical subjects—should continue to take a surgical attitude to the texts and concerns of past authors. I would point to social and institutional factors to explain this anomaly. As a social observation, I would conjecture that the tendency to ignore the connection between philosophy and science in the past may derive from unpleasant experiences with philosophers in the present. I think that philosophers tend to be bad at parties: overly earnest, seemingly literal-minded, likely on occasion to ask troublesome or difficult questions. Discomfort with philosophers now may shorten the historian's patience with philosophy in the past.

As an institutional factor, I would observe that as a result of the turn toward study of the institutionalized science of the late nineteenth and twentieth centuries, historians are trained to study science as it is conceived now, as something separate from, even opposed to philosophy. As a side effect, even historians of earlier periods of science are trained without attention to the history of philosophy. Indeed, in the intellectual landscape of the history of science the history of philosophy seems not to exist: one sees many discussions of the relation between the history of science and the philosophy of science, but few of the relation between the history of science and the history of philosophy. It may be that the history of philosophy has been confused with the sort of philosophical history done by Koyré and others. I would conjecture that what Porter really objected to in Koyré was his use of an historical narrative to support a favorite philosophical thesis, in this case, Platonic epistemology. What I am calling for is more attention to the history of philosophy, not specifically for a return to philosophically motivated history (though I think that has a place, too). A contextually sensitive approach to science in the seventeenth and eighteenth centuries demands no less.

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