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The Essential Readings

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I. Bernard Cohen, *Revolution in Science*, (Cambridge, Mass.: Belknap Press of Harvard University Press, 1985). © 1985 by the President and Fellows of Harvard College.

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Editor's Introduction: What was the Scientific Revolution?

Marcus Hellyer

Science is one of the most powerful forces in modern society, having enormous social, cultural, economic, and military influence. The science generating the technologies of the digital revolution is a crucial driver of modern economies. Chemistry and physics transformed the nature of warfare in the twentieth century. Legal cases, both civil and criminal, are often settled – or obscured – by the testimony of scientists as expert witnesses. People suffering from terminal disease wait in hope that scientists can develop a cure. In short, science pervades modern western societies, and through the processes of globalization it is coming to play a comparable role in many non-western societies.

This has not always been the case; for most of history there was no enterprise even remotely similar to our science. Thus, science has a history, although its history is not just a parade of changing, improving theories about particular natural phenomena, but a real history of human activity, of how and why we have investigated nature.

This history has been episodic. The investigation of nature has been relatively static in its contents, methods, and purposes at some times, but has changed rapidly at others. One era of fundamental change has come to be known as the Scientific Revolution. As with all revolutions, historians argue endlessly over its exact nature and periodization. Most agree that it occurred during the early modern period, from the early sixteenth century to the late seventeenth, although good cases can be made to extend it at either end. Historians are, however, virtually unanimous in regarding the Scientific Revolution as a European phenomena, occurring primarily in the western European regions of Italy, France, the Netherlands, Great Britain, and Germany.

Yet once we turn to the fundamental question, "What was the Scientific Revolution about?" we run into a lively debate. The answers that historians have provided to this question show why this is one of the most vibrant fields of the history of science and of history overall. The goal of this volume is to provide recent examples of the answers historians have given to this question. First this introduction will briefly outline historians' approaches to the Scientific Revolution for different approaches will give very different answers.[1]

The generation of scholars who introduced the history of science to the universities of Europe and North America in the decades either side of the Second World War created a coherent and compelling account of the Scientific Revolution. They focused primarily on the great advances in knowledge about natural phenomena and on theories in particular. This narrative primarily recounted the development of astronomy and mechanics and usually went something like this: it begins with Copernicus's (1473–1543) publication of his heliocentric cosmology in *De Revolutionibus Orbium Coelestium* (1543), in which he claimed the earth both rotated on its axis and revolved around the Sun. Copernicus was not seeking to overthrow ancient astronomy, but to restore perfect circular motion to the heavens. The story then moves to the late sixteenth century when a Danish nobleman Tycho Brahe (1546–1601) carried out astronomical observations of unprecedented accuracy and thoroughness on his island of Hven. Tycho also determined that comets and nova are celestial not meteorological phenomena, undermining Aristotle's (384–322 BCE) teaching on the perfection and immutability of the heavens.

The next figure to appear is Johannes Kepler (1571–1630), a German astronomer who was convinced of the truth of the Copernican system because it meshed seamlessly with the five perfect solids so important to his Neoplatonic world view, as he described in his *Cosmographic Mystery* of 1596. Kepler worked tirelessly yet unsuccessfully to reconcile Tycho's data to perfect circular orbits. Eventually he concluded that planetary orbits must be elliptical, thus breaking the ancient "spell" of perfect circular motion in the heavens, a finding published in his *Astronomia Nova* of 1609. At this point Galileo (1564–1642) enters the stage. Pointing the newly invented telescope at the heavens, he discovered phenomena which he described in his celebrated *Sidereus Nuncius* of 1610 such as the mountains on the moon, which further undermined the perfection of the heavens, and the moons of Jupiter, which indicated the earth need not be the center of all celestial motions. Galileo also set to work developing a system of mechanics to replace Aristotle's, in order to explain how heavy bodies can fly through the cosmos as well as fall down on earth, the results of which he eventually published in his *Two New Sciences* of 1638.

1 H. Floris Cohen, *The Scientific Revolution: A Historiographical Inquiry* (Chicago: University of Chicago Press, 1994), provides a complete overview of historical writing on the subject.

The culmination of the story occurs with Isaac Newton (1642–1727). In his *Mathematical Principles of Natural Philosophy* of 1687, Newton developed a mechanics based on the theory of universal gravity and the three laws of motion that could account for all motions, whether on earth or in the heavens, thereby erecting a complete system of physics that finally replaced Aristotle. Along the way he developed the necessary mathematical tools, the calculus, contemporaneously and independently of its other inventor Gottfried Wilhelm Leibniz (1646–1716). This conveniently offers a finishing line for the cosmic relay race towards truth begun in 1543 with Copernicus's *De Revolutionibus*.[2]

This short outline risks parodying a story that is told skillfully by excellent scholars, and one that is not without historical accuracy and narrative coherence, even when fleshed out with numerous lesser figures.[3] But the sheer success of the narrative raised problems. For one, it did not find clear parallels in disciplines outside of astronomy and mechanics. If developments had to be equally transformative to qualify as a revolution, then revolutions were hard to come by in chemistry or the various fields of natural history and medicine.

Certainly there were major achievements in these fields. One could also tell a narrative of medical discovery, particularly in anatomy and physiology. This begins in 1543 (conveniently the same year as Copernicus's *De Revolutionibus*) with Andreas Vesalius's (1514–64) work in anatomy, *On the Structure of the Human Body*. Based on dissections he himself performed, it set new standards both for empirical investigation and scholarly publishing. Eventually his investigations forced Vesalius to reject basic elements of Galenic anatomy, such as a permeable septum between the left and right ventricles of the heart. The narrative progresses to William Harvey's (1578–1657) discovery of the circulation of the blood, described in his *On the Movement of the Heart and Blood* (1628), and Richard Lower's (1631–91) work on the function of the lungs and his experiments on blood transfusions. The development of microscopy, particularly by Antoni van Leeuwenhoek (1632–1723) and Robert Hooke (1635–1703), is another highpoint of the narrative, leading to Marcello Malpighi's (1628–94) discovery of the capillaries in 1661 with the microscope and Leeuwenhoek's correct interpretation of their function in 1683.

But these developments led neither to a fundamental change in medical practice nor to greater diagnostic or predictive accuracy rivaling that of the

2 A recent and very useful resource, Wilbur Applebaum (ed.), *Encyclopedia of the Scientific Revolution from Copernicus to Newton* (New York and London: Garland, 2000), also adopts this chronology.

3 Prominent examples of this approach include Alexandre Koyré, *The Astronomical Revolution: Copernicus–Kepler–Borelli* (New York; Dover, 1992 [1961]); Richard S. Westfall, *Force in Newton's Physics: the Science of Dynamics in the Seventeenth Century* (New York: American Elsevier, 1971).

astronomers. It was hard to assess this history as revolutionary. Similarly natural history has long been the neglected stepsister in the narrative of the Scientific Revolution. Although there was a vast increase in knowledge about plants and animals sent back to Europe by merchants, missionaries, and explorers from around the world, it did not map easily on to the model established in astronomy. Natural history, it was said, had to wait until the nineteenth century for Darwin.

In general, the various branches of what we now term physics remained a much easier sell as revolutionary. Certainly the development of experimental instruments such as Evangelista Torricelli's (1608–47) mercury tube barometer, invented in 1644, and Otto von Guericke's (1602–86) air-pump, devised in the 1650s and soon improved upon by Robert Boyle (1627–91) and Robert Hooke in England, was extraordinary. Such instruments allowed the investigation and identification of the various characteristics of atmospheric air, such as its weight, pressure, and elasticity, as well as its role in combustion, respiration, and the transmission of sound. Similar giant strides were made in the study of electricity in the eighteenth century. The work of Kepler, Newton, René Descartes (1596–1650), and many others in both theoretical and practical optics and the physiology of vision resulted in major advances such as the law of refraction, the determination of the composition of white light, and steadily superior telescopes and accurate observations.

Historians attempted to overcome this disunity of different disciplinary narratives by determining features that they all shared. One approach traced a trajectory of differentiation from the ancients. Most sixteenth-century practitioners did not consciously set out to create a revolution; they were trying to revive ancient scholarship. Later, as they became aware of its inadequacies, they sought to repair its gaps or inaccuracies, for example, by adding to Pliny's *Natural History* (first century CE) plants and animals from the New World (Hooykaas and Ashworth's essays discuss the impact of the New World), or by removing abhorrent constructions such as the equant from Ptolemy's (fl. second century CE) astronomical masterpiece, *The Almagest* (see Westman).

Gradually, this movement to restore and augment became a drive to overthrow and replace. Seventeenth-century practitioners were very conscious of the novelty of their enterprises. The term new (*nova* in Latin) occurs again and again in the titles of their works.[4] Outside of the university there was widespread hostility towards Aristotle in particular, the most influential of the ancient philosophers, whose works still dominated the universities' curriculum in the seventeenth century. Descartes hoped to replace Aristotle's natural

4 Johannes Kepler's *New Astronomy*, Galileo's *Two New Sciences*, and Francis Bacon's *New Atlantis* and *New Organum* are prominent examples. Otto von Guericke and Robert Boyle both wrote works on the air-pump entitled *New Experiments*.

philosophy in the curriculum with his own. Thus a trajectory that began in the Renaissance with restoring the ancients moved to repairing their gaps or errors, and finally to rejecting and replacing them.

Another approach that tried to unify various fields of natural knowledge focused on the metaphysical underpinnings of the Scientific Revolution.[5] One fundamental element of the new natural philosophy was termed the mechanical philosophy. Strongly influenced by actual machines, particularly clocks and automata, it sought to project a clockwork mechanism onto the entire universe and all its components. The mechanical philosophy held that all natural bodies consisted of particles of matter in motion and nothing else. All perception was the result of particles of matter acting upon the particles of matter that comprise our sensory organs. Descartes's version was perhaps the best known, but there were numerous competing schools of mechanical philosophy.[6] They disagreed on the number of kinds of particles (from one to three to many to infinite), on whether the particles are infinitely divisible or ultimately irreducible, on whether they move in a vacuum or a plenum, and on whether matter is completely inert and lacking in any active or spiritual element.

The mechanical philosophy did not just make ontological claims about the world, that is, the kinds of things that exist, but also epistemological claims, that is, what counted as real knowledge and explanation. Reacting to the substantial forms of the universities' Aristotelian philosophers and the endless occult similitudes, sympathies and other qualities of the natural magicians, the mechanical philosophers insisted that an explanation of physical processes had to be expressed in mechanical terms, in the direct contact of particles on other particles. This led to perhaps the greatest irony of the Scientific Revolution, namely that many of Newton's contemporaries did not regard his theory of gravity as being truly scientific since he refused to identify a mechanical cause of gravity. Yet while a narrative structure focusing on the mechanical philosophy can unify natural philosophy with psychology (as Dear's piece shows) and even physiology, many areas of investigation paid little or no attention to it, as Ashworth's essay argues.

A similar approach that seeks to provide a coherent narrative focuses on method, arguing that the fundamental novelty of the Scientific Revolution was how practitioners examined nature and made their claims. The problem is that the range of methods used in the investigation of nature in early

5 E. A. Burtt, *The Metaphysical Foundations of Modern Physical Science: A Historical and Critical Essay* (New York: Harcourt, Brace, 1925).

6 The literature on Descartes's natural philosophy is enormous, see William R. Shea, *The Magic of Numbers and Motion: The Scientific Career of René Descartes* (Canton, Mass.: Science History Publications, 1991); Daniel Garber, *Descartes' Metaphysical Physics* (Chicago: University of Chicago Press, 1992); Stephen Gaukroger et al. (eds), *Descartes' Natural Philosophy* (London and New York: Routledge, 2000).

modern Europe is as bewilderingly varied as the disciplines and their practitioners themselves. Descartes's rationalism that built from a priori first principles was not the same as Newton's hypothetico-deductive method that eschewed speculation. Furthermore, an explicit affirmation of a particular method was often a declaration of adherence to the new philosophy, not necessarily an accurate statement about how one actually studied nature; Francis Bacon's (1561–1626) admonition to proceed by the inductive collection of individual facts was repeated approvingly by practitioners of all kinds, even those whose own method differed radically from Bacon's.[7] Also, in the question of method, radical distinctions between medieval and early modern blur. While Galileo's method, the regressus, has often been termed the modern scientific method, it was largely derived from scholasticism, although his insertion of mathematics and experiment into it was innovative. In addition, Galileo's insistence that natural philosophy had to provide certain demonstrations stands in clear contrast to the insistence by Boyle and other experimentalists at the Royal Society on the provisional and hypothetical nature of knowledge.[8]

As part of the process of rejecting the ancients outlined above, virtually all fields of natural philosophy and natural history came to privilege experience over authority. Hooykaas's piece stresses the importance of facts in the Scientific Revolution. But this emphasis certainly was not limited to the study of nature, and indeed, as Ashworth argues, may have been imported from humanistic disciplines such as antiquarianism. So a narrative that stresses the privileging of facts over textual authority dilutes and dissipates the uniqueness of natural inquiry in this period.

Other historians saw the revolutionary aspect as mathematical. In contrast to earlier systems of natural knowledge which rigidly distinguished between the domains of natural philosophy and mathematics, the Scientific Revolution experienced a trajectory that integrated mathematics and natural philosophy, culminating again in Newton's mathematical mechanics. This trajectory maps very neatly on the astronomical and mechanical one outlined above. Copernicus famously wrote in his *De Revolutionibus* that he was writing mathematics for mathematicians even though he was also speaking about the nature of the heavens and not just their motions. Both Kepler and Galileo held that the Book of Nature was written in the language of mathematics and only those versed

7 On Bacon see Julian Martin, *Francis Bacon, the State, and the Reform of Natural Philosophy* (Cambridge: Cambridge University Press, 1992; Stephen Gaukroger, *Francis Bacon and the Transformation of Early-Modern Natural Philosophy* (Cambridge: Cambridge University Press, 2001).

8 See William A. Wallace's numerous publications, particularly *Galileo and His Sources: The Heritage of the Collegio Romano in Galileo's Science* (Princeton: Princeton University Press, 1984); and his essays collected in *Galileo, the Jesuits and the Medieval Aristotle* (Aldershot: Variorum, 1991).

in geometry could comprehend it. The title of Newton's masterpiece proclaimed the complete integration of mathematics and natural philosophy. But again, how well does this mathematical revolution describe fields such as natural history, chemistry, or medicine?

These approaches were largely based on assumptions about science that can be termed "internalist." Again at risk of parody, this view held that science was primarily a cognitive activity quite distinct from society and culture. Science proceeded by observations and by the interaction and testing of theories. When society and culture did impinge upon science, it was as a foreign influence, quite different from science itself.[9]

But there was an alternative approach, one which saw the force driving science as coming from outside science itself, from the broader society. Marxist historians, for example, argued that the developments of the Scientific Revolution arose in response to the needs of early capitalism, in particular trade and navigation.[10] Certainly the great figures of Scientific Revolution were interested in solving practical problems. Many of them were intensely practical and technically gifted. But to reduce the Scientific Revolution to a quest for material and technological progress is a misrepresentation. The pursuit of truth and utility are hard to disentangle, even more so if we apply our standards of utility to the early modern period.

A more stimulating example of an externalist approach was provided in 1938 by Robert Merton, who suggested that certain social systems or ideologies provided values that were more conducive to science. Merton s particular case-study was seventeenth-century English Puritanism, which he claimed was in large part responsible for the flourishing of science in mid-seventeenth-century England.[11]

The divide between internalism and externalism can and has been overstated.[12] There was considerable overlap, and most historians from both camps accepted that there was a Scientific Revolution.[13] This "founding" generation of historians of science produced excellent studies that retain considerable merit. Two selections by members of that group (Reijer Hooykaas and

9 This is not to say that internalist historians did not see science as the product of Europe's unique culture and rationality.

10 J. D. Bernal, *Science in History. Vol. 2. The Scientific and Industrial Revolutions* (Cambridge, Mass.: The MIT Press, 1971 [1954]) presents a modern version of this approach.

11 Robert K. Merton, *Science, Technology & Society in Seventeenth-Century England* (New York: H. Fertig, 1970 [1938]).

12 For an overview of the debate see Steven Shapin, "Discipline and Bounding: The History and Sociology of Science as Seen Through the Externalism–Internalism Debate," *History of Science*, 30 (1992), pp. 333–69.

13 One should note that there is also a school of historians, mainly scholars of medieval science, who denied the revolutionary aspects of early modern science. Following the lead of Pierre Duhem in the early twentieth century, they argue that the origins of modern science lay in the Middle Ages and stress the continuities between medieval and early modern science.

I. Bernard Cohen) are included in this volume as illustrations their achievement. As a historical narrative, the Scientific Revolution perhaps reached its zenith in 1949 with Herbert Butterfield's famous comparison, in which he claimed it "outshines everything since the rise of Christianity and reduces the Renaissance and Reformation to the rank of mere episodes, mere internal displacements, within the system of medieval Christendom."[14]

Around the 1970s, however, historians of science adopted different approaches and consequently the questions they asked changed. There are several explanations for this development, one being the changing attitudes to science in general (discussed by Cunningham and Williams in this volume). Another shift was in the education of historians of science. Members of the founding generation had generally been trained as philosophers or scientists. Thus it is not surprising that they were interested in philosophical questions of method, metaphysics, and epistemology, or the internal histories of their scientific disciplines. Increasingly, however, scholars trained as historians entered the field. The historical profession had long since expanded from political and military history with its focus on "great men" to social and cultural history. They brought to the history of science the historian's concern for placing events in their wider cultural and social context.

Additionally, there was a fundamental shift in historians' understanding of the nature, production, and transmission of scientific knowledge. Many scholars from numerous disciplines contributed to this development, but among the most influential was Thomas Kuhn, who was, ironically, a philosophically inclined physicist.[15] Kuhn argued that scientists are trained and work within a paradigm that shapes their questions and methods, Most of what they do is simply normal science, solving problems that arise within the paradigm. Occasionally, as inexplicable anomalies accumulate, a new paradigm arises that can explain them. The new paradigm attracts its own adherents, mainly from the younger generations, thereby causing a revolution. Crucially, Kuhn insisted a scientist's decision to adhere to or abandon one paradigm could not be rationally explained, but depended on many cultural and social commitments. Later scholars, particularly sociologists, realized that Kuhn's work broke down the wall between science and society. In essence, all knowledge, even scientific knowledge, was social. Not only did members of scientific disciplines bring cultural commitments from other areas of their culture to their work, but the disciplines themselves were in effect societies which socialized their members. A vigorous sociological literature about science blossomed and offered historians

14 Herbert Butterfield, *The Origins of Modern Science, 1300–1800* (London: G. Bell, 1957 [1949]), p. vii.
15 Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962).

the hope of overcoming the internalist/externalist debates.[16] Knowledge was a social product, and without social organizations, there could be nothing that counted as knowledge.

While we should not draw a line too sharply between internalist and externalist approaches, or between the older and more recent history of science, we can nonetheless identify significant results of the shift within the history of science. One of the most important has been an increased concern with the social role and self-conceptions of practitioners. They were not scientists as we know them, but were radically different in their views of themselves and their enterprise.[17] A significant element of early modern science was how these self-conceptions changed as new disciplinary boundaries and hierarchies arose, When, following his discovery of the moons of Jupiter, Galileo moved from being a university mathematician to the court philosopher to the Grand Duke of Tuscany, he did so not for a larger salary, but for the greater institutional freedom and higher disciplinary standing his new position offered. This standing, he hoped, would allow him to make claims that he could not as a mere mathematician.

Similarly, since science is an inherently social activity historians are devoting greater attention to the institutions in which it is practiced. Studies have moved beyond the flagship scientific societies, such as the Royal Philosophical Society of London (founded 1660) and the Paris Royal Academy of Sciences (1666), to include the regional learned societies that copied them on a local level. The princely courts provided opportunities for mathematicians, natural philosophers, and physicians and often directed their attention to particular problems – Galileo did not find the time he hoped for at court as he was constantly drawn into disputes in which he as court philosopher was obliged to participate.[18]

Historians now also count among the institutions that fostered science international "corporations" such as the Society of Jesus with its worldwide missions and colleges, and international trading companies like the Dutch East India Company that collected plant and animal specimens from around the

16 For example, Barry Barnes, *Scientific Knowledge and Sociological Theory* (London: Routledge and Kegan Paul, 1974). Jan Golinksi, *Making Natural Knowledge: Constructivism and the History of Science* (Cambridge: Cambridge University Press, 1998) provides an excellent discussion of the implications of the social and cultural understanding of science for the history of science.
17 One of the most influential early works on this subject was Robert S. Westman, "The Astronomer's Role in the Sixteenth Century: A Preliminary Study," *History of Science*, 18 (1980), pp. 105–47.
18 See the essays in Bruce Moran (ed.), *Patronage and Institutions: Science, Technology, and Medicine at the European Court 1500–1700* (Rochester: Boydell, 1991); Mario Biagioli, *Galileo, Courtier: The Practice of Science in the Culture of Absolutism* (Chicago: University of Chicago Press, 1993); Lisa T. Sarasohn, "Nicolas-Claude Fabri de Peiresc and the patronage of the new science in the 17th century," *Isis*, 84 (1993), pp. 70–90.

world and developed botanical gardens.[19] Even if these institutions are not the same as our institutions of "Big Science," they produced something that was radically different to what existed before 1500.

Universities have also attracted renewed attention. While they were not primarily responsible for the major innovations of the early modern period, they provided education and employment for mathematicians, natural philosophers, and physicians and institutional support in the form of botanical gardens, anatomical theaters, and cabinets of instruments.[20] Granted, it was not until the eighteenth century that universities really adopted and taught experimental physics and Newtonian mathematics and mechanics. Medical societies could also promote or hinder the spread of new approaches to natural philosophy and medicine, as Allen Debus shows in his essay.

As claims can only count as knowledge once they are transmitted and accepted, but are also transformed in the process of dissemination, the media of transmission are particularly worthy of study. Scholarly publishing changed dramatically in the sixteenth and seventeenth centuries. Correspondence served a vital role in the dissemination of knowledge and in claims of priority for discoveries, and much of it was intended for actual publication. In the mid-seventeenth century, Marin Mersenne (1588–1648) in Paris and Athanasius Kircher (1602–80) in Rome both sat at the center of vast networks that stretched around the globe. Kircher published much of what he received in his numerous books; Mersenne forwarded what he received on to other savants around Europe. By the end of the seventeenth century, the function of claiming priority and dissemination was being replaced by journals, in particular the *Philosophical Transactions*, the *Journal des sçavans* (both founded 1665), and the *Acta Eruditorum* (published in Leipzig from 1682). The two media flowed into each other; Henry Oldenburg (ca. 1619–77), the secretary of the Royal Society, himself sat at the center of a network of correspondence which supplied much of the *Philosophical Transactions*' material. All aspects of print culture, particularly the role of illustration, are also receiving greater attention.[21]

Social history focuses on everyday practice. Most modern scientists are not Nobel Prize winners, but patient contributors to a larger enterprise. Early

19 Steven J. Harris Harris, "Long-distance corporations, big sciences, and the geography of knowledge," *Configurations*, 6 (1998), pp. 269–304; Richard H. Grove, *Green Imperialism: Colonial Expansion, Tropical Island Edens and Origins of Environmentalism* (Cambridge: Cambridge University Press, 1995).

20 John Gascoigne, "A reappraisal of the role of the universities in the Scientific Revolution," in *Reappraisals of the Scientific Revolution*, eds David C. Lindberg and Robert S. Westman (Cambridge: Cambridge University Press, 1990), pp. 207–60.

21 Brian J. Ford, *Images of Science: A History of Scientific Illustration* (Oxford: Oxford University Press, 1993); William B. Ashworth, Jr, "Iconography of a New Physics," *History and Technology*, 4 (1987), pp. 267–97; Adrian Johns, *The Nature of the Book: Print and Knowledge in the Making* (Chicago: University of Chicago Press, 1998).

modern practitioners were no different. Yet if our account is to have any claims on completeness, their stories must be included. Professors of natural philosophy at the many minor universities, gentlemen who sent contributions to the scientific societies, noblewomen who produced and consumed literature popularizing and disseminating natural knowledge, and ships' captains who tested and improved methods of cartography and navigation all have a place in this more inclusive history of early modern science. Margaret Jacob tells us how the dissemination of the Scientific Revolution among broad classes of people in eighteenth-century England produced the Industrial Revolution.

This concern with practice has meant that the role of practical activities is being reassessed outside of a Marxist, externalist framework in order to break down simplistic dichotomies between pure science and artisanal or technological work.[22] Similarly, extending the history of science beyond conceptual developments to the practices of science has led to closer study of experimental natural philosophy. For the first time natural philosophers were constructing instruments that artificially created phenomena that did not exist or could not be observed in nature. The air-pump is the classic example, but experiment was not limited to physics; physicians carried out physiological experiments on animals, often to show that organs or muscles worked in mechanical ways. The development of experimental philosophy tied in neatly with the spread of the mechanical philosophy since most experimenters sought to provide mechanical accounts of the phenomena they investigated, such as Robert Boyle's suggestion that spring-like particles accounted for the elasticity of air.[23]

One of the main assumptions of newer scholarship is that current hierarchies of knowledge are not necessarily accurate when applied to other times. Rather, one should treat forms of knowledge symmetrically and without projecting onto the past the disciplinary boundaries of the present. The result is that disciplines which were once dismissed as pseudo-sciences have received fundamental reevaluation. The involvement of leading figures in these pursuits was once seen as an aberration to be explained away or simply ignored. But early modern practitioners' engagement with these disciplines was real and sincere. Newton's exhaustive engagement with alchemy is now seen as a fundamental part of his investigative program.[24] Concern with

22 Lisa Jardin, *Ingenious pursuits: building the scientific revolution* (New York: Nan A. Talese, 1999); J. A. Bennett, "The challenge of practical mathematics," in eds Stephen Pumfrey et al., *Science, Culture and Popular Belief* (Manchester: Manchester University Press, 1991).

23 Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton; Princeton University Press, 1985); Peter Dear, *Discipline and Experience: The Mathematical Way in the Scientific Revolution* (Chicago: University of Chicago Press, 1995).

24 Betty Jo Teeter Dobbs, *The Foundations of Newton's Alchemy: or, "The Hunting of the Greene Lyon"* (Cambridge: Cambridge University Press, 1975); and idem, *The Janus Faces of Genius: the Role of Alchemy in Newton's Thought* (Cambridge: Cambridge University Press, 1991).

improving the accuracy of astrological predictions was one of the major motivations behind the desire to improve astronomical models and observations. Copernicus, we now know, was motivated by a desire to respond to criticisms of astrology.[25]

In fact it is difficult to distinguish between the desire of natural magicians, such as Giambattista della Porta (1535–1615) and Heinrich Cornelius Agrippa von Nettesheim (1486–1535), to use their knowledge of occult sympathies to manipulate nature to useful ends and the Baconian program of using natural philosophy to benefit humanity. One could argue that science appropriated natural magic's goals while abandoning its similitudes and sympathies in favor of mechanical causation.[26]

Similarly the distinctions between a supposedly pseudo-scientific alchemy and a rational, scientific chemistry have become blurred. Simply, dichotomies between alchemy and chemistry, whether based on theory, method, purpose, or chronology, no longer hold. William Newman and Lawrence Principe have proposed using the term "chymistry" for both alchemy and chemistry in the early modern period to avoid imposing an arbitrary and anachronistic distinction on them.[27] There were alchemists of all stripes. They were prominent members of the Royal Society. There were Paracelsian alchemists who sought to reform medicine (see Debus's piece). There were alchemists who employed various forms of mechanical philosophy such as atomism. In fact, alchemy was probably at its height in the seventeenth century and it did much more than simply try to turn lead into gold.

Cultural and social approaches to early modern science have devoted considerable, if still inadequate, attention to issues of gender. Since all of the great figures of the Scientific Revolution were male, women were almost completely absent from the historical narrative. While nobody is suggesting that a long-lost female Newton will be rediscovered, women's activities in early modern natural philosophy are being recovered from historical silence.[28] Aristocratic women were particularly prominent as patrons and correspondents. Princess Elizabeth of Bohemia (1618–80) and Queen Christina of Sweden (1626–89)

25 See Robert S. Westman, *The Copernican Question* (Chicago: University of Chicago Press, forthcoming).

26 For an overview see John Henry, "Magic and science in the sixteenth and seventeenth centuries," in *Companion to the History of Modern Science*, eds R. C. Olby et al. (London: Routledge, 1990), pp. 583–96.

27 William R. Newman and Lawrence M. Principe, "Alchemy vs. chemistry: The etymological origins of a historiographic mistake," *Early Science and Medicine*, 3 (1998), pp. 32–65. See also Pamela H. Smith, *The Business of Alchemy: Science and Culture in the Holy Roman Empire* (Princeton: Princeton University Press, 1994).

28 Londa Schiebinger, *The Mind Has No Sex?: Women in the Origins of Modern Science* (Cambridge, Mass.: Harvard University Press, 1989); idem, *Nature's Body: Gender in the Making of Modern Science* (Boston: Beacon Press, 1993).

supported Descartes. Sophia, Electress of Hanover, (1630–1714) and her daughter Sophia Charlotte (1668–1705), who became Queen of Prussia, both conducted correspondence and conversation with Leibniz.

Despite the constraints on women, such as limited access to education and stereotypes accepted by both men and women about women's limited and flawed intellectual capacities, women were themselves active in the production of knowledge. Women worked in private astronomical observatories, for example. The astronomer Johannes Hevelius's second wife Katherina Elizabetha Koopman (1647–93) assisted with his observations and published two of his works after his death. Maria Sibylla Merian (1647–1717) traveled to the New World to collect specimens and write and illustrate works of New World natural history. Both these women, it should be noted, received their training in the private realm of the family. Gradually, however, as distinctions between the public and private sphere solidified, women's place was confined to the private, excluding them from participation in the increasingly public world of science.

More controversial is work on the gendering of nature and natural knowledge itself. Since cultural approaches to scientific knowledge argue that the scientific enterprise reflects the cultural values and commitments of practitioners, conceptions of gender should be reflected in scientific knowledge. It has been argued that the entire mechanical worldview is an inherently male one, repressing and replacing a more "female" organic view of nature.[29]

The history of early modern science has also gone beyond tired old stereotypes about the supposed conflict of science and religion to examine their interaction. In fact, a sensitivity to religion is a defining feature of much recent work on early modern science.[30] The Galileo affair continues to receive considerable attention, although the story is no longer seen by historians of science as an example of Catholicism's supposedly inherent hostility to science (see Westman's article).[31] As Merton suggested, religion played an important role in promoting the investigation of nature, but it is now clear it was not just Puritanism which did so.

In fact the study of God's creation, his Book of Nature, was widely regarded by philosophers and mathematicians of all confessions as a valuable way of overcoming skepticism and the atheism to which many thought it inevitably led. Although the argument from design did not receive that name until the

29 Carolyn Merchant, *The Death of Nature: Women, Ecology, and the Scientific Revolution* (San Francisco: Harper & Row, 1980).

30 For an overview see John Hedley Brooke, *Religion and Science* (Cambridge: Cambridge University Press, 1991).

31 The best overview of the Galileo affair is without doubt Annibale Fantoli, *Galileo: For Copernicanism and the Church* (Vatican City: Vatican Observatory Publications, 1996).

eighteenth century, it was already widespread in the seventeenth as a weapon against atheism. It argued that the order and purpose we see in nature could only be the result of a divine intelligence.[32] The Protestant Kepler, Jesuit mathematics professors, the founders of the Royal Society – all saw themselves as serving God by studying his creation.

As a result of these studies, the Scientific Revolution as concept and narrative is in turmoil. In fact, all three elements of the phrase are questionable. "The" implies that there was just one revolution in the early modern period, which was not the case. Moreover, it also implies a hierarchy of significance; yet if the events of the sixteenth and seventeenth centuries were "the" Scientific Revolution, then the chemical revolution of the eighteenth century was merely "a" revolution and necessarily of secondary importance, something that historians of other eras would dispute.

Furthermore, with greater sensitivity to actors' categories, historians now accept that the word "scientific" is also misleading and anachronistic. The association between science and the study of nature was not one made in the early modern period. In a narrow sense science, from the Latin *scientia*, meant any kind of certain knowledge, that is, it referred to the epistemological status of knowledge rather than its object. In a broader sense, *scientia* referred to any intellectual discipline rigorously practiced (usually at a university), including theology and logic. The various disciplines that studied and manipulated nature in the early modern period had many different terms: natural philosophy, mathematics, mixed mathematics, natural history, to name the most common. No single term encompassed these different enterprises in the way that "science" encompasses the study of nature today.

And "revolution" seems somehow inappropriate for a process that lasted at least a century and a half or, by many accounts, even longer. Furthermore, the lens of revolution is distorting; whatever doesn't measure up as a radical advance from our standpoint is tossed out of the historical story – something quite at odds with the current emphasis on respecting actors' categories. Thus the term "Scientific Revolution" has fallen out of favor without being replaced. "Early modern science," which brings less intellectual baggage with it, has had some success.

So what, then, should we do with the Scientific Revolution? Cunningham and Williams propose the radical solution of simply throwing the whole thing out. While they raise important arguments, their call has not found universal favor. The Scientific Revolution does retain considerable usefulness as a shorthand name for the field and it certainly shows no signs of simply disappearing.[33] This volume provides examples of a more moderate approach that retains the term as one describing the totality of developments in the period. But rather than attempting to define the exact essence of the Scientific Revolution, they adopt one or more of the approaches outlined above: locating practitioners in their cultural context; revealing how knowledge is socially created and transmitted; expanding the narrative to include more disciplines; examining the connections between science, craft, art, and technology. They show us that whether we want to use the term revolution, whether we accept that early modern science was not the same as ours, the study of nature was fundamentally transformed between 1500 and 1700, not just in its theory, but in its methods, institutions, and everyday practices.

32 Amos Funkenstein, *Theology and the Scientific Imagination from the Middle Ages to the Seventeenth Century* (Princeton: Princeton University Press, 1986).

33 Witness the use of the term in several recent undergraduate survey texts: Steven Shapin, *The Scientific Revolution* (Chicago: University of Chicago Press, 1996); John Henry, *The Scientific Revolution and the Origins of Modern Science* (New York: St Martin's Press, 1997). Peter Dear, *Revolutionizing the Sciences: European Knowledge and Its Ambitions* (Princeton: Princeton University Press, 2001), reverses and pluralizes the terms.