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The Legacy of Ancient and Medieval Science

THE CONTINUITY QUESTION

My attempt, in this book, to reconstruct the lives, beliefs, and activities of historical actors from the ancient and medieval past has surely raised more questions than it has been able to answer. I would like to conclude this volume by approaching a cluster of questions that have doubtless occurred to most readers and that are also of great interest to me. What did all of that ancient and medieval scientific activity amount to? Was it really "science"? What difference did it make in the long run? Did it leave a permanent impression on the course or the shape of Western science, or was it an inconsequential culde-sac that ultimately led nowhere? Or to pose the question in one of its most common forms, were medieval and early modern science continuous with each other, or discontinuous? This is the celebrated "continuity question," which has been the basis of a persistent, but civilized, feud between medievalists and historians of early modern science. I would like to conclude this volume by cautiously approaching this question—circumspectly examining some of the outstanding scientific achievements of antiquity and the Middle Ages (both Islamic and Christian) in the interest of understanding the degree and shape of ancient and medieval influence on the science of sixteenth- and seventeenth-century Europe.[1]

But the first order of business is to do battle with centuries of entrenched opinion among those who denigrate medieval science, viewing the Middle Ages as a period of unrelieved scientific ignorance and superstition. Such opinions have received ample (if seriously misinformed) scholarly support, and in the mass media the adjective "medieval" has become a synonym for all that is deplorable. An early advocate of this negative opinion was Francis Bacon (1561-1626), who wrote in his *New Organon* (1620) that the ages between antiquity and his own era were "unprosperous" for the sciences, "for neither the Arabians nor the Schoolmen need be mentioned, who in the intermediate times rather crushed the sciences with a multitude of treatises, than increased their weight." A century later, Voltaire (1694-1778) elevated the level of anti-medieval rhetoric, writing of the "general decay and degeneracy" that characterized the Middle Ages, and of the "cunning and simplicity … brutality and artifice," of the medieval mind.[2]

The views of Bacon and Voltaire were sharpened and widely disseminated in the second half of the nineteenth century by the distinguished Swiss historian of the Renaissance, Jacob Burckhardt (1818-97), who argued in his *The Civilization of the Renaissance in Italy* (1860) that "the Middle Ages … spared themselves the trouble of induction and free inquiry." And in its most influential manifestation, Andrew Dickson White used the supposed ignorance and futility of medieval science as a weapon in his widely influential diatribe (1896) against the evils of a Christianity that, in his opinion, interfered with the development of the natural sciences: "The establishment of Christianity," he wrote, "arrested the normal development of the physical sciences for over fifteen hundred years…. There was created an atmosphere in which the germs of physical sciences could hardly grow—an atmosphere in which all seeking in Nature for truth as truth was regarded as futile." Finally, to demonstrate that such views are still alive and well, I quote Charles Freeman, in his *The Closing of the Western Mind: The Rise of Faith and the Fall of Reason* (2003): By the fifth century of the Christian era, he argues, "not only has rational thought been suppressed, but there has been a substitution for it of 'mystery, magic, and authority.' " It is little wonder, given this kind of scholarly backing, that the ignorance and degradation of the Middle Ages has become an article of faith among the general public, achieving the status of invulnerability merely by virtue of endless repetition.[3]

A pro-medieval counterattack was mounted in the early decades of the twentieth century by the French physicist and philosopher Pierre Duhem (1861-1916). While exploring the origins of the science of statics, Duhem encountered the works of fourteenth-century mathematicians at Oxford and Paris who, in his judgment, had laid the foundations for modern science, anticipating some of the most fundamental achievements of Galileo and his contemporaries.[4] Duhem's claims set off the continuity debate, which erupted with a certain regularity throughout the twentieth century. Early support for Duhem's campaign came from the influential medievalists Charles Homer Haskins (1870-1937) and Lynn Thorndike (1882-1965), writing in the 1920s and '30s.[5] The decades after World War II saw a dramatic expansion of historical research on medieval science; increased activity led to improved status and fresh claims about the magnitude and significance of the medieval scientific achievement. One of the leading figures in the postwar movement was Marshall Clagett (1916-2005), who made his mark primarily through the editing and translation of medieval scientific and mathematical texts. Another was Anneliese Maier (1905-71), who produced a series of brilliant studies in which she demonstrated by example how to read the sources more carefully and with closer attention to their philosophical context. While challenging many of Duhem's more extreme claims and offering an analysis of medieval natural philosophy far subtler and more cautious than his, Maier reaffirmed the importance of the medieval contribution, both conceptual and methodological, to the forging of modern science.[6]

Sparring has continued to the present, though to my eye the intensity level of the debate has diminished. For one thing, no informed historian of science would now support the extreme negative opinions of Francis Bacon, Voltaire, Burckhardt, or A. D. White. Alistair Crombie (1915-96) and Alexandre Koyré (1892-1964) traded opinions in the 1950s and 1960s—Crombie pleading that "a systematic theory of experimental science was understood by enough [thirteenth- and fourteenth-century] philosophers … to produce the methodological revolution to which modern science owes its origin." Koyré responded by denying the importance of methodology in the abstract for the origins of modern science and questioning whether, in any case, medieval methodologists had actually anticipated seventeenth-century methodology.[7] By now, early in the twenty-first century, both parties have made concessions, and despite an occasional quarrel, it appears that relative peace has broken out. The early modernists no longer question whether important scientific achievements emerged from the Middle Ages; and few medievalists now defend a strong version of the claim for continuity between medieval and early modern science.[8]

CANDIDATES FOR REVOLUTIONARY STATUS

Given the background sketched above, should we accept the construct of a seventeenth-century scientific revolution? And if the answer is affirmative, what was its relationship to the classical tradition of ancient and medieval science? Some observers of early modern science have expressed skepticism, on semantic grounds, about the very possibility of a seventeenth-century scientific revolution because we have no universally accepted definition of either "science" or "revolution." But the same is true of most interesting words. We have no universally accepted definition of "Middle Ages," "Renaissance," "Reformation," "fall of Rome," "art," "music," "religion," "philosophy," and so on. All of these are abstractions with debatable meanings that vary from one linguistic community to another—and from person to person within a given linguistic community. They are labels that we require if we are to communicate with one another, and they are inevitably fuzzy. To quibble about the label "scientific revolution" is thus (in my opinion) a waste of time. We should reserve our quibbling (if we can agree on the meaning of that word) for those occasions for which quibbling is suited—namely, discussion of such things as scientific beliefs and practices, rather than what to name them.

Not to quibble, then, but to inform: in my usage, the term "revolution" represents fundamental change, with no limits on elapsed time. The latter condition is my answer to those who have argued that a revolution that requires a century for its completion can't be a true revolution; revolutions, they believe, must be quick. I am unmoved by this argument; and my unabridged dictionary supports me, defining "revolution" simply as "radical and pervasive change." Call it what you like, do we see what can be regarded as examples of "radical and pervasive agents of change" in seventeenth-century European science—fundamental and with sufficient breadth, depth, and influence to qualify for *revolutionary* status?[9]

Two candidates, it appears to me, currently command significant support among historians of early modern science. The first is an alleged "healing" of an ancient schism separating physics and mathematics, and the creation, in the sixteenth and seventeenth centuries, of the new discipline (or collection of disciplines) that we call "mathematical science." Aristotle, it has been argued, distinguished between mathematics and physics (or natural philosophy) on disciplinary grounds and implicitly forbad the crossing of the disciplinary boundary that separated them. It is claimed, moreover, that ancient and medieval scholars largely (or almost entirely) accepted this prohibition, with the unfortunate consequence that physical science and mathematical science lived separate (and therefore mostly sterile) scientific lives until the early modern period. Medieval scholars could do physics and they could do mathematics, but disciplinary boundaries prohibited them from applying the content and techniques of the one to topics in the other. In short, mathematical modeling was separated by an uncrossable chasm from the exploration of physical reality. A revolution in science resulted, therefore, when Copernicus, Galileo, and other early modern scholars united the two enterprises, thereby creating genuine mathematical physics and setting science (or the physical sciences, at least) on the road to modernity.

We owe this argument largely to the influence of Pierre Duhem, writing in the first decade of the twentieth century, and resurrected by Robert S. Westman in an influential article published in 1980. Westman argued for the existence of disciplinary communities with rigorously patrolled boundaries, which prohibited pre-Copernican mathematical astronomers or any other kind of mathematical scientist from dealing with questions of physical reality. Westman then used this model to explain (precariously, I believe) certain elements of Andreas Osiander's prefatory letter to Copernicus's *De revolutionibus*.[10]

The only problem with this interpretation is the historical record, which casts serious doubt on its veracity. It is true that Aristotle clearly and frequently distinguished between mathematics and physics in various works, including his *Posterior Analytics*, *Physics*, *Metaphysics*, and *On the Heavens*; he also discussed disciplinary boundaries and principles of subordination. But he consistently *rejected* a prohibition against crossing the boundary between physics and mathematics. He wrote about such matters in his *Physics*:

> The next point to consider is how the mathematician differs from the student of nature [the physicist]; for natural bodies contain surfaces and volumes, lines and points, and these are the subject-matter of mathematics. Further, is astronomy different from natural science or a department of it? It seems absurd that the student of nature should be supposed to know the nature of sun or moon, but not to know any of their essential attributes, particularly as the writers on nature obviously do discuss their shape and whether the earth and the world are spherical or otherwise.[11]

In practice, Aristotle repeatedly and unapologetically applied mathematics to the physical world—most obviously in his analysis of motion, where mathematical proportionalities played a major role, and quantifiable things such as weight or power were considered intrinsic properties and therefore aspects of the natures of the things studied.[12] As for the Middle Ages, the historical record once again comes to our rescue, revealing astronomy, optics, dynamics (theory of motion), and theory of weights as examples of successful sciences that were rooted in both physics and mathematics—traditions adopted and extended by Copernicus, Galileo, Kepler, and many other early modern scientific practitioners.[13]

A convincing paradigmatic case can be made of medieval *perspectiva* (our geometrical optics). I have devoted many decades to research on the major figures in the history of ancient and medieval optics, and except for Euclid (fl. 300 B.C.) and one or two minor figures, have not encountered any evidence that would support the myth (for that is what it has become) that we are exploring. [14] I have no way of knowing what optical scholars thought about the crossing of disciplinary boundaries *in general*, but I do know that all of them regularly crossed the boundary between mathematics and physics without, apparently, the slightest apprehension—concerned equally to discover the physical realities of light, color, reflection, refraction, and vision, and to situate them within a mathematical framework. Mathematical physics was certainly not an invention of the sixteenth or seventeenth century.

The second candidate for early modern revolutionary status is methodological—the invention and practice of the "experimental method" (according to the defenders of this thesis) by such sixteenth- and seventeenth-century scientists as Galileo, William Gilbert, Robert Boyle, and many others. According to defenders of this theory, the sterile scholastic debates and syllogistic demonstrations of ancient and medieval natural philosophy came to an end, replaced by experimental science, with its firsthand observation and manipulation under controlled conditions.

Before we look at examples, I hope for agreement among readers on two matters. First, we need to recognize the gap that separates methodological *theory* from methodological *practice*. What Aristotle *said* about scientific method in abstract methodological treatises and what his followers (and Aristotle himself) *actually did* in their scientific pursuits were very often two different things; and the same claim can be made, in general, for scientists who have troubled themselves to write on scientific methodology. In any case, our concern here will be exclusively with methodological *practice*. Second, we need to define the word "experiment." For present purposes, I am inclined to define it narrowly, by what I take to be its primary epistemological function: an attempt to confirm or disconfirm a theoretical claim about the nature or behavior of the material world by an observation (under controlled conditions if necessary) made for that purpose, or the gathering of data against which future anticipated theoretical claims maybe tested.[15]

If these matters may be considered settled, we can go in search of ancient and medieval scientific experiments. They are not hard to find. Ptolemy (and his sources of astronomical data) are primary examples of planetary observation, employing a variety of astronomical instruments, in order to confirm or disconfirm the adequacy of his (and his predecessors') geometrical models for the planets. Similarly in his optics, Ptolemy deployed apparatus in contrived experiments, intended to gather the quantitative data that a successful mathematical theory of the refraction of light would be obliged to predict.[16] In medieval Islam, Ibn al-Haytham (ca. 965-ca.1039) performed experiments designed to prove or disprove the truth of optical theories.[17] Kamāl al-Dīn's fourteenth-century creation of a theory of the rainbow on the basis of experiments with light rays passing through water-filled glass globes is another excellent example—duplicated about the same time in medieval Christendom by the Dominican friar Theodoric of Freiberg.[18] We may also safely infer that the Maragha, Samarkand, and Istanbul observatories developed research programs based on organized observation of the heavens meant to deliver numerical data by which to confirm or disconfirm astronomical theories.[19]

Did experimental efforts continue in the European Middle Ages? Certainly! And, as in antiquity, they were most plentiful in the mathematical sciences, where Ptolemaic influence remained strong. One of the most striking occurred when the sixth-century Alexandrian Platonist John Philoponus simultaneously released two objects of different weights in order to disprove the Aristotelian theory that speed of descent is proportional to the weight of the body. According to Philoponus, “if you let fall from the same height two weights of which one is many times as heavy as the other, you will see that the … difference in time [of descent] is a very small one. And so if the difference in the weights is not considerable, that is, if one is, let us say, double the other, there will be no difference or else an imperceptible difference in time.”[20]

Experimentation continued through the later Middle Ages, wherever it met a scientific need. Levi ben Gerson (1288-1344) engaged in active astronomical observations, made with the assistance of a variety of instruments, in order to refute aspects of Ptolemy’s planetary models. Johannes de Muris, who taught at the Sorbonne in Paris during the first half of the fourteenth century, undertook observations to test and correct existing astronomical data on planetary motions and positions. His solar eclipse observations, for example, discredited certain predictions of the Alfonsine astronomical tables.[21]

Roger Bacon (ca. 1220-ca. 1292) does not deserve the reputation of “founder of experimental science” often bestowed on him. However, he did become an influential propagandist for empirical methodology, advocating the gathering of empirical evidence in all of the sciences. He argued that the first prerogative of experimental science is to verify conclusions drawn from arguments within the other sciences by submitting them to the test of experience; and it is clear from various publications that he practiced what he preached. See, especially, two parts of his *Opus maius*, one entitled *Scientia experimentalis*, where Bacon campaigned for the practice of experimental science, the other entitled *Perspectiva*, where he practiced (whenever possible) what he had been preaching.[22]

Roughly contemporary with Bacon, Peter Peregrinus of Maricourt manipulated magnets in order to gain an understanding of their properties and behavior—discoveries that anticipated many of those that would subsequently be made in the seventeenth century by William Gilbert, often identified as one of the founders of experimental science.[23] And who could deny the status of experimental scientist to the thirteenth-century Franciscan friar Paul of Taranto, who initiated an alchemical tradition characterized methodologically by laboratory manipulation of substances in the attempt to discover the pathway to transmutation?[24] Perhaps this litany of ancient and medieval experiments is overkill; but my purpose has been to make irrefutable the claim that ancient and medieval experiments were not rare exceptions to usual scientific practice but really quite plentiful, made whenever their ability to confirm or disconfirm a scientific claim was recognized.

If all of this is true, what credit is left for Francis Bacon (1561-1626), popularly celebrated as the founder (or *a* founder) of experimental science?[25] This Bacon (no descendant of Roger) argued, in books filled with references to *empiricism* and *experiment*, for the experimental interrogation of nature. However, what he and the Baconian tradition of the seventeenth century gave us was not a new method of experiment, but a new *rhetoric* of experiment, coupled with full exploitation of the possibilities of experiment in programs of scientific investigation.

THE SCIENTIFIC REVOLUTION

Where, then, can we locate this elusive revolution of sixteenth- and seventeenth-century science? I believe that Alexandre Koyré, who, in the 1950s and 1960s, disputed Crombie's focus on experimental science as the revolutionary agent, has put his finger on the right place. The underlying source of revolutionary novelty in the sixteenth and seventeenth centuries, he argued, was metaphysical and cosmological rather than methodological.[26]

Aristotelian and Platonic metaphysics shared a long and complicated relationship, including a certain amount of skirmishing, but in the later Middle Ages Aristotle's teleological metaphysics of nature, matter, form, substance, actuality and potentiality, the four qualities, and the four causes prevailed without serious challenge.[27] A rival metaphysics, Epicurean atomism, became known largely through the long philosophical poem by the Roman, Lucretius (d. ca. 55 B.C.), *On the Nature of Things*, known in Carolingian court circles by the early ninth century but not widely circulated before its early fifteenth-century revival. The atomism found in this treatise was reinforced by Diogenes Laertius' third-century *Lives and Teachings of the Ancient Philosophers* (which devoted a book to Epicurus) and various writings of Cicero (106-43 B.C.), which advocated a mechanistic universe of lifeless, indivisible atoms moving randomly in an infinite void.[28] Employed and developed in the seventeenth century by Galileo in Italy, René Descartes and Pierre Gassendi in France, Robert Boyle and Isaac Newton in England, and many others, by the end of the century the "mechanical philosophy" (as it has come to be called) had become dominant. The organic universe of medieval metaphysics and cosmology had been routed by the lifeless machinery of the atomists.[29]

The result was a radical conceptual shift, which altered the foundations of natural philosophy as practiced for nearly the preceding two thousand years. Consider some of the consequences. In exchange for the purposeful, organized, organic world of Aristotelian natural philosophy, the new metaphysics offered a mechanical world of lifeless matter, unceasing local motion, and random collisions. It stripped away the sensible qualities so central to Aristotelian natural philosophy, offering them second-class citizenship as secondary qualities, or even reducing them to the status of sensory illusions. In place of the explanatory capabilities of form and matter, it offered the size, shape, and motion of invisible corpuscles—elevating local motion to a position of preeminence within the category of change and reducing all causality to efficient and material causality. As for Aristotelian teleology, which discovered purpose *within* nature, defenders of this new mechanical philosophy substituted the purposes of a creator God, imposed on nature from without.

The metaphysics of the mechanical philosophy reverberated through the scientific disciplines of the seventeenth century, transforming the ways of thinking about all manner of subjects. I do not believe that we can go to the extreme defended by A. Rupert Hall, who argued that the scientific revolution was a wholistic, cultural transformation that "refuses to dissolve into fragments," that was "an unbroken and interlocking series of new discoveries." [30] Surely this is a huge overstatement: the seventeenth-century "scientific revolution" was not a single, all-encompassing event. No doubt there were connections, but surely we can agree that different disciplines have different histories, develop at different rates, pursue different questions, practice different methods, and respond differently to external circumstances. If we limit ourselves to the big, metaphysical picture, overlooking developments at a disciplinary level, we risk missing many of the central realities of seventeenth-century science. If our goal is to enrich and enlarge our understanding of medieval and seventeenth-century scientific change, we cannot limit our gaze to the metaphysician's study; we must look to the laboratory or workplace and the field, one discipline at a time.

Limitations of space do not permit any such venture here. But I conclude this book by returning to the question of continuity. Revolution is coupled in the minds of many people with repudiation of the past, severed connections, a throwing out of the old and bringing in of the new—in short, more or less complete discontinuity. And it is not difficult to find cases in the seventeenth century that appear to follow such a pattern. However, if we look at individual disciplines, we will find that *revolutionary* achievements in many disciplines were built *on medieval foundations* and *out of resources* provided by the classical tradition. Revolution does not demand total rupture with the past.

A sextet of examples will illustrate. Many more could be produced. (1) The individual planetary models in Copernicus's heliocentric model of the planetary system drew their mathematical structures and nearly all of their data from Ptolemy and the Ptolemaic astronomical tradition. Copernicus's contribution was to deploy these resources to build what was ultimately (with further additions by Kepler) a successful heliocentric model.[31] But the pieces and much of the pattern were of ancient vintage. (2) Kepler's new theory of the retinal image (genuinely new and of revolutionary significance for visual theory) emerged not by repudiation of the dominant medieval theory of vision, but by accepting and rigorously applying all of its defining claims—demanding that in a successful theory of vision all rays of light entering the eye must participate in producing an image of the visual field.[32] (3) Galileo's dynamics and kinematics of motion drew substantially from fourteenth-century developments at the Universities of Oxford and Paris. Central to Galileo's early dynamics was the idea that projectile motion is the result of an impressed force, an *impeto*—clearly a sixteenth-century cousin of the *impetus* of the fourteenth and subsequent centuries. And the first two propositions of his mature kinematics of uniformly accelerated motion, presented in his *Two New Sciences*, employ graphing techniques of the fourteenth century to replicate and prove the Merton rule (mean speed theorem).[33]

(4) Nicole Oresme (ca. 1320-82), perhaps the greatest mathematician of the later Middle Ages, devised a predecessor of Cartesian coordinates of the seventeenth century—the graphing techniques referred to just above.[34] (5) Galenic medical theory and practice dominated Western medicine into the seventeenth century and beyond.[35] (6) Finally, even the mechanical philosophy, which I regard as the centerpiece of the scientific revolution, was a replay of the Epicurean atomism of the third century B.C., passed down within the classical tradition and appropriately Christianized.

These examples are not meant to diminish the luster of the scientific revolution or its creators and practitioners. My aim is simply to introduce caution and realism into the picture. No scientist really begins at the beginning, without any expectations, theoretical knowledge, or methodological commitments. Twenty-first-century scientists (even newly minted ones) do not walk into the laboratory with vacant brains, but with minds chock full of knowledge and expectations. The same was true of the scientific leaders of the seventeenth century. The brilliance of the creators of the scientific revolution is revealed not only in their repudiation of the past and creation of theoretical novelties, but also in their ability to re-deploy inherited scientific ideas, theories, assumptions, methodologies, instrumentation, and data, and put them to new theoretical uses. The scientific revolution took place within an ideologically rich human environment; it had ideologically rich historical foundations, and with those foundations came continuities.[36]