



The early experimenters : Gilbert, Galileo, and Harvey
by Don Peter Mellon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Arts in History
Montana State University

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Abstract:

This thesis addresses a manifold problem in the history of 17th century science. The problem can be phrased as a compound question: Did the new experimental method of scientific inquiry constitute a genuine revolution in science, and, if so, what were the means by which experimentalism accomplished this revolution? An internal historiographic approach is used to analyze three case studies, meaning that the cases are assumed to be distinct and independent historical entities susceptible of analysis without reference to the larger forces of culture, politics, or religion. An “inside view” is developed by closely examining the primary sources that form the basis of each study. The analysis then attempts to discover structural similarities in the cases that may serve as a generalized historical model. Samples for analysis are taken from the works of William Gilbert (physics and cosmology), Galileo Galilei (astronomy and physics), and William Harvey (anatomy and embryology).

The thesis concludes that experimental science represented a wholly new method for extracting knowledge from nature, that it overturned the prevailing theoretical method, and that it became the driving force of what would eventually be known as the Scientific Revolution. Second, the thesis advances the argument that technology played a significant role in joining experimental and theoretical science to form the foundation of the modern scientific method.

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ABSTRACT

This thesis addresses a manifold problem in the history of 17th century science. The problem can be phrased as a compound question: Did the new experimental method of scientific inquiry constitute a genuine revolution in science, and, if so, what were the means by which experimentalism accomplished this revolution?

An internal historiographic approach is used to analyze three case studies, meaning that the cases are assumed to be distinct and independent historical entities susceptible of analysis without reference to the larger forces of culture, politics, or religion. An "inside view" is developed by closely examining the primary sources that form the basis of each study. The analysis then attempts to discover structural similarities in the cases that may serve as a generalized historical model. Samples for analysis are taken from the works of William Gilbert (physics and cosmology), Galileo Galilei (astronomy and physics), and William Harvey (anatomy and embryology).

The thesis concludes that experimental science represented a wholly new method for extracting knowledge from nature, that it overturned the prevailing theoretical method, and that it became the driving force of what would eventually be known as the Scientific Revolution. Second, the thesis advances the argument that technology played a significant role in joining experimental and theoretical science to form the foundation of the modern scientific method.

INTRODUCTION

There was a time, not so long ago, when the world was steeped in mystery, and nature's power over mankind was complete. Like a living immanent god her powers were witnessed every day in the swing of a compass needle, the fall of a stone, or the beat of a heart. She stood just beyond the circle of human perception, mute, invisible. The time was scarcely four centuries ago.

The common folk, not inclined or trained to speculate, and too caught up in their struggle for survival, sought everywhere the physical means by which nature might be forced to assist them in their labors. They made tools and instruments and mechanical contraptions to prod her this way and that in an attempt to elicit the response they desired. When their efforts failed, which happened more often than not, they turned to ceremony, incantation, and prayer in the hope that she would relent and reveal to them the secrets that they could not pry from her.

The learned men, not inclined or trained to labor with their hands, approached nature from a different direction, only to arrive at the same final destination. They wished to comprehend her mystery in its totality, to speculate on the ways in which she ruled the world. To this end they sought everywhere the abstract means by which she might be forced to reveal her knowledge, in syllogistic logic, in geometry and mathematics, in discourse and disputation. Whether in reality nature conformed exactly to their theories was not of great importance. What counted was a consensus opinion that she had

been adequately described and rationally explained. When the consensus broke down, which happened more often than not, they turned to ceremony, incantation, and prayer in the hope that she would relent and reveal to them the secrets that they could not pry from her.

When all else failed, the common folk and the learned men sacrificed each other.¹

Then a sign came from heaven, the precursor of a change in human affairs, the harbinger of the Scientific Revolution. It appeared late in 1572 when a nova at least as bright as Venus flared up in the constellation Cassiopeia. "Clearly it was a portent; astrological activity multiplied; and astronomers everywhere devoted their observations and writings to the 'new star' in the heavens."² The indomitable Tycho Brahe, then only a neophyte astronomer but working with the most accurate measuring instruments available, concluded that the object's location was well beyond the orbit of the planets and was likely near the Milky Way, that is, somewhere in the realm of the "fixed stars." The new star shined in the sky for nearly eighteen months, from November 11, 1572, until

¹ Dampier estimates that more than 750,000 alchemists, heretics, magicians, philosophers, sorcerers, and witches were burned at the stake between 1500 and 1700, in both Catholic and Protestant countries. In his opinion the torture and death subsided because science had succeeded in defining "the limits of man's mastery over nature" and had disclosed "the methods by which this mastery is attained." "It was not that the world grew more tolerant and humane, but that it had become more skeptical.... It was indeed preparing itself for the rationalistic philosophy and the cold intellectualism of the eighteenth century." William Cecil Dampier, *A History of Modern Science and Its Relations with Philosophy and Religion* (New York, 1944), pp. 156-58.

² Thomas S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Cambridge, 1985), p. 206. Crombie is more to the point in his assessment of the nova: "Scientific opinion received a marked shock from this object." A. C. Crombie, *Augustine to Galileo: The History of Science, A. D. 400-1650* (Cambridge, 1953), p. 314.

early in 1574. But by the time Brahe published his findings it had disappeared, and the question of Aristotle's immutable heavens was left in limbo. As had happened with a previous star of similar magnitude, only a few wise men were guided by it.³

But if any meaning can be attached to a symbol, as every science claims, then symbolically the Scientific Revolution began in a blaze of light when Giordano Bruno was burned alive on February 17, 1600. His fiery death is the better symbol because he not only gave his life to spread the gospel of the New Science—a sun-centered solar system, atoms, the void, infinite space—but he was transfigured by the flames into the spirit of free inquiry, the fundamental condition and *sine quo non* of revolution.

Symbolically then, Bruno's life of crime had spanned more than twenty years and nearly the entire continent of Europe. In Italy, France, Germany, and England, in universities and monasteries, both in print and in debate, he had preached the heliocentric heresy of Nicholas Copernicus to all who would listen. Not content with affronting the authority and dignity of both the Holy Roman Church and the Reformed Church, which held officially to the Aristotelian and Scholastic dogma that the Earth was the center of the universe and the dark sink of all sublunary refuse, Bruno went much further and taught that the universe had no center at all, was infinite in its extension, and that there was the possibility that God, in His almighty power, had created a plurality of worlds.

³ Astrology aside, the notion that the heavens can send intelligible information to mankind has always been an article of scientific faith. And thus it was no accident in 1610 when Galileo chose a title for his first great work: *Sidereius Nucius*, or roughly, *The Starry Messenger*.

Worse, Bruno resurrected and popularized the atoms and the void of Democritus, whose ghost had haunted the Peripatetics and the Christian Fathers for ten centuries. For these crimes and others of the same sort, Bruno was excommunicated from first the Catholic Church (he was a Dominican priest), and then from the Protestant Church (to which he had converted). He roamed from university town to university town between the years 1576 and 1591 leaving in his wake a fluttering trail of books and pamphlets on every subject from astronomy and physics to morality and magic. But when word reached him at a Carmelite convent near Frankfurt that the chair of mathematics at the University of Padua was vacant, Bruno's fate was sealed. He was drawn, as it were, magnetically to the university that had taught Copernicus.

Galileo Galilie, of course, was given the chair in mathematics sometime early in 1592. Bruno, for his part, was given to the Venetian Inquisition, only to be remanded eventually to the custody of the Roman Inquisition. He sat in a cell in the jail of the palace of Sant'Uffizio for seven years while the minions of Pope Clement VIII worked on him to recant his theories unconditionally. Bruno's trial ended on February 8, 1600, when, after repeatedly denying that he had any interest in theological matters whatsoever, he declared that he had no idea what it was he was supposed to retract. He was adjudged a "vehement heretic."⁴ On the seventeenth day of that month he was hauled out to the Campo di Fiori, his tongue tied in a gag for utilitarian reasons—which was not without

⁴ Some accounts describe the judgment as "unrepentant heretic."

symbolic content—fastened to a stake, and burned alive. Within a few months, England's foremost physician, William Gilbert, stunned the literate world by publishing the first experimental treatise on magnetism. The doctor declared Aristotelian-Ptolemaic astronomy was dead. About ten years later, Galileo aimed the first telescope toward the starry heavens and Bruno's universe appeared.⁵

Neither experiment nor theory could have saved Bruno, however; for when a philosopher turns vehement there is simply nothing that can be done with him. And such also was the general situation in science at the opening of the 17th century. Science—from the Latin *scientia* (*scire*, to learn, to know)—was everywhere vehement in its affirmation or denial of one school of natural philosophy or another. The experimenters, those begrimed common folk who sought salvation in the manual arts and cunning inventions, were caught in a viscous circle of hit-or-miss science where reproducible results were nearly nonexistent. They were dismissed by the theorists as “vulgar” simpletons completely incapable of following any logical course of action or of appreciating the elegant subtleties of geometry and mathematics. On the other side, the learned men were often characterized by the experimenters as mere lettered clowns, gramatists, sophists, and spouters who produced nothing but books.⁶ Moreover, theorist fell out with theorist and experimenter turned on experimenter. Only a small handful of men, usually working

⁵ “Bruno's mystical vision of a universe whose infinite extent and population proclaimed the infinite procreateness of the Deity was very nearly transformed into a sense datum.” Kuhn, *op. cit.*, p. 220.

⁶ These pejorative labels are borrowed from William Gilbert's seemingly endless supply.

in isolation, got anything accomplished. But for the most part nothing was accomplished. Science—to learn, to know—had reached a vehement impasse.

The passage of nearly four centuries since that time has tended to solidify what was once an extremely fluid relationship within the Scientific Revolution, i.e., the highly demarcated strata of experimental and theoretical science as unearthed today was in the process of deposition during the early 17th century and had by no means cooled or settled to the point where one could be separated easily from the other. The view from afar necessarily imputes structures to the Scientific Revolution that did not exist at its inception, where the line between experiment and theory was not always clearly drawn, and where the adherents of one or the other approach to science switched sides suddenly, often without recognizing when they had crossed the line. The modern historian, in this geological metaphor, simply sets his chisel on the proper line, taps ever-so-lightly, and the layers pop apart perfectly. But if any deeper understanding of the period is to be gained, it is not sufficient to merely stack up names and discoveries in artificial categories such as experimental science and theoretical science, or, as others have done, in two piles called “Baconian science” and “classical science.”⁷ The better approach is to dynamically analyze the process by observing experimental and theoretical science as they interact in real time. This is the view from inside.

⁷ Thomas S. Kuhn, *The Essential Tension: Selected Studies in Scientific Tradition and Change* (Chicago, 1977), pp. 41-52.

The three case studies presented here, from the work of Gilbert, Galileo, and Harvey, were not chosen as examples because they supported any preexisting conception of the Scientific Revolution. Rather the examples were chosen because all three men lived at the same time and the total elapsed time between their work was relatively short. Only ten years separates Gilbert's *Loadstone* from Galileo's *Starry Messenger*, and another ten years between Harvey's *Motions of the Heart* and Galileo's *Two New Sciences*. A total of 51 years serves to span the entire period between Gilbert's work and that of Harvey. Thus, all three men were products of the same time, which is not to say, of course, that they were all the same product. And therein lies their value to historical analysis: Each man represents to varying degrees the different methodological approaches to science that existed in the earliest stages of the Revolution. While it is true that they were the authors and founders of the New Science, it is equally true that they were also its first products.

That experimental and theoretical science eventually merged and thereby transformed Western civilization is not in doubt; only the particulars are in question. Traditionally, the beginning of the Scientific Revolution is associated with the publication of Copernicus's *De Revolutionibus* (1543), and therefore the presumption arises that the Revolution was foremost a change in men's thinking, i.e., a perfectly esoteric series of geometric symbols drawn on parchment by an obscure Polish mathematician operated so powerfully on men's minds they were driven to experiments that ultimately produced a new physical reality. This is roughly analogous to setting the date for the Russian Revolution at 1848 when the *Communist Manifesto* was first published. It is simply wrong,

according to Butterfield, "to imagine that the publication of Copernicus's great work in 1543 either shook the foundations of European thought straight away or sufficed to accomplish anything like a scientific revolution."⁸

A less lofty approach therefore seems to be required in the analysis of the case histories presented here, meaning that only an idealized and naive view of science and history would assume custom, ignorance, and cynicism are dispelled by symbols. Such an interpretation supposes that an abstraction is more potent than any reality. The ever-changing montage of arcane symbols that constitutes theoretical science is imagined to hold an iconographic power over men, and thus the bias of modern historiography is made manifest in its usual choice of Copernicus's book as the starting point of the Revolution.⁹ However, an alternative and perhaps more down-to-earth approach would assume that men change their minds when they *see* the truth as represented in real objects and in the interactions of real objects. Yet this seeing-is-believing approach is only the first part in a two part process; for no matter how impressive a particular physical phe-

⁸ Herbert Butterfield, *The Origins of Modern Science, 1300-1800* (New York, 1960), p. 55. Professor Butterfield is of course correct, but only from an internal perspective. He is cited as an authority here because the present essay is decidedly internalist in its historiographic technique. The external historian would likely look to the year 1517 for the first cause of the Scientific Revolution. An excellent survey and commentary on the internal versus external debate in the historiography of 17th century science may be found in Kuhn's *Essential Tension*, cited above, in Chapter 5, entitled, "The History of Science."

⁹ Galileo, the greatest theoretician of the time, was apparently not very convinced by Copernicanism until he looked through his telescope in the autumn of 1609. Although he admitted to Kepler that he had undergone a private conversion to Copernicanism sometime before 1597, he continued to teach Ptolemy's astronomy for his entire tenure at Padua. After 1609, however, as if seeing were believing, Galileo actively defended the Copernican system.

nomenon may be, no matter how demonstrative of some underlying theory, men must be convinced that it is potentially useful. There is both a *reality* component and a *utility* component of a theory that must be evident in the experiment if widespread acceptance is to be achieved. Note, however, that the order is not necessarily fixed, i.e., the utility of a theory may be understood before the reality is demonstrated. In the final moment before revolution, the ethereal abstraction is always transmuted into concrete reality. This is the meaning of the flash over Alamogordo or the footprint on the moon. There has never been a real revolution without real results.

To be fair, Copernicanism did produce some results, but these were abstractions also, namely numbers on a page. In its transposition of the Sun and Earth, the Copernican system obviated the need for numerous Ptolemaic epicycles and deferents and thereby greatly simplified and expedited the calculation of the rise and set times for the planets and constellations. This in turn led to a moderate increase in the accuracy of calendars and astronomical tables, or ephemerides, then commonly used by astrologers to cast horoscopes and by sailors for navigational purposes. The absence of any precise time-keeping device, however, nullified these minor gains for the most part. Heliocentrism was primarily an intellectual curiosity, mostly a source of scholarly debate and disputation within a very small circle near the cusp of the 17th century. In short, Copernicanism was a typical product of theoretical science, in that its method of proof differed in no substantial manner from the systems that had preceded it. In the first 67 years of its existence, while it had its supporters among philosophers and speculators, it completely

failed to lead astronomy into the true light. Only photons pouring through a telescope could do that.

In the first half of the 17th century experimentalism created a revolution in science. It was a revolution founded on "things" as many of its proponents declared, not on symbols. In those fifty years the necessity of experiment was demonstrated conclusively. Moreover, theoretical science, so long hobbled by philosophical factionalism and formal dispute, suddenly broke free and was snatched up by the whirlwind of experimentalism that was descending on European civilization. The experimental tradition of the common folk—their tools, instruments, and mechanical contraptions—had at last found a place among the logic, geometry, and mathematics of the learned men. Henceforth abstract representations of natural phenomena would always have to pass through the crucible of experiment and thus be transmuted into a tangible form. Otherwise, such theories would lie dormant, temporarily or permanently, to wither or to die according to circumstances. In a sense, the salvation of heliocentrism, and indeed of all valid scientific theories, was purchased at price: Technics, the actual physical objects of experimentalism, had indirectly seized control of the scientific enterprise.

The Scientific Revolution began first in physics when William Gilbert (1540-1603) experimentally proved the basic laws of magnetism. The year was 1600. The Revolution then spread into astronomy when Galileo Galilei (1564-1642) used a telescope to disclose the phases of Venus and thus prove a heliocentric solar system. The Revolution ended in biology when William Harvey (1578-1657) experimentally discovered the process of epigenesis in the ovum of a common chicken. The year was 1651.

The Scientific Revolution was complete because mankind had made the transition "from the closed world to the infinite universe."¹⁰ Gilbert's work turned men's eyes to the universe above and the universe below. Galileo would advance toward the macrocosm and Harvey toward the microcosm.

¹⁰ Alexandre Koyré, *From the Closed World to the Infinite Universe* (New York, 1957). Koyré uses this expression in reference to the expansion of men's thinking to encompass the idea of infinite space above or beyond the world that they inhabit, that is, the macrocosm. It is used in the present essay to include the infinitesimal inner world also, that is, the microcosm.

GILBERT

In 1600, the same year Bruno's soul was cleansed of its earthly element and was allowed to ascend into the realm of celestial fire where it naturally wanted to go, a little book appeared in England that claimed the "secret things" and "hidden causes" of nature could be revealed by "sure experiments." Dedicated to the "true philosophers," and "ingenious minds, who not only in books but in things themselves look for knowledge," William Gilbert's *On the Loadstone and Magnetic Bodies and on the Great Magnet Earth* quickly exerted a profound influence on the manner in which 17th century science was conducted by positing the experiment as the final arbiter of truth. Too late to call back Bruno from his impossible voyage, the book nonetheless convinced the leading thinkers of the time that heliocentrism was a true description of the world, that all material objects had a quality called "mass," and that all objects, from planets and stars to invisible "corpuscles," were fully capable of exerting a force upon each other even across the "vacuum" of space.

On the Loadstone begins by declaring itself to be different from all the treatises stretching back to 500 BC that had purported to explain magnetic phenomena, the difference being that the reader will not be required to submit to the authority of antiquity nor will he be implored to accept anything on the word of the writer, but rather he need only follow the demonstrations and then reproduce the proofs to the satisfaction of his senses

and reason. But the reader is warned not to proceed haphazardly; for *repeatability* is the key to acceptance of the magnetic theory:

Let whosoever would make the same experiments handle the bodies carefully, skillfully, and deftly, not heedlessly and bunglingly; when an experiments fails, let him not in his ignorance condemn our discoveries, for there is naught in these books that has not been investigated and again and again done and repeated under our own eyes.¹

And thus:

[E]ven as geometry rises from certain slight and readily understood foundations to the highest and most difficult demonstrations, whereby the ingenious mind ascends above the æther; so does our magnetic doctrine and science in due order first show forth certain facts of less rare occurrence; from these proceed facts of a more extraordinary kind; at length, in a sort of series, are revealed things most secret and privy in the earth, and the causes are recognized of things that, in the ignorance of those of old or through the heedlessness of the moderns, were unnoticed or disregarded.²

Note the repetition of the word “things” in the foregoing excerpt. This is not a casual or unconscious usage by Gilbert. Indeed, as with most early scientists he had an extraordinary grasp of the Latin language and was fully conversant with its nuances and shadings. When he says “things” he means things—real objects, material entities with or without names. The word appears repeatedly in his work, nearly always in the same context, nearly always opposed to or juxtaposed with ideas or abstractions. Consider the opening lines to Chapter 10, subtitled, “Iron ore has and acquires poles, and arranges itself with reference to the earth’s poles”:

¹ William Gilbert, *On the Loadstone and Magnetic Bodies and on the Great Magnet Earth* (1600), trans. P. Fleury Mottelay, in *Great Books of the Western World*, vol. 28 (Chicago, 1952), p. 2.

² *Ibid.*, p. 1.

Men are deplorably ignorant with respect to natural things, and modern philosophers, as though dreaming in the darkness, must be aroused and taught the use of things, the dealing with things; they must be made to quit the sort of learning that comes from books, and that rests only on vain arguments from probability and conjectures.³

It should be borne in mind that Gilbert was Royal Physician to Queen Elizabeth, and although he was widely proclaimed as a genius in chemistry, cosmology, mathematics, and physics, his day-to-day concern was the practice of medicine in all its multifarious aspects.⁴ By training and experience he had learned to look at an effect first and to consider its cause last, i.e., to diagnose symptoms. His life's work essentially entailed the analysis and manipulation of "things," whether it was the surgical excision of a tumor or the preparation of a medicinal mixture.

In any event, Gilbert's first task is to dispose of a large catalog of "various opinions and delusions" concerning the lodestone's reputed powers, such as its ability to drive an adulterous wife from her husband's bed when placed surreptitiously under a pillow, or when "pickled with the salt of the sucking-fish" to develop "the power to pick up a piece of gold from the bottom of the deepest well," among others.⁵ Two widely held beliefs,

³ Gilbert, *op. cit.*, pp. 17-18.

⁴ Gilbert received his M. A. in 1564 and a doctorate in medicine in 1569. He then left St. John's College, where he had been elected senior fellow, and traveled extensively throughout Europe. During a long stay in Italy, where he likely met all the principal philosophers of the time and with whom he later corresponded, he apparently was awarded the degree of Doctor of Physic. On his return to England he was admitted to the College of Physicians, probably in 1576.

⁵ *Ibid.*, p. 7. Gilbert spends two chapters on the medicinal folklore of the lodestone and common iron. He dismisses as futile all attempts to use the magnetic properties of lodestone to draw out foreign objects from the body, e.g., to extract iron arrowheads. Neither could headaches be cured by placing the stone on a patient's head. (*Ibid.*, Chapter 14.) He does, however, advocate the use of powdered iron when taken internally by "young women of pale, muddy, blotchy complexion," and claims that their skin color is returned [Continued on next page.]

probably derived from a combination of astrology and seafaring lore, must be given special attention at the outset, however, before Gilbert can proceed. First, that magnetic effects are extra-terrestrial phenomena, sometimes emanating from planets such as Mars or Saturn, other times from stars in certain constellations, usually Virgo or Ursa Major. When these celestial objects set, the power of the lodestone fades. Second, that there are regions of the earth, notably in the far northern latitudes, where huge mountains of lodestone mislead the compass needle by causing it to "dip" and swing wildly. When approached too closely these land masses will suck the nails out of a ship's planking.⁶ On the one hand, Gilbert knows the idea of an extra-terrestrial source of magnetism is absurd and has already been disproved by his experiments, although he does believe that all planets have their own magnetic force; on the other hand, magnetic anomalies are a fact of every long sea voyage that must be explained and if possible put to good use. He chooses to set aside for the moment these two classes of ideas, promising instead that in due course, once his magnetic theory is fully elaborated, extra-terrestrial magnetism will be exposed as a fraud, and magnetic anomalies will be understood as naturally occurring phenomena that are actually useful to navigation.

to "soundness and comeliness." This is very likely a description of an early ferric treatment for anæmia. (*Ibid.*, Chapter 15.) As for "vulgar" philosophical tracts that claimed a perpetual motion machine had been built that ran on the magnetic principle, Gilbert says: "May the gods damn all such sham, pilfered, distorted works, which do but muddle the minds of students!" *Ibid.*, p. 56.

⁶ Gilbert reports that this misconception caused many ships to be built with only wooden pegs as fasteners.

Gilbert then gives a rather thorough account of the lodestone in the literature of antiquity and of its widespread geological distribution in Europe.⁷ Soon, however, he has his reader busily fashioning a *terrella*, or little earth, out a large lump of lodestone using only simple handtools such as saws, files, punches, and so forth. This spherical magnet will become the centerpiece of Gilbert's experiments and eventually will be transformed by his incisive arguments and demonstrations into a convincing surrogate for a real planet. Next he urges his reader to build a "versorium," a magnetized little iron wire or needle set atop a nearly friction-free pivot. This instrument is of course no more than the pointer of a common mariner's compass; yet, by deftly sliding it around on the surface of the *terrella* and noting the direction toward which the needle swings, Gilbert is able to establish lines representing an "equator" and north and south "poles" on the stony sphere.⁸ His final conclusion, still more than 100 pages away, is already manifest in his choice of an experimental object: He is clearly predisposed to see the *terrella* as a real miniature earth, or "earthkin" as the name implies, that will accurately reproduce the physical effects he seeks to understand in its parent object. He need only transpose his findings in the laboratory to the world at large.⁹

⁷ Lodestone ("leading stone") is the iron oxide mineral magnetite (FeFe_2O_4). Usually black or brownish in appearance, it is normally associated with igneous and metamorphic rock formations.

⁸ Petrus Peregrinus de Maricourt first described the magnetic poles of a *terrella* in 1269.

⁹ A portrait of Gilbert at Oxford University shows him standing in his doctor's robes with a globe in his hand. Across the globe is written the word *terrella*. The medieval alchemical and magical article of faith was summarized in the incantation "as above, so below," meaning that the forces of the macrocosm were capable of being transferred to the microcosm, i.e., from heaven to earth, or from the earth into a particular object.

Disregarding for the moment the persuasiveness of his experimental proofs, the way in which Gilbert leads the student inexorably to conclude that the earth is a giant lodestone is a masterful piece of literary craftsmanship and organizational acumen in itself; and, therefore, in order to grasp the reasons why his work exerted such a powerful effect on men's minds, it may be useful to outline the logical steps he took to transform the little earth on his desk into the big earth in space.¹⁰

First, *On the Loadstone* works its way up from simple magnets cut into all shapes and sizes—from bits of cork, wires, needles, and an assortment of iron rods—into highly sophisticated navigational instruments designed to guide the transoceanic mariner in his perilous voyage to the New World. There is a sense of *usefulness* that permeates the entire work. No matter whether Gilbert's non-mathematical theory may seem confusing, bizarre or even mystical, if his improved compass and "dip instrument" perform as he says—and they did—sailors need no longer fear the starless night but instead can quickly locate their position anywhere on the globe.¹¹ In view of these immediate rewards alone the skeptic would suspend his disbelief. Second, *universality* is the unwritten common-

¹⁰ This order or progression in Gilbert's work was apparently lost on some men. Butterfield—and it is not clear from the context if he is speaking for himself or for Francis Bacon—declares, "Even Gilbert working on the magnet had no unity or order in his experiments—the only unity in his treatise lay in the fact that he had been ready to try out anything that there was to try out with a magnet." Butterfield, *op. cit.*, p. 101. This comment may be excused if it is predicated on a partial or superficial reading of Gilbert.

¹¹ Gilbert was known to fraternize with navigators and craftsmen, his exalted position as the first physician of England notwithstanding. (Butterfield, *op. cit.*, p. 92.) Crombie says: "[Gilbert] derived his methods largely from Peregrinus and from practical compass-makers such as Robert Norman, a retired mariner whose book, *The Newe Attractive* (1581), contains the independent discovery of the magnetic dip, which had been observed first by Georg Hartmann in 1544." *Op. cit.*, pp. 319-20.

sense law of all physical theories. The natural, even if recondite, principles that govern the terrella must govern the natural world, and every demonstration in Gilbert's book is directed to that end, to draw the reader onward from the needle set in a gently floating cork and orienting itself to the north pole of a magnet, to the compass onboard the storm-tossed sailing ship invariably pointing to the same truth: The little lodestone is the faithful offspring of the "Great Loadstone." It can be no other way.¹² And thus having moved from the spherical stone to the spherical earth, it was but one more logical step to the spherical planets and stars, although, on close inspection it was a leap of faith. Nevertheless, even those who looked askance at Gilbert's theory of a heliocentric solar system held together by the magnetic force, as Francis Bacon eventually did—even these unbelievers had something tangible to take away his work. One did not have to subscribe to the "magnetic philosophy" to make use of it.

What was this magnetic philosophy? And how did Gilbert convince the majority in his audience that he had found a better explanation for the observed mutual attraction of objects, terrestrial and otherwise? The key to his argument was the idea of an animating but unseen force at work in the universe, a force that for all intents was everywhere in evidence and that had the apparent ability to extend itself across unfilled space indefinitely, if not infinitely. He referred to this force as the "magnetic force" and drew a care-

¹² Gilbert, *op. cit.*, p. 78. Butterfield has said that Gilbert "laid himself open to the gibes of Sir Francis Bacon for being one of those people so taken up their pet subject of research that they could only see the whole universe transposed into terms of it." *Op. cit.*, p. 63.

ful distinction between it and what he called the "electric force."¹³ The electric force was an "attractive" force—the ability of a hard smooth object (an "electric body") that had been rubbed vigorously with a piece of wool or fur to pick up tiny objects such as straws, chaff, twigs, etc. While he agreed with Epicurus that an exchange of atoms was responsible for this effect, an "atomic outflow" as Gilbert called it, he denied that such was the case in magnetism. In his words: "The electric motion is the motion of coacervation of matter; the magnetic is that of arrangement and order."¹⁴ He argued that the electric force must reside at or near the surface of an electric body because it could be removed (today, discharged) by touching it with a finger or by blowing one's moist breath on it or by sprinkling water on it, and it could not be coaxed into activity by any amount of rubbing on cloudy (humid) or rainy days. He then demonstrated that the attractive force was utterly broken when an object, regardless of its composition, was interposed between an electric body and the target of its attraction. Conversely, the magnetic force worked wet or dry and operated around and through interposing objects. Gilbert's ability to make a distinction between what is now called an electrostatic field and a magnetic field represents a brilliant piece of early experimental science; yet this was only an intermediate step for him, albeit an important one, because it allowed him to afterward propose that the

¹³ Gilbert was likely the first experimenter to use the term "magnetic field" (see p. 49) and appears to have coined the word "electric" from the Greek word for amber. Dampier, *op. cit.*, p. 137.

¹⁴ Gilbert, *op. cit.*, p. 34. Both a particle and wave theory seem implied here.

“matter of the earth’s globe is brought together and held together by itself electrically,” while the “earth’s globe is directed and revolves magnetically.”¹⁵

Through repeated experiments, sometimes *ad nauseam*, Gilbert finally establishes the law of magnetic polarity, that like poles repel each other (what he calls “magnetic repulsion”) and that unlike poles attract (what he calls “magnetic coition,” to distinguish it from electric attraction). Interestingly, this simple rule turns the received wisdom on its head because Gilbert has proved that it is the *south* pole of a compass needle that points to the *north* pole of the earth. Through a further series of experiments he then demonstrates that not only is the power of a magnet related to its physical composition but that it varies proportionally to the “mass” of the magnet. This relative power of magnetic repulsion and coition Gilbert calls “verticity,” and he experimentally establishes that it is greatest at the poles of a magnet and decreases toward the magnet’s equator or midpoint. Verticity, as the name infers, is rotational by nature and is observed in the tendency of polar bodies to spin or whirl as they align themselves to the magnetic force.¹⁶

Whatever this magnetic force was, Gilbert knew that it was “not corporeal,” and he grew increasingly convinced that what he was observing in the lodestone’s behavior was not just an effect related to the earth’s globe but was indeed a “primal property” of

¹⁵ Gilbert, *op. cit.*, p. 34. Butterfield, among others, seems badly confused over this. He states, “The force of the magnetic attraction was the real cause of gravity, said Gilbert, and it explained why the various parts of the earth could be held together.” (*Op. cit.*, p. 141.) As pointed out in the text above, Gilbert made it very clear that the planet’s substance was held together by “electric attraction,” not the magnetic force.

¹⁶ Gilbert, *op. cit.*, pp. 18 and 25.

particulate matter itself. In the many samples of strong and weak lodestone that came into his possession, the consistency of which varied from extremely hard dark stones through clay-like whitish stones to simply a "clod of earth," Gilbert began to suspect that there might be some ultimate or purest form of the lodestone. After viewing several deposits of iron ore where he could actually see the "matrix" of lodestone in the ore body, and after extensive discussions with miners on the subject, he concluded that magnetic substances were "distinguished by divers qualities and by adventitious accretions" and that "pure native iron is produced when homogenic portions of the earth's substance coalesce to form a metallic vein; loadstone is produced when they are transformed into metallic stone or a vein of the finest iron or steel." This led him to surmise that the surface of the earth, down to some unknown depth, was composed of mixed substances jumbled together by time, as it were, that did not accurately reflect the planet's real interior; and that as one penetrated deeper into the interior, homogeneity tended to increase, i.e., tended toward a primal property. Therefore: "[T]he true earth-matter we hold to be a solid body homogeneous with the globe, firmly coherent, endowed with a primordial and (as in the other globes of the universe) an energetic form." The earth's interior "possesses a magnetic homogenic nature." The "whole world of things terrestrial" was derived from this "perfect material" according to Gilbert.¹⁷

¹⁷ Gilbert, *op. cit.*, p. 25. This "perfect material" was not Aristotle's "element" earth rediscovered in a pure form as Butterfield contends in his book at p. 141. Gilbert, as always, was quit clear and emphatic [*Continued on next page.*]

The magnetic force, then, as evidenced in the impure stones found on or near the surface of the planet, was also to be found in the interior of the planet in a much more pure and therefore more potent form. Further, the same substance must be found in the interior of the "other globes of the universe." Thus, just as the lodestone exhibits verticity, so, too, the planet: "[T]he earth has a fixed verticity, and necessarily revolves with an innate whirling motion: this motion the loadstone alone of all the bodies around us possesses genuine and true, less spoilt by outside interferences, less marred than in other bodies—as though the motion were an homogeneous part taken from the very essence of our globe."¹⁸

It is an astonishing sight to watch the experimenter at work in a dark and shuttered room, one eye on a candle flame to watch for the faintest flicker of an air current, the other eye on two lodestones in their little "floats" gliding round each other on a surface of water. It is not difficult to understand how Gilbert saw this duet as being orchestrated by a transcendent animating principle, something he will later call the "finger of God" and the "primary soul."¹⁹ Moreover, because these magnets "do not come together forthwith,

about this. Indeed, he condemned Aristotle's "simple element" as having "never appeared to any one even in dreams, and if it did appear would be of no effect in nature." *Ibid.*

¹⁸ Gilbert, *op. cit.*, p. 25. Kepler appears to have adopted this thinking and incorporated it into his early planetary studies as the *anima motrix*, a series of rotating rays emanating from the sun that pushed the planets around in their orbits. If the stars, sun, and planets are viewed as loci of verticity, and the intervening space between them is filled with invisible "corpuscles" that act according to the same law, then Descartes' vortex cosmology of 1633 might have its antecedents in Gilbert's work also.

¹⁹ "Wherefore, not without reason, Thales, as Aristotle reports in his book *On the Soul*, declares the loadstone to be animate, a part of the animate mother earth and her beloved offspring." *Ibid.*, p.105. The term "primary soul" appears at p. 111.

but first they wheel round, or the smaller obeys the larger and takes a sort of circular motion," his faith in magnetic verticity as the fundamental principle of celestial mechanics seems justified.

There is little doubt that *On the Loadstone* permanently changed men's thinking. In a purely technical sense, besides laying down the elementary principles of magnetism and electricity, it changed the general thinking about how an investigation into the forces of nature should be conducted—how those forces might be reproduced, analyzed and put to use by the methodical and very mechanical processes of experimental science. However, the evidence indicates that the book's greatest intellectual impact was elsewhere; for in its concluding chapters, as Gilbert aggressively advances his theory of magnetism and planetary motions, *On the Loadstone* becomes a revolutionary call-to-arms for all natural philosophers everywhere to cast off the chains of ancient dogma and end the tyranny of geocentrism.²⁰ Without any overstatement whatsoever, the final passages of Gilbert's book unleash the most devastating attack on Aristotelian-Ptolemaic astronomy to be found anywhere in the literature of the period. It begins quietly enough:

But since we see the sun, the moon, and the other planets, and the whole heavenly host, within the term of one day come and depart, then either the earth whirls in daily motion from west to east, or the whole heavens and all the rest of the universe of things necessarily speeds about from east to west. Besides, what genius ever has found in one

²⁰ Gilbert's assault on geocentrism and the theory of celestial spheres is too often overlooked by commentators in their rush to explain or criticize his magnetic discoveries. However, by explicitly injecting his theory of universal magnetism into the debate over celestial mechanics, he gave great courage to the gathering forces of revolution. Universal magnetism was a "factor of special importance if the world was to get rid of the crystal spheres and see the planets merely floating in empty space." Butterfield, *op. cit.*, p. 63.

same Ptolemaic sphere those stars which we called fixed, or ever has given any rational proof that there are any such adamantine spheres at all? No man hath shown this ever.²¹

After arguing that all the planets are observed to vary in their distances from the earth, and thus there is no reason to believe that the "fixed stars" do not conform to this rule also, Gilbert raises the possibility that the number of stars clearly visible to the naked eye, which he places at 1022, might be representative of only a small portion of those that actually exist. There are "innumerable other stars" that appear "minute" to the unaided eye, and "as regards others, our sight grows dim, and they are hardly discernible save by the keenest eye." Gilbert claims that every man who has ever looked into the sky when "the moon is below the horizon and the atmosphere is clear," knows that the number of stars appears to be indeterminate and "vacillating."²²

What, then, is the inconceivably great space between us and these remotest fixed stars? and what is the vast immeasurable amplitude and height of the imaginary sphere in which they are supposed to be set? How far away from earth are those remotest of the stars: they are beyond the reach of eye, or man's devices, or man's thought. What an absurdity is this motion of spheres.²³

The *primum mobile* is even more ludicrous according to Gilbert, residing as it does just beyond the circle of the fixed stars, yet transmitting its power downward through the numerous lesser spheres until all of its whirring motions stop just above planet Earth. He guesses that the *primum mobile* would have to be constructed from

²¹ Gilbert, *op. cit.*, p. 108, abridged.

²² *Ibid.*

²³ *Ibid.*

more matter than all the spheres, stars, and planets combined in order to enclose them physically and control them mechanically, yet it "presents no visible body, is in no wise recognizable." The whole idea is a "fiction believed in by some philosophers, and accepted by weaklings who wonder more at this terrestrial mass here than those distant mighty bodies that baffle our comprehension."²⁴ After considering the great distances involved, he is certain the *primum mobile* must be rotating at a fantastic speed. It is indeed a miracle that with all these "wild" motions going on, the earth remains aloof and still, disconnected and unmoving. The earth has somehow escaped the *universal* laws of nature:

O wondrous steadfastness of the globe of earth, that alone is unconquered! And yet the earth is holden nor stayed in its place by any chains, by no heaviness of its own, by no contiguity of a denser or more stable body, by no weights. The substance of the terrestrial globe withstands and resists universal nature.²⁵

Thus, at its inner extremity the universe is dead stopped, while at its outer, it is spinning madly. How can this be so?

But as regards this *primum mobile* with its contrary and most rapid career, where are the bodies that incite it, that propel it? and what mad force lies beyond the *primum mobile*?—for the agent force abides in bodies themselves, not in space, not in the inter-spaces.²⁶

As a logically self-consistent system, there is not much left of the Aristotelian-Ptolemaic astronomy when Gilbert of Colchester is through with it. Only a Copernican-

²⁴ Gilbert, *op. cit.*, p. 108.

²⁵ *Ibid.*, p. 110.

²⁶ *Ibid.*, p. 109.

Gilbertian interpretation seems plausible. The agent force abides in bodies themselves, not in space, not in the interspaces. Indeed. From the smallest particle of the lodestone to the ponderous planet to the scintillating stars themselves, the force of magnetism reaches out and universally binds all things together. Butterfield has noted:

Kepler and Galileo were both influenced by this view, and with Kepler it became an integral part of his system, a basis for a doctrine of almost universal gravitation. William Gilbert provided intermediate assistance therefore—brought a gleam of light—when the Aristotelian cosmos was breaking down and the heavenly bodies would otherwise have been left drifting blindly in empty space.²⁷

Regrettably, Gilbert's groundwork is more often overlooked or undervalued. Commentators both then and now have carped about his vaguely alchemic approach to experimentation, his failure to quantify his findings, and his lack of a sense of direction, although no navigator ever complained of the latter.²⁸ Galileo, for example, wished that Gilbert had done something more than mere experiments and had instead presented the world with a proper mathematical theory of magnetism.²⁹ Gilbert could have done so if he desired, for he was one of the most accomplished mathematicians of his time and worked for many years as the mathematics examiner of St. John's College, Cambridge. That he chose not to give magnetism a mathematical treatment says something about his

²⁷ Butterfield, *op. cit.*, p. 63.

²⁸ Crombie seems to have the proper perspective on Gilbert's work: "[T]hough containing some measurements, [it] was entirely non-mathematical in treatment, and is the most striking illustration of the independence of experimental and mathematical traditions in the 16th century." *Op. cit.*, p. 319.

²⁹ Butterfield, *op. cit.*, p. 144. Galileo admitted that he did not fully comprehend Gilbert's qualitative, non-mathematical description of the magnetic force.

dedication to pure experimentalism, a dedication to “things” rather than abstractions. That it took 150 years before the first mathematical formula appeared describing magnetism may also say something about Gilbert’s common sense.³⁰

William Gilbert was the first great experimenter of the Scientific Revolution, the first of the modern scientists to see the value in turning over things instead of books, to paraphrase his successor, William Harvey. He was the first to scientifically demonstrate a correlation between large- and small-scale phenomena, to insist on the universality of physical laws, and to demonstrate that the incantation of the ancient magus was true: “As above, so below.” He was a natural philosopher in every sense of the term, lynx-eyed, astute, curious.

Gilbert was not by any means, however, a model of methodological perfection. Even though he warned his readers at the outset of his book that he would speculate on many different causes when he had finished presenting his experimental proofs, he

³⁰ John Michell discovered the inverse-square law of magnetic repulsion in 1750. Gilbert held that scientific truth rested on the “*prima facie* cogency” of an argument “confirmed by subsequent experiments and demonstrations.” He believed that his work would “stand as firm as aught that ever was proposed in philosophy, backed by ingenious arguments, or buttressed by mathematical demonstrations.” (*Op. cit.*, p. 23.) [Continued on next page.]

speculates freely throughout, mixing fact with opinion in such a swirl that the student's mind develops a verticity all its own. No matter, because there is nothing called "the scientific method," at least not yet. To be sure, Gilbert is not just spinning magnets and wild ideas, rather he is busy at work hewing the bedrock that will become the foundation of modern science itself: He is building the scientific method for all to see.

"Men of acute intelligence, without actual knowledge of facts, and in the absence of experiment, easily slip and err." *Ibid.*, p. 29.

GALILEO

Some modern scholars have argued that Copernicanism was already triumphant before Galileo first saw the face of the moon through a telescope late in 1609. Thomas Kuhn, for example, has characterized Galileo's astronomical observations as a mere "mopping-up action, conducted after the victory was clearly in sight"¹ meaning, presumably, that all the important theoretical problems related to the heliocentric model were essentially solved before 1610. As noted, the nova of 1572 cast serious doubt on the proposition for an immutable heavens, and subsequent observations of six different comets by Tycho Brahe between 1577 and 1596 deflated the Aristotelian belief that these objects were atmospheric events, i.e., they occurred in the space between the earth and moon. After 1600 William Gilbert's *On the Loadstone*, as the previous section has shown, caused the crystalline spheres of antiquity to clink and clang most inharmoniously, and if his book did not fully halt the wild spinning in the heavens, it at least started men's minds to spinning. Moreover, Johannes Kepler, Gilbert's faithful reader and Brahe's heir and successor, had crushed the perfect orbital circles of the planets into less-than-divine ellipses by 1609, although Galileo seems not to have noticed Kepler's work until sometime later. Yet, in all this, there was no experimental proof that the solar system belonged to Copernicus.

¹ Kuhn, *The Copernican Revolution*, p. 220.

It is therefore an understatement, and metaphorically derogatory, to call Galileo's astronomical discoveries a mopping-up action; for they were the first in a long line of necessary commonsense proofs that eventually formed the underpinnings of what had been previously a purely geometric and mathematical model of the solar system.² Were it not for the first-hand reports contained in *The Starry Messenger*, the Ptolemaic-Copernican debate, already fast approaching its 100th anniversary, would have gone on interminably, regardless of the mathematical elegance or simplicity claimed by either side. Alexandre Koyré, contra Kuhn, seems to have the proper historical perspective when he assesses *The Starry Messenger* as "a work of which the influence—and the importance—cannot be overestimated, a work which announced a series of discoveries more strange and more significant than any that had ever been made before."³

Yet Kuhn's lapse in judgment cannot be overlooked for another reason. It is an atavism that can be traced to a widely held notion among early theoretical scientists, perhaps inherited from those airy Scholastics whom they so ridiculed, that, namely, if the symbols can be manipulated according to previously agreed upon rules, nature has no choice but to conform. Experimentation, in this view, is at best redundant and perfunctory. At worst, it is a spectacle for the unbelievers and dimwitted. Galileo, to be sure,

² Stillman Drake, *The Discoveries and Opinions of Galileo* (New York, 1957), p. 72.

³ Koyré, *Closed World*, p. 88.

was not completely immune from this thinking either, as evidenced in his works after *The Starry Messenger*.⁴

But setting aside temporarily further discussion of the relationship between scientific experiment and theory, it is only necessary to observe that *The Starry Messenger* transformed Galileo, nearly overnight, from a somewhat unassuming mathematics professor into a demi-god of astronomy. If stereotypes are any help, he was a typically underpaid professor toiling away in the obscurity of a large university, teaching his classes every day and writing Delphic letters to his colleagues every night. Then curiosity drove him to build a telescope. The next moment he had a royal stipend for life, his own apartments, library and research facilities, and had joined the retinue of the Grand Duke of Tuscany. When he attempted to resign from his lowly university position, his superiors would hear none of it. They granted him a lifetime tenure as the chair of mathematics, a release from all his teaching duties and a significant salary increase, whether or not he ever visited the university again.⁵ As demands for copies of his little book or for one of his telescopes poured into Italy from all over Europe, weird street scenes erupted whenever Galileo's name was mentioned. In Florence, when a courier arrived with a package from Galileo addressed to a fellow scientist, neighbors jostled each other for a

⁴ His *Two New Sciences* is the case in point and is examined later in this section.

⁵ More accurately, Galileo claimed that his salary increase and appointment to a lifetime professorship resulted from his construction of the telescope itself, i.e., he was rewarded for building an instrument and not for the discoveries he later described in *The Starry Messenger*. (Cf. *The Assayer* in Drake, pp. 244-46.) The possibility that the telescope was the initial or primary goal of Galileo's experiment is discussed in the last section of the present essay.

chance to congratulate the man and to inquire what was in package. Was it one of those new spyglasses? Would he let them see it? Could they *look* through it?⁶

Even discounting the legendary pride, effusiveness, and volubility of the Italians, history was likely witnessing its first episode of what might be called heroic experimentalism. Galileo, in the eyes of his countrymen, had literally discovered another New World and understandably received all the laurels and plaudits customarily reserved for the explorers and navigators of the previous century. In the eyes of his fellow progressive scientists, however, he had proved what most had postulated in their general theories, yet the particulars of his discoveries still stupefied them and represented an enormous trove of "things" that warranted immediate investigation. What was not noticed at the time, except by a few sour-faced Peripetetics who very badly botched their chance, was that Galileo's fame rested, at least momentarily, on a technic.

In any event, not much imagination is needed to understand all the excitement, for the opening passages of *The Starry Messenger* radiate the sheer joy and exaltation of a powerful mind at last turned loose in the new cosmos. It is an open invitation for all those who trust their senses to step forward and look for themselves:

Great indeed are the things which in this brief treatise I propose for observation and consideration by all students of nature. I say great, because of the excellence of the

⁶ It was only a copy of Galileo's new book, but the recipient was nevertheless required to read it aloud to all his neighbors. The scene is reported in Drake, p. 58.

subject itself, the entirely unexpected and novel character of these things, and finally because of the instrument by means of which they have been revealed to our senses.⁷

Note, first, that William Gilbert's favorite word "things" has reappeared. Next, note that Gilbert's supposition concerning the existence of numberless stars beyond normal vision is immediately vindicated:

Surely it is a great thing to increase the numerous host of fixed stars previously visible to the unaided vision, adding countless more which have never before been seen, exposing these plainly to the eye in numbers ten times exceeding the old and familiar stars.⁸

As far as Galileo is concerned the cosmos is becoming more complex, not less. Indeed, it is filling up with "entirely unexpected and novel" things. This does not appear to be the start of a mopping-up action. Most importantly, however, Galileo has unabashedly included his telescope as one of the great things in his treatise, an instrument—a technic—by means of which the unknown and perhaps unknowable has been revealed to the human senses. A few lines farther on he declares that the construction of his telescope would never have been possible had not his mind been "illuminated by divine grace." He then spends the next several pages giving detailed instructions on how "all students of nature" can design and build their own telescopes, the same approach Gilbert took in describing the terrella and the versorium for the world-be experimenter.⁹ When

⁷ Drake, *op. cit.*, p. 27.

⁸ *Ibid.*

⁹ This is a very strong theme in the literature of early experimentalism, what might be called, without any facetiousness, the *Popular Science* or *Popular Mechanics* theme. Galileo wrote *Starry Messenger* in the [Continued on next page.]

the student is done he will be able to see the "body of the moon" as a "very beautiful thing, and most gratifying to the sight," and in this way he will "learn with all the certainty of sense evidence" the true appearance of the moon.¹⁰

However, *The Starry Messenger* did not produce a garden of heavenly delights for Galileo in the end, for it also sowed the seeds of future disputes that would grow wildly out of control. In one compound sentence Galileo managed to delineate the controversy that would eventually consume his life. Promising further elucidation of planetary astronomy in a forthcoming book (*System of the World*), Galileo declared, "We shall prove the earth to be a wandering body surpassing the moon in splendor, and not the sink of all dull refuse of the universe; this we shall support by an infinitude of arguments drawn from nature."¹¹ This statement contains three essential argumentative positions. First, the Copernican theory that the earth was not fixed at the center of the solar system but was in motion like any other planet. Second, the earth was not the universe's dark garbage dump toward which all sublunary material gravitated. Third, that real-world, empirical sense data would be the means of proving all assertions, rather than the rationalizations of philosophy or the symbology of mathematics.

vernacular and addressed it to "the consideration of every man, and especially of philosophers and astronomers."

¹⁰ Drake, *op. cit.*, p.28. The "true appearance of the moon" is actually what the moon *would* look like if it were at a distance of two earth radii rather than the normal sixty.

¹¹ *Ibid.*, p. 45.

Events took on a life of their own, however, and the battle of the “mathematical astronomers” vs. the “philosophical astronomers” was joined well before *System of the World* was published.¹² In 1613 Galileo issued a collection of letters written during 1612 which he entitled *History and Demonstrations Concerning Sunspots and Their Phenomena*, usually referred to as *Letters on Sunspots*. Addressed to an intermediary named Mark Welser, Galileo wrote these three letters in response to essays published by “Apelles,” the pseudonym of Father Christopher Scheiner, S. J., who seems to have been encouraged by church authorities to get into the ring with Galileo, but Scheiner was forbidden to publish under his own name, which somewhat defeats this metaphor immediately.

In any event, Apelles, apparently hungry for glory and having taken his cue from Galileo's discovery of “planets” orbiting Jupiter, jumped to the conclusion that sunspots were also solid objects passing before the disk of the sun. This had to be so, Apelles argued, because the sun was a “most pure and lucid body” that admitted of no imperfections, namely, ugly spots.¹³ Disregarding this obvious and pathetic appeal to Peripatetic prejudices—which may have also been a not-too-subtle attempt to bait Galileo into a theological trap—in his first response Galileo contended that solid objects were not necessary to cause spots on the sun: “[W]e need not assume the material of the sunspots to

¹² Drake, *op. cit.*, p. 97. The terms “mathematical astronomers” and “philosophical astronomers” belong to Galileo.

¹³ *Ibid.*, p. 92.

be very dense and opaque as we may reasonably suppose with regard to the material of the moon and planets. A density and opacity similar to that of a cloud is enough, if interposed between us and the sun, to produce the required obscurity and blackness."¹⁴

Then, without warning, the revolution in astronomy suddenly moved onto the broad highway toward the future, quietly, smoothly, powerfully; for without missing a beat, while commenting on Apelles' suggestion that sunspot observations might lead to a proof or disproof of heliocentrism, Galileo publicly announced that his telescopic observations of Venus had already conclusively proved the Copernican theory: "I'm astonished that nothing has reached [Apelles'] ears—or if anything has, he has not capitalized on it.... This is the fact that Venus changes shape precisely as does the moon."¹⁵ He went on to gently chide the Jesuit professor for not keeping up with his (Galileo's) latest discoveries, then patiently described the phases of Venus as it changed from an evening star to morning star in its orbit around the sun, and finally summed up: "These things leave no room for doubt about the orbit of Venus. With absolute necessity we shall conclude, in agreement with the theories of the Pythagoreans and of Copernicus, that Venus revolves about the sun just as do all the other planets."¹⁶

¹⁴ Drake, *op. cit.*, p. 93.

¹⁵ *Ibid.* Drake believes that the discovery of the phases of Venus carried great weight: "This discovery proved Ptolemy wrong in a vital part of his planetary theory.... [I]t showed that this planet must not move around the earth but around the sun." *Ibid.* p. 74.

¹⁶ *Ibid.*, p. 94.

By examining the phases of Venus with an experimental instrument, Galileo subjected mathematical astronomy to the test of commonsense observations; and while not all of his and subsequent investigator's deductions from the observations were correct—because speculation is always commingled and sometimes confused with real knowledge—he nonetheless deepened the distinction, first laid down by Gilbert, between what was theorized to exist and what did exist. He accomplished this by using a device, an instrument now called the telescope, that allowed him to shift his perspective by one incremental degree beyond that which had been previously allowed. The more exact optical measurements necessary to confirm or refute existing theory then became possible, while, conversely, new phenomena emerged that would be forced to await the further improvement of the telescope and the development other technics before they could be adequately understood and incorporated into new theories. Thus, on the one side there is a sort of mopping-up action involved, insofar as all the little untidy and disputed details of an existing theory are concerned, but on the other side the extension of human sense perception into realms formerly inaccessible presents a host of observations that necessitate the further refinement, amendment, or complete abandonment of an existing theory.

Viewed in a larger historical frame, however, Galileo's topographical observations of the moon's mountains and "seas," his discovery of Jupiter's satellites, the phases of Venus, his notes on sunspots, and the multitude of "new" stars that actually comprised the Milky Way—all these things represented nothing less than a "destruction of the cosmos," to borrow Koyré's phrase. All scientific conceptions of the macrocosm,

whether handed down from antiquity or from the Renaissance, either in their generality or in their specifics, had been permanently swept aside. Significantly, access to the new universe, whether only for a soul-inspiring tour or to extract further knowledge from nature, was reserved exclusively for those who possessed the technic key. Put another way, every future theory of the macrocosm would be shackled to the telescope and its technic successors.

While Galileo's astronomical discoveries were an outstanding success and proved to be of immediate utility to the theoretical and experimental scientific communities, unfortunately his inquiry into the properties of motion became a source of consternation and, to some extent, a disappointment. In the *Dialogues Concerning the Two New Sciences* (1634, Leiden ed. 1638), Galileo presented a fully rationalized and mathematical physical theory to account for the observed acceleration of falling bodies, replete with geometric proofs, drawings, formulae, tables, and descriptions of experimental apparatus. The consternation and disappointment arose afterwards when it became apparent that Galileo had not performed many of the claimed experiments; that his results could not be reproduced to any degree of reliability; and that his numbers simply did not add up. To be fair, there are many mitigating circumstances that should be mentioned in defense of Galileo, and these must be dispensed with before the core of the problem is revealed.

It has already been noted briefly above that theoretical science, meaning science that purports to discover true relationships in nature based solely on the outcome of symbol manipulations, has an inbred disdain for experimentation. As Koyré as succinctly put

it, "That which should happen, does happen; and that which cannot happen, does not happen."¹⁷ Inferentially, this conceit is always raising the rhetorical question, Why bother with an actual demonstration? What works on paper or across the blackboard of the mind always reflects what works in nature. Such, however, was also the conceit that doomed Aristotelian physics, for it, too, had been fully thought through:

Aristotelian physics is false, of course; and utterly obsolete. Nevertheless, it is a "physics", that is, a highly though non-mathematically elaborated science. It is not a childish phantasy, nor a brute and verbal restatement of common sense, but a theory, that is, a doctrine which, starting of course with the data of common sense, subjects them to an extremely coherent and systematic treatment.¹⁸

Aristotelian physics thrived for 1900 years because "that which should happen, does happen; and that which cannot happen, does not happen." But once subjected to the crucible of experimentation—the very crucible Galileo helped to build—it proved false. Thus it is somewhat ironic that Galileo would fall prey to this conceit as he approached the end of a fruitful scientific life. Traditionally, it has been argued that he set aside his investigations in astronomy and took up the physical studies of his youth to avoid further confrontations with the Church, and therefore it may be that he had simply reverted to an earlier mode of thought or method of science. He was, after all, trained as a mathematician, and a predominately mathematical approach to this old subject matter would seem a natural choice.

¹⁷ Alexandre Koyré, *Metaphysics and Measurement: Essays in the Scientific Revolution* (Cambridge, 1968), p. 88.

¹⁸ *Ibid.*, p. 23, punctuation. and spelling original.

In any event, the reasons for Galileo's return to physics are not of great concern, rather it is the methods he employed and the results he obtained. The story of his fall from grace is instructive for other reasons also; for it underscores the confusion that arises in theoretical science when it attempts to go forward without experiments, and it illustrates the impotency of experimentalism without technology.

In the third part of *The Two New Sciences*, which is also the third day of discussions among Galileo's stock characters Sagredo, Salviati, and Simplicio, the investigation begins to focus on "naturally accelerated motion," that is, the rate-of-fall of a body from a position of rest. Salviati begins the discourse by drawing a parallel between the previous discussion on uniform motion, which he defines as motion "when equal distances are traversed during equal time intervals," and that of naturally or "uniformly" accelerated motion, which he defines as occurring "when starting from rest" a body "acquires, during equal time intervals, equal increments of speed."¹⁹ Sagredo immediately demurs:

Although I can offer no rational objection to this or indeed to any other definition, devised by any author whatsoever, since all definitions are arbitrary, I may nevertheless without offense be allowed to doubt whether such a definition as above, established in an abstract manner, corresponds to and describes that kind of accelerated motion which we meet in nature in the case of freely falling bodies.²⁰

¹⁹ Galileo Galilei, *Dialogues Concerning the Two New Sciences* (1638), trans. Henry Crew and Alfonso de Salvio, in *Great Books of the Western World*, vol. 28 (Chicago, 1952), p. 200.

²⁰ *Ibid.*

Galileo clearly sees the essence of the problem at the outset. Definitions are arbitrary and abstract and therefore may or may not have any correlation to nature, that is, to the real world.

After some further preliminary sparring, and several appeals to commonsense experience, Salviati proceeds to his first experimental proof, a highly geometrized argument that employs the use of lead weights (apparently musket balls) suspended from varying lengths of thread that are nailed to a hypothetical vertical plane. "Imagine this page to represent a vertical wall with a nail driven into it," Salviati says, "and from the nail let there be suspended a lead bullet of one or two ounces by means of a fine vertical thread." Salviati then lets the hypothetical bullet fall from the horizontal plane that intersects the perpendicular line beneath the nail. The bullet swings in an arc that passes beneath the nail and then rises to an equal degree on the opposite side. This "experiment" is repeated several more times as shorter and shorter threads are attached to the nail, which is in turn moved lower and lower on the vertical axis; and each time the weight's momentum carries it to the same height along the horizontal plane, although through decreasing arcs.

None of this works in reality, however. Friction, air resistance and other factors conspire to cause the bullet to just miss hitting the opposite horizontal plane. A perfect vacuum is necessary for the experiment to work, something Salviati is unaware of. But he is hardly deterred and dismisses the problem by saying, "In striking these planes some of its [the bullet's] momentum will be lost and it will not be able to rise to the line CD [the horizontal plane that bisects the vertical axis]; but this obstacle, which interferes with

the experiment, once removed, it is clear that the momentum—which gains in strength with descent—will be able to carry the body to the same height.”²¹ This is a fine piece of nonsense, of course, since the plane that the bullet is supposed to strike is a pure abstraction, that is, it is only an imaginary line with no physical ability (mass) to absorb the momentum (energy) of the swinging bullet. Salviati’s rapt listeners, however, raise no objection to this sleight-of-hand, where a geometric object, a line, suddenly becomes a real object; and thus Galileo passes on to the presentation of his theorems, Theorem II, Proposition II being the most important and that which became the subject of controversy: “The spaces described by a body falling from rest with a uniformly accelerated motion are to each other as the squares of the time-intervals employed in traversing these distances.”²²

The rate-of-fall problem is now transferred to a hypothetical inclined plane, and Salviati patiently explains the geometric basis of the argument to his listeners. Simplicio, the earnest but not-too-smart Aristotelian, admits that he is quite pleased with Salviati’s explanation, and that he, Simplicio, is “convinced that matters are as described, once having accepted the definition of uniformly accelerated motion.” But, and here is the eternal question, Is this symbol manipulation a true representation of nature? “I am still doubtful,” Simplicio says, “and it seems to me, not only for my own sake but also for all

²¹ *Ibid.*, p. 205.

²² *Ibid.*, p. 206.

those who think as I do [the unbelievers and the dimwitted], that this would be the proper moment to introduce one of those experiments—and there are many of them, I understand—which illustrate in several ways the conclusions reached.”²³

Simplicio’s request for a tangible demonstration of the proposition will not be a burden. Indeed, Salviati seems to relish and welcome the idea:

The request which you, as a man of science make, is a very reasonable one; for this is the custom—and properly so—in those sciences where mathematical demonstrations are applied to natural phenomena, as is seen in the case of perspective, astronomy, mechanics, music, and others where the principles, once established by well-chosen experiments, become the foundation of the entire superstructure.²⁴

The experimental apparatus, the famous inclined plane, is then described in detail, from its overall dimensions, to the manner in which it was grooved, sanded, polished and lined with parchment. A “hard, smooth, and very round bronze ball” is then rolled down the incline, which has been set at a precise angle. After repeatedly timing the interval for the ball to traverse the entire length of the incline, which time did not vary by more than “a tenth of a pulse beat,” the ball is then allowed to roll only one-quarter the length of the incline. The interval is “precisely one-half of the former.” The experiment is then “repeated a full hundred times,” using different angles of descent and distances. In all cases whatsoever the rule holds true: “The spaces traversed were to each other as the squares of the times.”²⁵

²³ *Ibid.*, p. 207.

²⁴ *Ibid.*, pp. 207-208.

²⁵ *Ibid.*

Well then, how did Galileo measure the time interval? No one asks this question, but Salviati seems eager to answer it nevertheless:

For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, whether for the whole length of the channel [the groove in the inclined plane] or for a part of its length; the water thus collected was weighed, after each descent, on a very accurate balance."²⁶

The "differences and ratios of these weights" were then translated into differences and ratios of time. All this measuring was done with "such accuracy" that although the experiment was repeated over and over many times, "there was no appreciable discrepancy in the results."²⁷

Poor Simplicio is overwhelmed by this New Science. He can only say—one imagines, *sotto voce*—"I would like to have been present at these experiments." Indeed, for the next twenty years the best experimenters in Italy and France will mutter Simplicio's same words; for not a one of them will be able to reproduce Galileo's results. The entire experiment, as it will come to light, is flawed and the results have been faked. All the same, Galileo fills Simplicio's mouth with the final damning words: "I am satisfied and accept them as true and valid."²⁸

²⁶ *Ibid.*, p. 208.

²⁷ *Ibid.*

²⁸ *Ibid.*

What can be said of these “experiments,” which school children are still shown today as proof of Galileo’s theories? Why would the foremost natural philosopher of the early Scientific Revolution pass off these things as diligently designed and executed demonstrations, when they could not have been carried out in the manner described or could not have been done at all? Is this an instance of what Koyré called the “use and abuse of imaginary experiments”?

First, both experiments, that of the swinging pendulum and that of the inclined plane, are possible within the constraints of the technological imperative that existed at the time, i.e., all the instruments necessary to carry out these experiments existed in Galileo’s workshop and were ready to hand. That he lacked *additional* instruments necessary to the successful proof of his theory is another matter to be discussed below. In all likelihood Galileo did perform the experiments as described and in both cases obtained results that did not agree with his theory. It could not have been otherwise because he lacked a vacuum pump and a mechanical clock, two techniques that did not exist at the time. Yet Koyré excuses Galileo’s false experimentalism quite emphatically:

I do not reproach him on this account.... [T]he experiments were unrealizable in practice with the facilities at his disposal. How, indeed, could a fall in vacuum be realized before the invention of pneumatic pumps? And as for experiments in a plenum [filled space or the atmosphere], how could an insignificant loss or gain in motion of bodies thrown from the top of some tower be measured *exactly* before the invention of precision clocks?²⁹

²⁹ Koyré, *Metaphysics*, p. 75, notes omitted, italics original. A few pages later, in a slightly different context, Koyré declares that Galileo merely “corrects” his experiments: “He holds it [the experiment] in his [Continued on next page.]”

While there is no intention here of entering into an extended indictment of Galileo's experimental technique, a few more words must be addressed to the problem before this section can be concluded. Galileo, perhaps deliberately, made it nearly impossible for his reader, then or now, to differentiate between those experiments he actually conducted and those that were products of his imagination, what are today called "thought experiments." There are many instances in *The Two New Sciences* where an experiment is laid out in detail and apparently executed, only to have the author state belatedly that he did not really do it. Conversely, many feats of mental gymnastics are referred to as "experiments," yet there is little doubt that they ever took any tangible form, and Galileo makes no representations to the effect that they did. But, laying aside all excuses, there are obviously only two classes of experiments: real and not real. In the cases cited above, both the pendulum and inclined plane experiments might have been real experiments given the technical imperative of the time, i.e., any reader of the early 17th century would be naturally predisposed to believe them, as did Simplicio. That many others believed in them also is evidenced by the fact that Mersenne and Riccioli labored endlessly to reproduce Galileo's results, to no avail, of course.³⁰ It is only when these experiments are viewed from the technological vantage point of later centuries that they become impossi-

imagination and suppresses the experimental deviation. Was he wrong to do so? Not at all! for it is not by following experiment, but by outstripping experiment, that the scientific mind makes progress." (*Ibid.*, p. 80.) Koyré's "deviation" most certainly is Kuhn's "anomaly," and one wonders what science would be like without them.

³⁰ For an in-depth discussion of the problems Mersenne and Riccioli encountered while trying to reproduce Galileo's experiments, see Koyré, *Metaphysics*, pp. 98-108.

ble, and a charitable philosopher such as Koyré may then relegate them to the category of justifiable imaginary experiments.

Last, and here a little speculation seems in order, it may be that Galileo did not clearly understand the difference between a real and a not real experiment, although he certainly knew the difference between a true and a not true story. It should be remembered that he stands just inside the threshold of a revolution—a revolution that in large measure he helped to create—and it should come as no surprise that in this individual may be found the old way of demonstration hopelessly mixed up with the new way of demonstration. That is, experimental and theoretical science had not yet settled to the point where their respective boundaries were clear. Contrarily, the suggestion is strong that Galileo was so certain he was right, and he was right, that the end justified the means.

When the Galileo of *The Starry Messenger* is compared to the Galileo of *The Two New Sciences*, which is essentially a comparison of Galileo the experimentalist astronomer to Galileo the theoretical physicist, several striking observations can be made. As an experimental astronomer, Galileo (and Western civilization) had the good fortune of having the telescope fall into his competent hands at a time when Copernicanism, though ascendant, could not advance further nor be transformed into a more refined theory without demonstrable proof of its propositions. And there seems little room for argument that there would have been no *Starry Messenger* had not there been a telescope first. Furthermore, while it is not impossible to imagine Galileo somehow distinguishing himself as an astronomer without the aid of the telescope, that is, by using instead the conven-

tional instruments of his day, the idea is hard to entertain. Tycho Brahe and Johannes Kepler, the two greatest naked-eye astronomers of the time and in possession of the best instruments then available, could not prevail. Did Galileo have some special frame of mind that the others lacked, a certain intuition that permitted him to immediately grasp the telescope as the means of validating Copernicanism? It seems not, the evidence being decidedly to the contrary.³¹

Suffice it to say, the telescope is *The Starry Messenger*. Galileo's use of this instrument to observe celestial objects, in a very real sense, represents a free-ranging experiment undirected by any preexisting theoretical framework. He was not engaged in a "puzzle-solving" exercise, as Kuhn might say, but rather just curious about what he might see. Curiosity! Such a powerful word in the history of science, yet so often used without the slightest understanding of its import. Granted, Galileo had his university training in the astronomy and mathematics of the day, but such was hardly preparation for what he would see. What he saw was not only without precedent but was also without context. A lead tube with two pieces of ground glass at either end, as if a lightning rod, had drawn down a new reality from the skies that blasted away the old reality forever. The telescope technic opened the heavens for Galileo and all mankind. As in Gilbert's work, this is

³¹ Refer to Note 5, above.

another clear case of experimental science confirming and then outstripping theoretical science.³²

The same praise cannot be applied to *The Two New Sciences*, however. Galileo the theoretical physicist wanders about in a Neoplatonic geometrized unreality of his own making, vainly invoking the name of experimental science to be his witness. He knows symbolic logic will not suffice to convince the unbelievers and dimwitted, but he cannot summon the power from the real world, the power of nature as embodied in technics, to produce the tangible result he needs. He and theoretical science have run up against the technological imperative, a very real barrier, as measured by the number and kind of technics available to experimentation, that thwarts the conversion of symbols into reality. Until the barrier is pushed back by the development of the mechanical pendulum clock and the ability to produce a vacuum, Galileo's geometric proofs will be just so many lines on paper. In the meantime, the followers of the New Science will have to be satisfied

³² Koyré thinks that the "scientific mind" makes progress not by following experiment but by outstripping it. (*Metaphysics*, p. 80.) This might be so, as far as abstract progress is concerned. But it is only through experimentation that unanticipated real-world phenomena appear. These new "things" are the true sustenance of the scientific mind.

with the persuasiveness of his argument and the perfection his symbols as they leaf through his book.

HARVEY

In the spring of 1602 William Harvey received a degree in anatomy from the University of Padua and returned to England, where in that year Cambridge University bestowed upon him the degree of Doctor of Medicine. Over the next three decades he lectured on the art of anatomy at the College of Physicians, attended patients at St. Bartholomew's Hospital, and became Royal Physician to Charles I. In all respects a product of the Humanist tradition in learning, he was intimately familiar with the works of Aristotle, Galen, Vesalius and all the principal physicians and anatomists of his day. Yet he taught his students that anatomy was not learned "from books, but from dissections, not from the positions of the philosophers but from the fabric of nature,"¹

Harvey is without question the consummate experimenter of the Scientific Revolution. Unfortunately, however, he was in the vanguard of that "other revolution," the revolution in biology and medicine that was often overshadowed by advances in astronomy and physics and has therefore been sometimes reduced to a position of secondary importance by the chroniclers of science. This is particularly ironic because for all purposes Harvey's generation of medical practitioners was forced to overcome the same intellectual impediments to the advancement of knowledge as did those who practiced as-

¹ William Harvey, *On the Motion of the Heart and Blood in Animals. On the Circulation of the Blood. On the Generation of Animal*, trans. Robert Willis, in *Great Books of the Western World*, vol. 28 (Chicago, 1952), from the translator's biographical note, p. 263.

tronomy and physics. The authority of antiquity, again for the most part the authority of Aristotle, was operative in every sector of the field and was essentially beyond reproach. Unlike Gilbert and Galileo, Harvey had no recourse to any system of symbolic logic, such as geometry or mathematics, that might theoretically demonstrate the inadequacy of the received wisdom.² He had to rely exclusively on appeals to commonsense perceptions and interpretations of real world phenomena, those things that all could see, hear, touch, or smell. Thus his science was developed from and based solely upon the tangible results of experiments, experiments any competent anatomist could perform with the standard instruments then available.

This is not to say, however, that Harvey rebelled against the authority and wisdom of antiquity, and he cannot be classed philosophically, therefore, with Gilbert or Galileo.³ Rather Harvey venerated Aristotle and saw himself as continuing the tradition of experimentation first described in Aristotle's *On Animal Generation*. To Harvey's mind it was a scandal to accept the teachings of antiquity without question, for the ancients had questioned everything, "and by their indefatigable labours and by their varied experimental inquiries into the nature of things, bore an unfailing torch" for Harvey's generation of

² Harvey did quantify his work to a greater degree than Gilbert, however.

³ Gilbert and Galileo may be generally described as Neoplatonists. The essential difference between the two was that Gilbert took a strongly Archimedean approach to science, while Galileo preferred a Pythagorean interpretation. This may also serve as a loose rubric for separating northern European or Protestant experimental science from southern European or Catholic experimental science.

medical men.⁴ And thus it was the responsibility of the experimenter to go forward in the same spirit of inquiry, adjusting, modifying, and if necessary, expunging the traditional wisdom whenever necessary. There is no hint of a programmatic attack on Aristotelian biology in Harvey's work. It is instead a respectful reconsideration and a somewhat humble attempt to add refinement and further insights to a body of knowledge that Harvey deemed inherently valid.

Every accepted theory of anatomy or physiology susceptible of proof by actual mechanical manipulation or inspection, i.e., by dissection, was a potential subject of investigation for Harvey. If the heart's septum or dividing wall was commonly believed to contain minute pores through which blood and "spirits" moved from one cavity of the heart to the other, then Harvey wanted to see those pores with his eyes, and if possible, those energetic spirits. Did arteries pulsate of their own accord, as most practitioners believed, or was there some other efficient cause? What Harvey had been taught did not always conform to what he saw. Indeed, it seemed as though every time he performed a dissection he observed something at variance with accepted theory and was therefore compelled to advance an alternative explanation for the phenomenon, and in the overwhelming major of cases his explanation was correct. Only when his instruments failed him, that is, in those circumstances where he could not locate or see the mechanism re-

⁴ Walter Pagel, *William Harvey's Biological Ideas: Selected Aspects and Historical Background* (New York, 1967), p. 31.

sponsible for the effect he had noted, did he sometimes arrive at an erroneous conclusion. Otherwise, his judgment of the causal relationships among observed phenomena approached infallibility.

Harvey's fame rests on four papers that he wrote between 1628 and 1651 on the motion of the heart, the circulation of the blood (two papers), and animal reproduction.⁵ In all of these works can be found the same invitation extended by Gilbert in *On the Loadstone* and Galileo in *The Starry Messenger*. Namely, that the reader is invited to look over the shoulder of the experimenter and see first hand the wonders of nature. However, unlike Gilbert and Galileo, who were somewhat indiscriminate in their invitations, Harvey extends his welcome only to the seasoned anatomist, or at least to the self-motivated and open-minded student of anatomy.

In the first group of examples that follow, which are taken from Harvey's work in the circulation of blood, the examples are intended to be illustrative of Harvey's experimental technique only and should not be construed as necessarily representative of his most important discoveries, although all of them contributed to his ultimate success in proving his hypothesis. The second group of examples, of a much later origin, is drawn from his work on animal generation. These examples show how Harvey's experiments

⁵ The first paper, *An Anatomical Disquisition on the Motion of the Heart and Blood in Animals* (1628), is usually referred to as *On the Motions of the Heart*. The second and third papers are disquisitions addressed to his critic, John (Jean) Riolan, a contemporary French anatomist, and are usually lumped together under the title, *On the Circulation of Blood* (1628). The fourth paper, known originally as *Anatomical Exercises on the Generation of Animals* (1651), is often shortened to *On the Generation of Animals*.

led him progressively deeper into the mysteries of nature until he collided with the technological imperative and could go no further.

"There is no science which does not spring from preexisting knowledge, and no certain and definite idea which has not derived its origins from the senses."⁶ Thus Harvey makes clear his philosophical predisposition at the outset of his essay on the circulation of blood.⁷ True science is based upon the building up of knowledge that has been subjected to the test of commonsense perceptions. He points out that his previous work on the motions of the heart has fairly well demonstrated the circulation of the blood, at least to the satisfaction of the majority, by his use of "experiment, observation, and ocular inspection, against all force and array of argument."⁸ And while there are still a few who demand further proofs, which Harvey will soon give them, he summarily dismisses those critics of his first work who satirized him for his lack of philosophical sophistication and for suggesting that experiments with animals could in any manner provide insights into

⁶ Harvey, *op. cit.*, p. 305.

⁷ Harvey adopted the ancient concept of the circle as the symbol of perfection. To him it was perfectly "natural" that blood would *circulate*. "This was the *Leitmotiv* of his investigation and a truly Aristotelian stimulus to natural philosophy at that—a motive that explains much in his life and work." Pagel, *op. cit.*, p. 25. Harvey did not care very much for the new astronomy that had disavowed the supremacy of the circle and disparaged the idea of celestial spheres. Further, he thought that many astronomical proofs relied on ridiculous transpositions of commonsense perceptions, such as mentally placing one's self beyond the orbit of the moon in order to comprehend an eclipse. *Ibid.*, p.30.

⁸ Harvey, *op. cit.*, p. 313. Ocular probably refers to the use of a magnifying glass, then called a "burning glass." Galen had taught that ingested nutriment was converted by the liver into blood and then passed on to the heart. From there the blood moved outward to the body's organs and extremities where it was consumed. "The salient point in Harvey's discovery, then, lies in the *preservation* of the blood as against its *consumption*: instead of being used up in the peripheral organs and tissues, the blood returns periodically or 'cyclically' to the heart—it circulates." Pagel, *op. cit.*, p. 51, italics original.

human anatomy: "There are some, too, who say that I have shown a vainglorious love of vivisection, and who scoff at and deride the introduction of frogs and serpents, flies, and others of the lower animals upon the scene, as a piece of puerile levity, not even refraining from opprobrious epithets." Harvey will not deign to address these detractors in their own language, which language is "unworthy in a philosopher and searcher after the truth." He will destroy their arguments instead with the "light of faithful and conclusive observation." Then, not heeding his own advice, he declares that although it cannot be helped if "dogs bark and vomit their foul stomachs, or that cynics should be numbered among philosophers," he can still make sure that they do not spread their contagion or "with their dog's teeth gnaw at the bones and foundations of truth."⁹

In addition to his clinical experience as a surgeon and the numerous autopsies he performed, Harvey was also highly accomplished in the dissection of over eighty kinds of animals. He cared little about the sources from which knowledge might be extracted and believed that "the great and Almighty Father is sometimes most visible in His lesser, and to the eye, least considerable works."¹⁰ However, in *The Circulation of the Blood*, Harvey for the most part forgoes any resort to animal anatomy for his proofs and concentrates instead on using examples taken from normal practice, all of which were familiar to his readers. He discusses several problems then vexing the scientific community, among

⁹ Harvey, *op. cit.*, p. 313.

¹⁰ *Ibid.*

which are the pulsation of arteries and the observed differences between arterial and venous blood.

Galen and Vesalius both held that the pulsation of an artery was the result of a direct mechanical transmission of energy from the heart along the coat or "tunic" of the artery, i.e., an artery pulsated according to the diastole and systole of the heart because it was directly connected to the heart. Harvey believed, and thought he had proved it in *The Motions of the Heart*, that the force or "shock" of the blood surging through the artery caused the pulsation. Both Galen and Vesalius had claimed that by making an artificial joint in an artery the transmission of energy would be halted, that is, by inserting a reed into the cavity of a severed artery all pulsation beyond the point of insertion would stop. Needless to say, this sort of experiment would tax the skill of the best anatomist, and Harvey is quick to point out that not only are his contemporaries afraid to attempt it, but that "neither Vesalius nor Galen says that he tried the experiment." Then he adds, "However, *I did*."¹¹

Harvey showed conclusively that by opening the artery below the insertion point of the reed, or by inserting another tube beyond the same point, the vessel still rose and fell with the beating of the heart and blood issued forth accordingly. But perhaps it is best if the doctor speaks for himself:

If you suffer the efflux to go on uninterruptedly, either from a simple divided artery or from a tube inserted into it, you will be able to perceive by the sight, and if you

¹¹ Harvey, *op. cit.*, p. 313, italics added.

apply your hand, by the touch likewise, every character of the stroke of the heart in the jet [of blood]; the rhythm, order, intermission, etc., of its pulsations, all becoming sensible there.... I have occasionally observed the jet from a divided carotid artery to be so forcible, that, when received on the hand, the blood redounded to the distance of four or five feet.¹²

Seeing is believing for William Harvey. He concludes his argument in favor of the "pulsific power" being caused by the circulation of the blood by referring to a patient whose body had unfortunately reproduced the selfsame conditions as those found in the experiment recommended by Galen and Vesalius. In the corpse of a nobleman Harvey discovered a section of the aorta near the heart had been "converted into bone," presumably meaning the artery had hardened to the degree that it *appeared* to be bone. The experiment suggested by Galen and Vesalius, "or at all events, a state analogous to it," had been reproduced by nature. Yet Harvey recalled that he had often checked the pulse in the legs and feet of this patient, who was "a very particular friend," and "whilst he lived" had found no apparent interruption of the pulse. "The arteries in the inferior extremities of this nobleman must therefore and of necessity have been dilated by the impulse of the blood like flaccid sacs, and not have expanded in the manner of bellows through the action of their tunics."¹³

Harvey's experimental technique gives uneven results, however, when he turns to the problem of analyzing arterial and venous blood. The medical schools at the time

¹² Harvey, *op. cit.*, p. 314, spelling original.

¹³ *Ibid.*

taught an elaborate theory of spirits that moved through various conduits of the body or occupied various cavities in the body. The three most widely agreed upon spirits were the "natural" spirits that flowed through the veins, the "vital" spirits that flowed through the arteries, and the "animal" spirits that flowed through the nerves.¹⁴ Obviously, if Harvey's circulation of the blood were true, there should be no perceived difference between the blood that entered the heart and that which left it, since it was all supposed to be the same blood, i.e., arterial blood should not differ in appearance from venous blood. But observation seemed to contradict Harvey, in that the two kinds of blood appeared to diverge in both consistency and color. This divergence, of course, was attributed to the action of the different spirits in the blood.

Before continuing, it might be instructive to consider Harvey's attitude toward the theory of physiological spirits generally. His attitude is important because, when combined with his experimental bias for accepting as real only that which he could see and dismissing all else, he was lead into an intellectual trap from which he was able to only partially extricate himself. While he was kind enough to allow for the possibility that the then-current ambiguity surrounding the theory of spirits would someday be resolved (no doubt by dissection rather than argument), he noted, in the characteristically acerbic fashion for which he was famous, that:

Persons of limited information, when they are at a loss to assign a cause for anything, very commonly reply that it is done by the spirits; and so they bring the spirits into

¹⁴ Harvey, *op. cit.*, p. 316.

play upon all occasions; even as indifferent poets are always thrusting the gods upon the stage as a means of unraveling the plot, and bringing about the catastrophe.¹⁵

Plainly, he had heard enough stories about spirits. Yet he knew that the composition of blood was such that it could assume many different appearances, both in the living and the expired organism, and that it was, at least to some extent, incumbent upon him to show that all these different kinds of blood, so to speak, were all one and the same; otherwise, the idea of circulating blood might be cast into doubt. Thus he took the position that because the heart always continued to beat for a while after respiration ceased, the lungs and the right chamber of the heart would always be found devoid of blood after death. These cavities never held any spirits during life but rather only blood. He then pointed out that there was essentially no observable difference between arterial blood and venous blood when they were allowed to collect and stand for a time, contrary to the practice of analyzing their qualities as they came forth from the arteries and veins of the body; and whatever differences there had been on expulsion from the body, whether of consistency, color, or perceived level of heat, these things disappeared within a short time. According to Harvey, arterial blood was like milk or honey that had been heated to a froth, but once removed from the flame, it returned to its normal appearance.

All of this of course did not explain very well for the bright red color of the richly oxygenated arterial blood as compared to that of the oxygen-depleted venous blood, and

¹⁵ Harvey, *op. cit.*, p. 316.

Harvey was forced to accept a limited role for spirits in the blood, although he would not concede that the spirits gave heat to the blood but rather it was the other way around. The spirits in the blood had to be regarded as "fumes and excrementitious effluvia proceeding from the body in the manner of odours."¹⁶ Ironically, in casting about for an explanation—an explanation that his dissections could never produce—Harvey very nearly summed up the gas exchange process between the blood and the lungs:

They [the spirits] are at best of a very frail and evanescent nature. Whence also it becomes probable that the expiration of the lungs is a means by which these vapors being cast off, the blood is fanned and purified; whilst inspiration is a means by which the blood in its passage between the two ventricles of the heart is tempered by the cold of the ambient atmosphere....¹⁷

Harvey's mode of experimentation could carry him only so far, and his theory of the circulation of the blood answered as many questions as it posed. But, like Copernicus before him, who by a simple substitution of place forced an entirely new astronomy and physics to arise in explanation, Harvey's theory eventually called into question the entire system of anatomy and physiology passed down from antiquity. Phrased differently, there is no way to predict all the possible ramifications of a discovery, and Harvey cannot be held accountable for his failure to explain the entire human anatomy. That burden was shouldered by his fellow physicians, who for the most part took it upon themselves willingly and carried it forward with missionary zeal and great success. As his friend Tho-

¹⁶ Harvey, *op. cit.*, p. 317.

¹⁷ *Ibid.* The dominate theory of lung function at the time held that air was necessary to cool the blood, which would naturally begin to "boil" otherwise. Harvey generally accepted this theory.

mas Hobbes observed, "You are the only one I know who has overcome public odium and established a new doctrine during his own lifetime."¹⁸

William Harvey withdrew from all further debate after the publication of his first two masterpieces of experimentalism. The uproar they caused, not to mention his association with the crown during a civil war, was the excuse he needed to drop from sight. But he did not tarry in his studies for a moment. Like Galileo, Harvey returned to several problems that had confronted him in his youth, problems that would occupy the remainder of his life.

Many years before, in Chapter 6 of *The Motions of the Heart*, Harvey had observed that the flow of blood in an animal fetus seemed to bypass the lungs completely and instead traveled straight through the heart, but that when the animal was born, or in the case of man, upon further development, the blood appeared to "percolate" through the lungs before entering the left chamber of the heart.¹⁹ This phenomenon Harvey mentioned again near the end of his discourse on the circulation of the blood, although in a slightly different context:

Who can tell us why the foetus *in utero*, breathing no air up to the tenth month of its existence, is yet not suffocated? Born in the course of the seventh or eight month, and having once breathed, it is nevertheless speedily suffocated if its respiration is interrupted. Why can the foetus still contained within the uterus, or enveloped in the mem-

¹⁸ Harvey, *op. cit.*, from the translator's biographical note, p. 263.

¹⁹ *Ibid.*, p. 282.

branes, live without respiration; whilst once exposed to the air, unless it breathes it inevitably dies?²⁰

These questions and many others were raised early in Harvey's career, but implicitly there were others of a deeper nature that seemed to haunt his work: When did the heart first appear in the developing organism? Where did the blood come from in the beginning? And deeper still: How does life begin? In Harvey's last major work, *On Animal Generation*, he journeys into what he called the "unknown countries" of scientific investigation, "eager for novelty," as he put it, and eager to see with his own eyes those things that others had reported. He must follow the "traces of nature" with his eyes and hands, pursue her "through devious but most assured ways" until she is "reached in the citadel of truth."²¹ He opens his discourse by reviewing the state of knowledge in reproductive biology as he finds it:

Physicians, following Galen, teach that from the semen of the male and female mingled in coition the offspring is produced, and resembles one or the other, according to the *predominance* of this one or that; and, further, that in virtue of the same predominance, it is either male or female. Sometimes they declare the semen masculinum as the *efficient cause*, and the semen femininum as supplying the *matter*; and sometimes, again, they advocate precisely the opposite doctrine. Aristotle, one of Nature's most diligent inquirers, however, affirms the *principles* of generation to be the male and the female, she contributing the matter, he the form; and that immediately after the sexual act the vital principle and the first particle of the future foetus, viz., the heart, in animals that have red blood, are formed from the menstrual blood in the uterus.²²

How will Harvey pursue all these subjects into the "citadel of truth"?

²⁰ Harvey, *op. cit.*, p. 324.

²¹ *Ibid.*, p. 331.

²² *Ibid.*, p. 331, italics original.

But that these are erroneous and hasty conclusions is easily made to appear: like phantoms of darkness they suddenly vanish before the light of anatomical inquiry. Nor is any long refutation necessary where the truth can be seen with one's proper eyes; where the inquirer by simple inspection finds everything in conformity with reason; and where at the same time he is made to understand how unsafe, how base a thing it is to receive instruction from other's comments without examination of the objects themselves, the rather as the book of Nature lies so open and is so easy of consultation.²³

Harvey will do what he has always done, use his eyes and his hands and his mind to unlock the secrets of nature. His faith is complete:

For although it is a new and difficult road in studying nature, rather to question things themselves than, by turning over books, to discover the opinions of philosophers regarding them, still it must be acknowledged that it is the more open path to the secrets of natural philosophy, and that which is less likely to lead into error.²⁴

On Animal Generation is much more than a polemic on experimentalism, however. Composed of 72 anatomical exercises, the book is written in a didactic fashion that allows the student to stand beside the master and watch each dissection as it develops. "Now look," Harvey seems to say, "look at this object. What can we make of it? How shall we describe it? What function does it seem to fulfill?" Across the dissection table stand Aristotle and Harvey's former professor at Padua, Hieronymus Fabricius of Aquapendente, the undisputed grand master of anatomy. These spirits are neither aloof nor silent but rather are active participants in the experiments at hand. "Now, what did Aristotle say of this?" Harvey seems to ask as he points to the object of his inquiry. Aristotle

²³ Harvey, *op. cit.*, p. 331.

²⁴ *Ibid.*, Harvey seems to be mistaken in the next paragraph, where he states that the ancients performed numerous experiments to prove their assertions. This must be a reference to the biological work of Aristotle and the early anatomists, not the ancients generally.

is allowed to respond. "And this, what did Fabricius hold?" And so forth. The student is thunderstruck by this amazing three-way conversation, yet the lesson is plain: What was claimed then as *theoretically* true must now be proved *experimentally* true, otherwise it is deemed false for lack of evidence. There is no other test.

On Animal Generation is divided into two dissimilar but related experimental investigations, those concerning the development of the common chicken and those concerning the development of the semi-domesticated roe deer, although the account is entirely weighted toward the former, with only 7 of the 72 exercises devoted to the latter. In both the hen and the deer, Harvey first gives a complete survey of the distinct organs within each animal's reproductive system, as revealed by dissection, and a vivid description of the changes these organs undergo on a day-to-day basis during the various stages of gestation. But, of necessity, his investigation eventually focuses on the product of sexual intercourse, i.e., the manner in which new life first appears and subsequently assumes the familiar shapes of the embryo and the fetus.

While it is unnecessary to review the 14 or 15 separate inspections of the incubating hen's egg that Harvey made over as many days, each inspection representing an entire exercise in his book, it may be of some value to catalog a few of his observations, as these will be used by him to support his conclusions. First, however, it is important to note the reasons why Harvey chose the chick embryo as the subject of his investigation, the foremost reason being that both Aristotle and Fabricius had written at length on the same example, and, next, that hen's eggs were widely available and inexpensive. Harvey

would have preferred to experiment on the larger and "more perfect" animals for the simple reason that everything inside them is bigger, i.e., easier to see with the unaided eye. But these animals were more expensive, and had not the king's deer park been made available to Harvey, he likely would have passed over the deer as a subject of experiment, too. In any event, and this he could not have foreseen, his investigation into animal generation would take him finally to the threshold of the microcosm, and the size of the animal subject he had chosen to begin with would have no bearing on the ultimate impasse he reached.

Even an incomplete listing of the theories on animal generation that Harvey proved or disproved is instructive, not to mention humorous at times, because it gives a good idea of the anatomy, embryology, and physiology that Harvey inherited, the directness of his experimental approach, and the soundness of his reasoning. The prevalent theory that he called into question may be easily deduced in most cases by simply inferring the opposite of what he proved. To begin, and taken in no special order, Harvey proved that an eggshell was not produced by contact with the air as it emerged from the hen, but rather that it was formed within the body of the bird and progressively hardened as it dried; that the egg has no umbilical cord; and that the chick pecked its way free from the shell and did not call the hen to its aid, who, on hearing its cheeps, broke open the shell. Harvey proved the first two cases by cutting open a hen and removing its fully formed egg. The third case was a little more difficult, in that Harvey's theory had to explain for all oviparous animals, but he was nevertheless able to observe the exit hole in

numerous eggs of different species and piece back together the shell fragments whenever possible. He let the matter rest when he realized that anyone who ever saw a broken windowpane would at once know the direction from which the force was applied.²⁵

Under the heading of more momentous discoveries, Harvey demonstrated that no organs appeared suddenly and fully developed in the embryo, such as a miniature brain, heart, or liver, but that instead the entire chick itself first appeared as an indistinguishable "globular mass" floating in the "colliquament" contained within the egg. This is an extremely important departure from the dominate thinking that held the process to be metamorphic in nature:

In generation by metamorphosis forms are created as if by the impression of a seal, or as if they were adjusted in a mould; in truth, the whole material is transformed. But an animal which is created by epigenesis attracts, prepares, and elaborates, and makes use of the material, all at the same time; the process of formation and growth are simultaneous.²⁶

And thus, "[I]t appears clear from my history that the generation of the chick from the egg is the result of epigenesis, rather than of metamorphosis, and that all its parts are not fashioned simultaneously, but emerge in their due succession and order; it appears, too, that its form proceeds simultaneously with its growth, and its growth with its form."²⁷ The process of epigenesis began, he said, similar to the manner in which

²⁵ Harvey, *op. cit.*, p. 382.

²⁶ *Ibid.*, p. 413.

²⁷ *Ibid.*

“mouldiness grows in moist places” or like “moss upon rocks and the bark of trees.”²⁸ It is at this stage of his investigation that Harvey gets his first glimpse of the boundary that he is approaching:

But now when I look at the thing more narrowly, I am of the opinion that the blood exists before any particle of the body appears; that it is the first-born of all the parts of the embryo; that from it both the matter out of which the foetus is embodied, and the nutriment by which it grows are derived; that it is in fine, if such a thing there be, the primary generative particle.²⁹

What Harvey is hinting at is a theory of biological first cause, what he shall later call in the same essay the “vital principle” or “innate heat.” Thus, his work starts to veer away from its initial concentration on describing observed sequences of embryological development, since he has followed the subject as far as his eyes can take him, and begins to move toward a purely hypothetical explication. Moreover, the discussion begins to wander between anatomical comparisons of various animal embryos and fetuses and those of the human being. However, Harvey’s knowledge of embryology in the chicken misleads him when it is applied to the human system, and although he correctly surmises that the human amniotic fluid is not entirely waste fluid—fetal sweat and urine—as his predecessors had held, he incorrectly assumes the amniotic fluid serves to nourish the fetus in the same fashion as the hen’s “colliquament” did the chick. This mistaken parallel—when combined with his observations that human fetuses have relatively large

²⁸ *Ibid.*, p.374.

²⁹ Harvey, *op. cit.*, p.374.

mouths and that during post-mortem evaluations have been found to hold amniotic fluid in their stomachs and fecal material in their bowels—leads Harvey to conclude that the human fetus takes its nourishment directly from the amniotic fluid via the normal processes of ingestion and digestion: “[I]t is impossible to regard this liquid as either sweat or urine; its seems far more probable that like the colliquament in the hen’s egg, it is a fluid destined by nature for the nourishment of the fœtus.”³⁰ Eventually, these errors are compounded to the degree that Harvey declares the human infant’s uncanny ability to suck at the breast—by gulping the whole nipple as if to swallow it—was learned in the womb.³¹

The William Harvey found in *The Motions of the Heart* and *On the Circulation of the Blood* seems not to be the same William Harvey found in *Animal Generation*, at least not as the essay nears its conclusion. But this is decidedly not the same case as found in Galileo, where the scientist has discarded experimentalism and attempts to move forward on theory alone. What is found instead is an exasperated experimenter, a man who, having all the evidence before him, is incapable of assembling it into a coherent and rational system that consistently explains for the observed phenomena. He has no new theory to guide him, and his tools will not allow him to penetrate any deeper into the specimens.

³⁰ Harvey, *op. cit.*, p. 452. Pagel is mistaken on this point and confuses Harvey’s success with his failure: “Harvey rightly concluded that amniotic fluid is not sweat or urine, *but that it served nutritional purposes.*” (*Op. cit.*, p. 330, italics added.) As for the infant’s inbred ability to suck, Harvey admittedly derived his hypothesis in part from the work of Hippocrates.

³¹ *Ibid.*, p.460.

He has pursued his inquiry to the brink of a new world with only a knife, a magnifying glass, and common sense. And now all these things seem to fail.

Aristotle and other ancients, Fabricius and other moderns, the folklore of midwives, personal biases, religious beliefs, and sheer speculation—all become jumbled together in the concluding exercises of Harvey's book. What has happened to the infallible judgment of this premier experimenter? Walter Pagel dismisses much of this perception of Harvey as having changed his experimentalist approach as merely a judgment of history, meaning that Harvey's last work on generation failed to reach the very neat conclusions of his earlier work on circulation and is therefore not readily remembered: "What *is* different is the result: the spectacular discovery which altered history in one and a collection of data and conclusions which do not seem to have influenced history in the other."³² Be that as it may, Pagel has nevertheless very accurately identified the reasons for Harvey's scientific failure in *Animal Generation* and almost as an afterthought has placed his finger on the nub of the problem:

It is, then, not the fault of the author [Harvey], nor any personal factor such as old age, which accounts for the difference in results. Nor is it a tendency on Harvey's part to lose himself in speculation in the "late" work. The main error which marred its success may be said to lie in his principal conclusions: 1. that nothing passed from the female testis (ovary) into the uterus in mammals and 2. that the uterus did not receive the sperm from the male. The backwardness of the optical equipment available at his time explains much....³³

³² Pagel, *op. cit.*, p. 328, italics original. This is a fairly specious argument, in that it imputes a power to historiography that even historians do not believe.

³³ *Ibid.*

It is quite true that Harvey practically cut a swath through his king's deer population and dissected numberless hens in his quest to locate the exact place where male and female gametes joined, and failed. It would also be easy to suggest that Harvey had come face to face with the Great Mystery, i.e., the infinitesimal essence of existence as represented by the most minuet particle of developing life, and has been rendered awestruck thereby and thus was reduced to incoherent speculation.³⁴ But all this, while to some extent accurate, seems not to be the case. Rather it appears that he had deliberately set aside his now-useless instruments and had shifted the focus of his inquiry. He was, it seems, struggling to understand the "plastic force" in the interior of a living organism that controls it from the first moment of life to the last:

Whatever it is in the egg [that] performs the duty of a most skillful artificer, producing and fashioning the parts of the pullet, warming, cooling, moistening, drying, concocting, condensing, hardening, softening and liquefying at once, impressing distinctive characteristics on each of them by means of configuration, situation, constitution, temperament, number and order—still is this something at work, disposing and ordering all with no less of foresight, intelligence, and choice in the business of transmuting, than in the processes of nutrition, growth, and formation.³⁵

Obviously, Harvey is no longer concerned with those singular objects that are susceptible of dissection and visual inspection. He wants to grasp the functional mecha-

³⁴ Pagel suggests that Harvey's "failure to detect the male and female components at an early stage after coition" was not too important to him. Rather Harvey was philosophically "intent on divesting generation of any materialist trace." (*Op. cit.*, p. 45.) This seems to disagree with Harvey's often-expressed frustration at not being able to see the first formation of new life and his desperate attempt to apply the then-current theory of "contagion" to the mechanics of fertilization. Clearly, Harvey was looking for a direct physical contact of components and could not find any evidence of it.

³⁵ Harvey, *op. cit.*, p. 443.

nisms of the life process itself. But these mechanisms and their constituent parts lie below the human-scale that he inhabits and are beyond the reach of his eyes and instruments, just as the particles and stars Gilbert sought stood outside the circle of perception. Although, if Harvey's past performance is any guide, the things he seeks are not beyond the scope of his genius. He has been halted, nonetheless, at the boundary of the microcosm, and that world, to borrow Koyré's metaphor, is closed.

Harvey thus turned to philosophy for his final proofs, a particularly bad decision because he was no philosopher. Naturally, having spent his entire life investigating the subject of blood, he argued that the blood was the be-all and end-all of existence, a substance that transcended Aristotle's "element" of fire and consequently produced within and of itself the innate heat of life. It became, in Harvey's imagination, not just "the cause and author of youth and old age, of sleep and waking," but the soul of man and the "instrument of the Great Workman." The blood was of the same substance as the stars. It was, in Harvey's considered opinion, the philosopher's stone.³⁶

³⁶ Harvey, *op. cit.*, p. 493.

CONCLUSION

Theoretical science had operated since antiquity on the general premise that a valid description of natural phenomena need only be logically consistent. Whether the description happened to coincide with the reality of observed phenomena, or explained all cases whatsoever, was only of secondary importance. Self-containment and self-sufficiency were enough. So long as men were not assisted by the instruments necessary to physically alter or manipulate nature, that is, to move her this way and that to show her many different sides, there was little chance that any challenge to the accepted description could arise, especially if it had been constructed with great care in the beginning. Only alternative theories could be offered to dispute the received wisdom, and these theories would rise or sink according to their logical integrity, the conviction, eloquence and reputation of their advocates, and the receptivity of the prevailing intellectual climate. A successful theory, as measured by the number of earnestly nodding heads it could produce, tended to create clusters of adherents or schools of thought whose only purpose for existence was to perpetuate the accepted dogma and to defend it against all upstart theories. Thus theory succeeded theory as the controlling logical description of nature was amended or repealed without regard to nature herself, and consequently science failed to firmly root itself in the soil of reality and yielded no fruit.

Experimental science opened the road to revolution by showing men how they could consistently break through intellectual roadblocks or find their way around them.

By "tormenting nature," as Bacon said, that is, by using instruments to poke and prod her and to observe her reactions to these intrusions, experimental science quickly cleared the theoretical debris of antiquity out of the way. More often than not, however, experiment was at a loss to explain the new phenomena it encountered along its line of march; rather all it could say, perhaps self-consciously, was that nature did not act in the manner theory had prescribed or predicted. And this is the irony of nearly all early 17th century experimentalism: In its determination and predisposition to disprove more so than to prove, it tended to get hopelessly disoriented once the dominant wisdom had been pushed aside. The early experimenters created teleological voids, so to speak, that they were incapable of filling in, either by training or by disposition, and thus when they did resort to theorizing, which was usually not their forte, they created new intellectual impediments to the advancement of science. Yet, having demonstrated a very effective method for debunking beliefs, their new theories could be assailed only by further experiments, which usually had to await the development of new instruments. The cycle of theory succeeding theory had been replaced by a cycle of experiment succeeding experiment.

The three case studies presented in the previous sections portray the relationship between experimental and theoretical science in its early development. While the narrow temporal focus of these studies is antagonistic to a comprehensive understanding of the overall historical development of science, nevertheless it is conducive to a close inspection of the inchoate infrastructure that will determine the shape of science as it travels through the Newtonian epoch. In the work of Gilbert, Galileo, and Harvey may be found

the mechanisms of "modern science" in their nearly unadulterated state, i.e., mechanisms that have not yet merged to form a larger and more complex system of inquiry. This internal view demands first, however, that labels such as "experimenter" and "theorist" be affixed to each scientist before the analysis can proceed. But these labels are reusable in that they do not adhere permanently and can be easily exchanged, as was the case in the early 17th century. Although the evidence has already shown that all three men seemed to have made very sharp intellectual distinctions between experiment and theory, some of them adamantly so, none of them faithfully maintained those distinctions in practice; and it therefore does their memory no violence to temporarily type cast them as experimenters or theorists.

Gilbert and Harvey were cut from the same scientific cloth and each showed a keen understanding of what experiments needed to be conducted to win their points. Unfortunately, they often wanted to make different points simultaneously, i.e., they were moved by a desire not only to disprove existing theories handed down by antiquity but also to advance their own theories as alternatives. On the one side they used experimentation to topple authority, and on the other to erect it, which of itself is no crime, unless it is the same experiment. This is to say that their choice of experiments was sometimes calculated to have a dual effect, and while such an accidental economy in experimental science is laudable, it becomes suspect when it is premeditated. Under normal circumstances the scientist rarely finds himself in the lucky position of denying and confirming two different things at same time. The methodology used by Gilbert and Harvey, if it can

be called that, was to set up an experiment that proposed to disprove an old idea and, if sufficiently convincing, then substitute their ideas as an explanation for the observed phenomenon. This was proof by disproof. The experiment had punched a hole in accepted theory and the new theory rushed in as if by atmospheric pressure, which at most only proved nature—human nature—abhorred a vacuum. Further experimentation, of course, would be required to establish the new theory.

When these two men set out to prove their own theories or that of another with whom they agree, rather than bashing an existing theory they deem fallacious, they are virtuosos. And here Galileo, as represented in his telescopic work, joins their esteemed company, but only conditionally, for it appears that he did not intend to construct an experiment that would prove or disprove Copernicanism once and forever, but rather that he began by merely gazing at the new sky, taking notes, and making sketches. In any event, the demonstrations of magnetic polarity, the phases of Venus, the motions of the heart, and so forth are all genuine scientific discoveries that resulted from the application of experimentalist techniques. All of these may be classed as positive proofs of one theory or another, and all were immediately useful, either to the further improvement of scientific knowledge or to the general improvement of mankind's estate. And all gained relatively rapid acceptance therefore.

Theoretical science as practiced by Gilbert and Harvey looks quite different from that of Galileo, however. Neither of the two physicians were inclined to quantify their findings, although, admittedly, Gilbert's work in magnetism as compared to Harvey's

work in anatomy was the better candidate.¹ They preferred instead to step off into philosophy, or plunge perhaps, when they had reached the end of their experiments; that both were out of their depth is evidenced by how quickly most of their philosophically based theories sank. They began their investigations by aggressively attacking philosophical speculation and ended by desperately trying to embracing it. Galileo, as physicist, relies almost entirely on geometry and mathematics to promote his ideas. From start to finish his motion studies are a symphony of arcs and tangents, operators and operands—all very appealing to the abstract faculties of the intellect and all logically convincing. Galileo the theoretical scientist outshines his protégés by an enormous magnitude. But, to the degree that Gilbert and Harvey fumbled theoretical matters, Galileo equally proved himself to be no experimenter. The suspicion is strong that he never really understood the tradition of manipulating nature, of placing her in newly contrived situations in order to observe her response. This he did with his telescope, apparently without fully realizing it, but could not do in his rate-of-fall experiments.

The technology of experimental science comes into play differently for each of the three investigators. The scope of Gilbert's work in magnetism—not cosmology—was sufficiently limited to allow him to succeed with only rudimentary instruments, i.e.,

¹ Two quantifications deserve mention. First, Gilbert was able to translate his findings on magnetic anomalies into a very precise mathematical table that was used in conjunction with his dip instrument to find global coordinates. Second, Harvey often turned to measuring, timing, and weighing quantities in his experiments, the most famous example being his proof that the weight of the blood expelled by a single artery in only a few minutes exceeded the weight of the nutriment taken in by the body.

technics, the tools and devices used in experiments. Surely he would have liked it otherwise, and the electro-magnetic test apparatuses developed by his successors in the following centuries testified to the necessity of technics in pursuing the "magnetic philosophy." But Gilbert never complained about the insufficiency of his instruments and seemed oblivious to the idea that he might need something much more than the bits and scraps of materials at his disposal. Being the first of the new experimental scientists, he went into the fray virtually barehanded. When the dust had settled, science saw quite clearly the two paths that it would have to travel, the one upward into the macrocosm of causes and effects, the other downward into the microcosm. The technological wherewithal to begin these experimental journeys, however, was lacking momentarily.

To Galileo fell the opportunity to take the first steps above. The telescope technic allowed him to go forward with immediate success. And although some might dismiss the coincidence of a new technology coming into the hands of an obscure mathematics professor, who just so happened to turn it on the heavens, there is little room to doubt that it was Galileo's scientific curiosity that drove him to investigate the rumors he had heard about the new device, build it with his own hands, and use it to collect light from every possible source. However, technics do not usually make an experimenter, but rather it is the other way around. That is, a scientist seeking to prove or disprove an idea designs and builds an instrument to help him evoke from nature the response he needs to support his argument. But there is no record to indicate that Galileo intentionally designed and built a telescope to prove or disprove Copernicanism, and his telescopic discoveries were

therefore not the outcome of a preplanned experiment. That his stargazing evolved into a logical investigation of planetary astronomy is not doubted, either. And thus, without deeper scrutiny it seems supremely ironic, not to mention nonsensical, that the first great theoretician of the Scientific Revolution would make his mark as an experimenter only to fall into confusion and failure in his later attempts. One possible explanation, wholly speculative at this stage, is that Galileo intended to perform an experiment in optics, not in astronomy. If he had set out to demonstrate the ability of paired lenses to collect and focus light and thereby magnify distant objects, then his discoveries in astronomy may be understood as the logical and intentional application of a technic that had been produced by his original optical experiments, not merely the concurrence of numerous fortuitous events.

Last, Harvey's case is particularly poignant because he was acutely aware of the shortcomings of his instruments. The extension of his experimental investigation into the biological microcosm was contingent upon an optical technic that did not yet exist, and more than once did he mention in passing that he had lost sight, literally, of his goal. Harvey's ability to quickly purge himself of a long-held opinion when he could find no experimental evidence to support it is admirable; however, the same simple instruments that took him beyond the conventional wisdom left him stranded at the boundary of the new knowledge he needed, and the upshot was, at least in his embryological studies, that he only knew precisely what was *not* true. All the same, the modern mind is seized with awe and wonder when it beholds Harvey the experimenter at work, and the impression is

strong that if by some miracle a powerful microscope had appeared on his workbench one morning, by noon all the mysteries that had perplexed him would have been solved. There is no underestimating the role of technics in the experimental work of this man, nor is it possible to avoid a sympathetic response.

The first act in the unfolding drama of experimental science came to a close with the publication of Harvey's last research in 1651. Standing in the wings was the next generation of experimenters, men such as Boyle, Hooke, Huygens, and Newton, the latter usually being credited with bringing the Scientific Revolution to a synthetic conclusion. But the revolutionary stage had already passed when Newton published his *Principia* in 1687, for by that time no thinking man doubted the efficacy of experimentalism, and science everywhere was beginning to move into the open universe. The ancient philosophical squabbles for the most part having been settled, or at a minimum banished from scientific inquiry, there was little, if any, looking back once Gilbert, Galileo, and Harvey had set science on the highway to the future.

By the close of the 17th century experiment and theory had finally formed a solid partnership for their mutual benefit and ultimately to the great benefit of mankind. Rather than operate in exclusive domains, where only one set of symbols could be used to challenge another set or where only one set of instruments could be arrayed against another, where ideas tested ideas and things tested things, the two came together and allowed the one to be the judge of the other and vice versa. What is called "modern science" is glimpsed for the first time. Experiment proved or disproved theory and simultaneously created new opportunities for it. Theory then built upon the findings of experi-

ment or filled in the voids it had created. All was not perfect in this new marriage, however, because the continuing progress of the relationship always depended on the mediation of a third party: technology. The technic became the nexus between experimental and theoretical science, without which the new agreement would fail or fall into disuse. Just as the one partner discovered its dependence on the other, so also did the two discover their dependence on the third, and with their future prosperity predicated on the cultivation and growth of technology, experimental and theoretical science would begin to divert an ever-increasing portion of their labor to its maintenance and further development. Eventually, Gilbert's versorium will become a cyclotron, Galileo's telescope, an array of parabolic dishes dotting a desert floor, and Harvey's burning glass, a scanning electron microscope. As this tripartite relationship grew, this engrafted tree of science, the fruit fell everywhere at the feet of mankind.

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