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Mechanisms and Mechanics
RICHARD S. WESTFALL

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Mechanisms and Mechanics

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To Alfred, Jennifer, and Kristin

He was able to show as well that bodies experience identical accelerations for all equal vertical displacements. If one body falls freely from rest and another, also starting from rest, descends by an inclined plane through the same vertical distance (which means of course that its path along the inclined plane must be longer and the time for the movement greater), they acquire equal velocities.

The last conclusion played an important role in Galileo's picture of the universe, and it brings us back again to the Copernican system which furnished his cosmology. The circular motion which conserves the integrity of a well-ordered universe is identical to the inertial motion of heavy bodies around a gravitating center. So long as they neither approach the center nor recede from it, no cause operates to change their velocity. Inertial motion, however, can only preserve a velocity; it can never generate one. The motion of heavy bodies toward a gravitating center is the sole natural source of increased velocity, and recession from the center the means whereby motions are destroyed. In both cases, equal increments of velocity correspond to equal radial displacements. For Galileo, the acceleration of gravity was a constant for all distances from the center, just as weight was the constant property of all bodies, however unknown its cause might be.

Between them, Kepler and Galileo confirmed and completed the Copernican revolution. When Galileo died in 1642, probably a minority even among astronomers accepted the heliocentric system. Nevertheless, in the work of Kepler and Galileo its full advantages had been revealed and the major objections to it answered. Its general acceptance had become a matter only of time. The importance of Kepler and Galileo, however, lies less in their relation to Copernicus and the past, than in their relation to the 17th century which followed. In solving the problems of the past, they posed the problems of the future, Kepler in opening the question of celestial dynamics, Galileo that of terrestrial mechanics. In the completion of the work they inaugurated, 17th century science realized its grandest achievements.

CHAPTER II

The Mechanical Philosophy

KEPLER AND GALILEO were not the only scientists of lasting importance at work when the 17th century dawned. In the very year 1600, an English doctor, William Gilbert (1544–1603), published a book entitled *De magnete,** one of the minor classics of the scientific revolution. By universal agreement, Gilbert is recognized as the founder of the modern science of magnetism. His book is revealing in its exposition of the prevailing philosophy of nature.

In its frankly experimental, not to say empirical, approach, *De magnete* stands in marked contrast to the work of Galileo. Galileo regarded experiments primarily as devices by which to convince others; as for himself, he was ready confidently to announce their results without bothering to perform them. Gilbert, on the other hand, undertook to establish the basic facts of magnetism by empirical investigation. From the stories he mentioned, and put to the test, we can learn something of the special awe with which the magnet was regarded; it was the very epitome of the occult and mysterious forces with which the universe was thought to be filled. Stories abounded of such things as magnetic mountains jutting from the sea, which would tear the nails from a ship sailing near. Magnets were said to act as protection against the power of witches. Taken internally (one was allowed first to reduce a loadstone to powder), they were used as a medicine to cure certain diseases. A magnet under the pillow, it was held, drives an adulteress from her bed. (The story was obviously male in origin, and more than good fortune was involved in the apparent immunity of adulterers.) Gilbert took it as his function to winnow fact from fable, and by experi-

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* *Concerning the Magnet.*

mental investigation to establish the truth of magnetic action. Is it true that diamonds have the power to magnetize iron? Seventy-five diamonds later, Gilbert felt prepared to answer—it is not true.

Gilbert was not the first man to investigate the magnet, and every fact to which he attested was not his own discovery. Nevertheless, the systematic presentation of *De magnete* may be said to have established the basic corpus of facts concerning magnetism. Before Gilbert, magnetic phenomena were frequently confused with static electric phenomena; he distinguished them clearly and definitively. With ample experimental evidence, he demonstrated that the earth itself is a huge magnet, and he insisted that attraction is only one among five magnetic phenomena (or "motions" as he called them). The other four, direction, variation (we say declination), dip and rotation, were all related to the magnetic field of the earth, and assumed greater importance than attraction in Gilbert's eyes.

Gilbert's book, in which so many facts familiar to the student of elementary physics are established on firm evidence, has frequently been hailed as the first example of modern experimental science in action. When we read the work closely, however, and attempt to understand, not solely what modern science has appropriated, but what Gilbert himself maintained, much that is less familiar appears. The title already promises more than the reader from the 20th century expects in a text on magnetism—*Concerning the Magnet, Magnetic Bodies, and the Great Magnet the Earth: a New Physiology Demonstrated both by Many Arguments and by Many Experiments.* A new physiology—that is, a new philosophy of nature—Gilbert saw magnetism, not as one phenomenon among the many which nature displays, but as the key to understanding the whole. The whole, as he understood it, was no less occult and mysterious than the fabled powers of the magnet which he tested so carefully.

Whereas electric attraction is a corporeal action wrought by invisible effluvia, magnetic attraction is an incorporeal power in Gilbert's philosophy. Material bodies do not obstruct it; a magnet attracts iron through glass or wood or paper. If iron can shield a body from attraction, it does so, not by blocking the power, but by diverting it. Especially revealing in his eyes was the ability of a loadstone to excite the magnetic faculty of a piece of iron without suffering any loss in its own potency. Iron (or loadstone, for the two are really identical in his opinion) is genuine telluric matter. Magnetism is its innate virtue, a power it loses only with difficulty and stands ever ready to regain. Utilizing the categories of Aristotelian metaphysics, he argued that if electricity is the action of matter, magnetism is the action of form. Magnetism is the active principle in primal earth matter.

> "Magnetic bodies attract by formal efficiencies or rather by primary native strength. This form is unique and peculiar: it is the form of the prime and principal globes; and it is of the homogeneous and not altered parts thereof, the proper entity and existence which we may call the primary radical, and astral form; not Aristotle's prime form, but that unique form which keeps and orders its own globe. Such form is in each globe—the sun, the moon, the stars—one; in earth 'tis one, and it is that true magnetic potency which we call the primary energy."

As he said in another place, "True earth-matter is endowed with a primordial and an energic form." In perhaps more revealing terms, he identified magnetism as the soul of the earth.

"Attraction" is the wrong word to apply to magnetic action. As Gilbert said, attraction implies force and coercion; it applies properly to electrical action. Magnetic motion, in contrast, expresses voluntary agreement and union. Inevitably the two poles suggested the two sexes, and in language less suited to the Age of the Reformation than to the Restoration, he spoke of the loadstone embracing iron and conceiving magnetism in it. The other magnetic actions seemed more significant to Gilbert than the so-called attraction. Direction, variation, dip—these motions (or rotations) express the underlying intelligence that organizes the cosmos. Gilbert regarded north and south as real directions in the universe, and the magnetic soul of the earth exists to order and to arrange. The compass was "the finger of God," and iron deprived of its magnetism was said to wander lost and directionless. The needle's dip measures latitude; perhaps variation could be used to measure longitude. In Gilbert's fifth motion, revolution, reason itself was ascribed to the magnetic soul of the earth. By "revolution," he referred to the diurnal rotation of the earth upon its axis, a motion he traced to magnetism just as he traced to it the steady direction of the earth's pole as it circles the sun. Placed near the sun, Gilbert asserted, the earth's soul perceives the sun's magnetic field, and reasoning that one side will burn while the other freezes if it does not act, it chooses to revolve upon its axis. It even chooses to incline its axis at an angle in order to cause the variation of seasons.

The first exemplar of modern experimental science turns out to be a very strange book indeed. That is, to the mind of the 20th century it is strange. In the year 1600, however, it must have appeared very familiar because it expressed a prevalent philosophy of nature, what has been called Renaissance Naturalism. To Gilbert, as to many others of his age, nature appeared veritably to pulse with life. The magnetism of primal earth matter corresponded to the active principles present in all things. Matter is never found without life. Neither is it found without perception. As magnetic bodies join in voluntary agreement and union, so sympathies and antipathies, by which likes respond to likes and reject unlikes, relate all bodies one to another. Magnetic attraction indeed was the prime example of the occult virtues that pervaded the animistic universe of Renaissance Naturalism. Gilbert's very empiricism reveals itself as an aspect of the same philosophy. Where Scholastic Aristotelianism had asserted the rational order of nature which the human intellect could probe, the natural philosophy of the 16th century proclaimed the mystery of a nature opaque to reason. Experience, and experience alone, could learn to know the occult forces pervading the universe. As the words "sympathy" and "antipathy" suggest, and as Gilbert's magnetic soul clearly reveals, the occult forces of nature were conceived in psychic terms. Renaissance Naturalism was a projection of the human psyche onto nature, and all of nature was pictured as a vast phantasmagory of psychic forces. Gilbert's *De magnete* was a relatively restrained if unmistakable expression of an established approach to nature.

If the 16th century was the heyday of Renaissance Naturalism, Gilbert was by no means its last representative. Its influence shaped the characteristic conceptions of the Paracelsian chemists of the early 17th century, and in Jean-Baptiste van Helmont (1579–1644) it found a last great figure. It is well known that van Helmont regarded water as the matter from which all things are formed. In a famous experiment, he planted a small tree in a carefully weighed quantity of earth, watered it faithfully, and after it had grown a considerable amount, separated the earth from the roots and weighed it again. The earth had scarcely diminished in quantity, and all of the increased weight of the tree must therefore have derived from the water, converted now to solid wood. In van Helmont's mind, the experiment with the tree fitted neatly into a vitalistic natural philosophy. Water—that is, matter—represents the female principle which requires for its fertilization and animation the male seminal or vital principle. No individual thing is generated in nature, he said, not limiting the statement to what we consider organic today, "but by a getting of the water with childe." Of course, the vital or seminal principle constitutes the ultimate essence of every being, the very source of what it is and does. He referred to it as the image of the master workman, not a dead image but one with "full knowledge" of what it must do and with the power to fulfill itself. The vital principle "doth cloath himself presently with a bodily cloathing;" and molding the matter to the image, it creates the body it animates.

To van Helmont as to Gilbert, magnetic attraction, far from appearing anomalous, represented the very model of action in an animate world. There are, he said, "a Magnetism, and Influential Virtues, every where implanted in, and proper to things." All things are equipped with perception of a sort whereby they perceive those bodies that are like them and those that are foreign—what he called sympathies and antipathies. One of van Helmont's favorite themes was the sympathetic unguent which cures wounds by being applied, not to the wound, but to the weapon which inflicted it. A similar principle explained why the blood of a murdered man runs when the murderer comes near—the spirit in the blood, perceiving the presence of the mortal enemy, boils in rage, and the blood flows. Helmont saw his doctrine as a conscious rejection of materialism, as an assertion of the primacy of spirit. In Aristotelian philosophy, what he referred to in a striking phrase as the "whorish appetite" of matter was given an active role in nature. Quite the contrary, he asserted, the material world "is on all sides governed and restrained by the Immaterial and Invisible."

How can man gain knowledge of the vital principles which constitute the reality of nature? Certainly not by the discursive faculty of reason, which ever falsifies and distorts. "Logick," van Helmont proclaimed, "is unprofitable," and "nineteen Syllogismes do not bring forth knowledge." Instead of reason, which dwells on the surface, understanding alone is adequate to the truth of things. The intellect must be drawn down into the deep; the understanding must transform itself "into the form of the things intelligible; in which point of time indeed, the understanding for a moment is made (as it were) the intelligible thing it self." Things "seem to talk with us without words, and the understanding pierceth them being shut up, no otherwise than as if they were dissected and laid open." Only the understanding, by an immediate intuition of truth, knows things as they are, and knowing things, knows their operations.

In the tradition of Renaissance Naturalism, we are clearly dealing with an ideal of scientific knowledge utterly different from the one we hold. It is the ideal of Faust, the scientist-magician, whose knowledge is of the occult powers of nature.

> "Why are we so sore afraid of the name of Magick? [van Helmont asked.] Seeing that the whole action is Magical; neither hath a thing any Power of Acting, which is not produced from the Phantasie of its Form and that indeed Magically. But because this Phantasie is of a limited Identity or Sameliness, in Bodies devoid of choice, therefore the Effect hath ignorantly and indeed rustically stood ascribed, not to the Phantasie of that thing, but to a natural Property; they indeed, through an Ignorance of Causes, substituting the Effect in the room of the Cause: When as after another manner, every Agent acts on its proper Object, to wit, by a fore-feeling of that Object, whereby it disperseth its Activity, not rashly, but on that Object only; to wit, the Phantasie being stirred after a sense of the Object, by dispersing of an ideal Entity, and coupling it with the Ray of the passive Entity. This indeed hath been the magical Action of natural things. Indeed Nature is on every side a Magitianess."

To which Descartes replied in the following terms:

> "We naturally have greater admiration for things which are above us than those on the same level or below us. And although the clouds are scarcely higher than the summits of some mountains, nevertheless, because we must turn our eyes toward heaven to look at them, we imagine them to be so elevated that poets and painters see in them the throne of God. All of which leads me to hope that if I explain the nature of clouds in this treatise well enough that there will no longer be any occasion to admire anything that we see in them or that descends from them, it will be readily believed that it is possible in the same way to discover the causes of everything above the earth that appears admirable."

In the 17th century, Descartes spoke for the ascendant school of natural philosophy, whereas van Helmont's voice was one of the last echoes in a fading tradition. Renaissance Naturalism rested ultimately on the conviction that nature is a mystery which in its depth human reason can never plumb. Descartes' call for the abolition of wonder by understanding, on the other hand, voiced the confident conviction that nature contains no unfathomable mysteries, that she is wholly transparent to reason. On this foundation, the 17th century constructed its own conception of nature, the mechanical philosophy.

No one man created the mechanical philosophy. Throughout the scientific circles of western Europe during the first half of the 17th

century we can observe what appears to be a spontaneous movement toward a mechanical conception of nature in reaction against Renaissance Naturalism. Suggested in Galileo and Kepler, it assumed full proportions in the writing of such men as Mersenne, Gassendi, and Hobbes, not to mention less well known philosophers. Nevertheless, René Descartes (1596–1650) exerted a greater influence toward a mechanical philosophy of nature than any other man, and for all his excesses, he gave to its statement a degree of philosophic rigor it sorely needed, and obtained nowhere else.

In the famous Cartesian dualism, he provided the reaction against Renaissance Naturalism with its metaphysical justification. All of reality, he argued, is composed of two substances. What we may call spirit is a substance characterized by the act of thinking; the material realm is a substance the essence of which is extension. *Res cogitans* and *res extensa* —Descartes defined them in a way to distinguish and separate them absolutely. To thinking substance one cannot attribute any property characteristic of matter—not extension, not place, not motion. Thinking, which includes the various modes which mental activity assumes, and thinking alone, is its property. From the point of view of natural science, the more important result of the dichotomy lay in the rigid exclusion of any and all psychic characteristics from material nature. Gilbert's magnetic soul of the world could have no place in Descartes' physical world. Neither could the active principles of van Helmont—Descartes' choice of the passive participle, *extensa,* in contrast to the active participle, *cogitans,* which he used to characterize the realm of spirit, served to emphasize that physical nature is inert and devoid of sources of activity of its own. In Renaissance Naturalism, mind and matter, spirit and body were not considered as separate entities; the ultimate reality in every body was its active principle, which partook at least to some extent of the characteristics of mind or spirit. The Aristotelian principle of "form" had played an analogous role in a more subtle philosophy of nature. The effect of Cartesian dualism, in contrast, was to excise every trace of the psychic from material nature with surgical precision, leaving it a lifeless field knowing only the brute blows of inert chunks of matter. It was a conception of nature startling in its bleakness—but admirably contrived for the purposes of modern science. Only a few followed the full rigor of the Cartesian metaphysic, but virtually every scientist of importance in the second half of the century accepted as beyond question the dualism of body and spirit. The physical nature of modern science had been born.

Descartes was fully aware of his revolutionary role in regard to the received philosophic tradition. In his *Discours de la Méthode** (1637), he described his reaction to that tradition as his education had introduced him to it. He had entered upon his education filled with the promise that at its conclusion he would possess knowledge. Far from knowledge, alas, it left him with total doubt. Two thousand years of investigation and argument, he came to realize, had settled nothing. In philosophy, "one cannot imagine anything so strange and unbelievable but that it has been upheld by some philosopher." Descartes decided simply to sweep his mind clear of the past. By a process of systematic doubt, he would subject every idea to a rigorous examination, rejecting everything the least bit dubious until he should come upon a proposition, if such there were, that was impossible to doubt. On such a proposition as a rock of certainty, he could rebuild a structure of knowledge that shared the certainty of its foundation, a structure built anew from the very bottom by reason alone. With the perspective of hindsight, we can see that his repudiation of the past was far less complete than he thought. Nevertheless, his mechanical philosophy of nature was a sharp break with the prevailing conception as represented by Renaissance Naturalism, and scarcely less of a break with Aristotelianism; and in his sensation of making a fresh start he spoke for 17th century science as a whole.

As everyone knows, Descartes found the rock of certainty for which he was searching—that which could not be doubted—in the proposition, *"cogito ergo sum"* (I think, therefore I am). The *cogito* became the foundation of a new edifice of knowledge. From it, he reasoned to the existence of God, and then to the existence of the physical world. In the process of doubt, the existence of a world outside himself had been one of the first items to go; its existence had appeared to depend on the evidence of the senses, and the manifest propensity of the senses to err had called its existence into doubt. From the new foundation of certainty, he now felt able to demonstrate, as a conclusion also beyond doubt, that the physical world external to himself does exist. But to the conclusion he added a condition, perhaps the most important statement made in the 17th century for the work of the scientific revolution. Although the existence of the physical world can be proved by necessary arguments, there is no corresponding necessity that it be in any way similar to the world the senses depict. On the heap of sympathies, antipathies, and occult powers already pruned from the physical world were now thrown the real qualities of Aristotelian philosophy. A body appears red, Aristotle had said, because it has redness on its surface; a body appears hot because it contains the quality of heat. Qualities have real existence; they comprise one of the categories of being; by our senses we perceive reality directly. Not so, Descartes retorted. To imagine that redness or heat exist in bodies is to project our sensations onto the physical world, exactly as Renaissance Naturalism projected psychic processes onto the physical world. In fact, bodies comprise only particles of matter in motion, and all their apparent qualities (extension alone excluded) are merely sensations excited by bodies in motion impinging on the nerves. The familiar world of sensory experience turns out to be a mere illusion, like the occult powers of Renaissance Naturalism. The world is a machine, composed of inert bodies, moved by physical necessity, indifferent to the existence of thinking beings. Such was the basic proposition of the mechanical philosophy of nature.

In essays on *La dioptrique* (1637) and *Les météores* (1637), and in the *Principia philosophiae** (1644), Descartes spelled out the details of his mechanical philosophy. One of its foundation stones was the principle of inertia. The mechanical philosophy insisted that all the phenomena of nature are produced by particles of matter in motion—that they must be so produced since physical reality contains only particles of matter in motion. What causes motion? Since matter is by definition inert stuff consciously pruned of active principles, it is obvious that matter cannot be the cause of its own motion. In the 17th century, everyone agreed that the origin of motion lay with God. In the beginning, He created matter and set it in motion. What keeps matter in motion? The very insistence with which the mechanical conception of nature repudiated active principles meant that its viability as a philosophy of nature depended on the principle of inertia. Nothing is required to keep matter in motion; motion is a state, and like every other state in which matter finds itself, it will continue as long as nothing external operates to change it. In impact, motion can be transferred from one body to another, but motion itself remains indestructible.

Descartes attempted to analyze impact in terms of the conservation of the total quantity of motion, a principle which approaches the conservation of momentum formulated later in the century. Since he held that a change in direction alone (without any change in speed)

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* *Discourse on Method.*

* *Dioptrics, Meteorology, Principles of Philosophy.*

entails no change in the state of another body, the conclusions at which he arrived vary widely from those we accept. Nevertheless, Descartes' analysis of impact was the starting point of later efforts that bore more fruit. Meanwhile, his rules of impact provided the model of all dynamic action; in a mechanical universe shorn of active principles, bodies could act on one another by impact alone.

It was no accident that the men who constructed the two leading mechanical systems of nature, Descartes and Gassendi, also contributed significantly to the formulation of the concept of inertia. With Galileo, inertia was stated in terms of circular motion corresponding to the diurnal rotation of the earth on its axis. Descartes and Gassendi were the first to insist that inertial motion must be rectilinear motion and that bodies that move in circles or curves must be constrained by some external cause. Such bodies, Descartes asserted, constantly exert a tendency to recede from the center around which they turn. Although he did not attempt to express a quantitative measure of the tendency, his demonstration that such a tendency to recede from the center exists was the first step in the analysis of the mechanical elements of circular motion.

If circular motion ceased to represent perfect motion to Descartes, it continued to play a central role in his philosophy of nature. Although it was not natural, nevertheless it was necessary. Descartes' universe was a plenum. The equation of matter with extension meant that every extended space must, by definition, be filled with matter—or better, must be matter. There can be no vacuum. If there is no empty space into which a body can move, how is it possible that there be any motion at all? It is possible, Descartes replied, only because every body that moves moves into the space that it vacates, as it were, at the same time. Put in other terms, every moving particle in a plenum must participate in a closed circuit of moving matter, like the rim of a wheel turning on its axis. Hence every motion must be circular—although, of course, the word "circular" in this context refers to a closed orbit of some shape, not to the perfect circle of Euclidean geometry. Because circular motion, though necessary, is unnatural, it sets up centrifugal pressures in the plenum. Descartes traced the major phenomena of nature to such pressures.

The first consequence of the introduction of motion into the infinite plenum that is our universe is the establishment of an infinite number of vortices. Descartes pictured the vortex in which our solar system is located as a whirlpool of matter so huge that the orbit of Saturn is to the whole no more than a point. Most of the vortex is filled with tiny balls turned into perfect spheres by the incessant bumping of one on another. These he referred to as the "second element." The "first element," the "aether" as it was often referred to in the 17th century, is composed of the extremely fine particles which fill up the spaces between the spheres of the second element and all other pores as well. There is also a third form of matter in Descartes' universe, bigger particles which are collected into the large bodies we call planets. As the whole vortex whirls about its axis, every particle in it endeavors to recede from the center, but in a plenum one particle can move away from the center only if another moves toward it. Like every other body, each planet tends to recede from the center, but at some distance from the center its tendency to recede is just balanced by the tendency of the swiftly moving matter of the vortex beyond it. An orbit is established by the dynamic balance between the centrifugal tendency of a planet and the counterpressure arising from the centrifugal tendency of the other matter composing the vortex.

The vortical theory constituted the first apparently plausible system designed to replace the crystalline spheres. To be sure, Kepler's celestial mechanics had preceded it, but Kepler's system had been constructed on principles unacceptable to the mechanical philosophy. Descartes' vortex, needless to say, was acceptable, and for half a century it dominated physical accounts of the heavens. To understand scientific thought in the 17th century, it is important to realize what it pretended to explain and what it did not pretend to explain. The vortex offered a mechanical account of the gross celestial phenomena. It explained why the planets are carried about the sun, all in the same direction and all in (about) the same plane. By the covert introduction of arbitrary factors, it explained why the planets move more slowly the further they are removed from the sun. These things it explained, moreover, as the necessary consequences of matter in motion, without recourse to any occult powers. To science in the 17th century, the type of mechanical explanation that the vortex offered was important, and it is not difficult to understand the theory's appeal. What the vortex made no attempt to treat were the precise details of planetary orbits which constituted the domain of technical astronomy. Kepler's three laws were not mentioned by Descartes, and it is hard to see how he could have derived them from the vortex. But the sort of mathematical description that Kepler's laws represent was also important to 17th century science. The mechanical philosophy, with its concentration on physical causation, existed in tension with the Pythagorean tradition of mathematical description. The highest achievement of science in the 17th century, the work of Isaac Newton, consisted in the resolution of that tension.

The solar system was not the sole topic of Descartes' philosophy of nature. It was also not the most difficult. As its fundamental proposition, the mechanical philosophy asserted that all the phenomena of nature are produced by inert matter in motion. What about light? No philosophy of nature that ignores light can pretend to be complete, and light appears to be the least obviously mechanical of all phenomena. In Descartes' system, however, it stands revealed as a necessary mechanical consequence of the vortex. The sun is the principal source of light in our system, and the sun is also at the center of the vortex. We have already seen that circular motion sets up centrifugal pressures throughout the vortex, and the physical reality of light is nothing more than such pressure. Received on the retina of the eye, it causes a motion in the optic nerve which in turn produces the sensation we call "light." Moreover, Descartes added, since pressure is a tendency to motion, it obeys the laws of motion, and the laws of reflection and refraction can be shown to follow as necessary consequences.

Gravity (i.e., *gravitas,* the heaviness of bodies near the surface of the earth) scarcely appears more mechanical in origin than light. To explain it, Descartes posited a small vortex around the earth, turning with the earth and terminating at the height of the moon. Again the centrifugal tendencies inherent in circular motion were called upon, and again the necessities of the plenum. What is gravity? It is a deficiency of centrifugal tendency by which some bodies are forced down toward the center by others, with a greater centrifugal tendency, which rise. It emerged as a regrettable consequence of Descartes' theory that bodies should fall, not along the perpendicular to the surface of the earth, but along the perpendicular to the axis. Mechanical philosophers, who were concerned to reveal the cause of every phenomenon, had to learn to tolerate minor discrepancies.

Perhaps the crucial case for the mechanical philosophy of nature was magnetism. To an earlier age, it had represented the very epitome of an occult power. Correspondingly, the mechanical philosophy had to explain away magnetic attraction by inventing some mechanism that would account for it without recourse to the occult. Descartes' was particularly ingenious. In considerable detail, he described how the turning of the vortex generates screw-shaped particles which fit similarly shaped pores in iron. (See Fig. 2.1.) Magnetic attraction is caused by

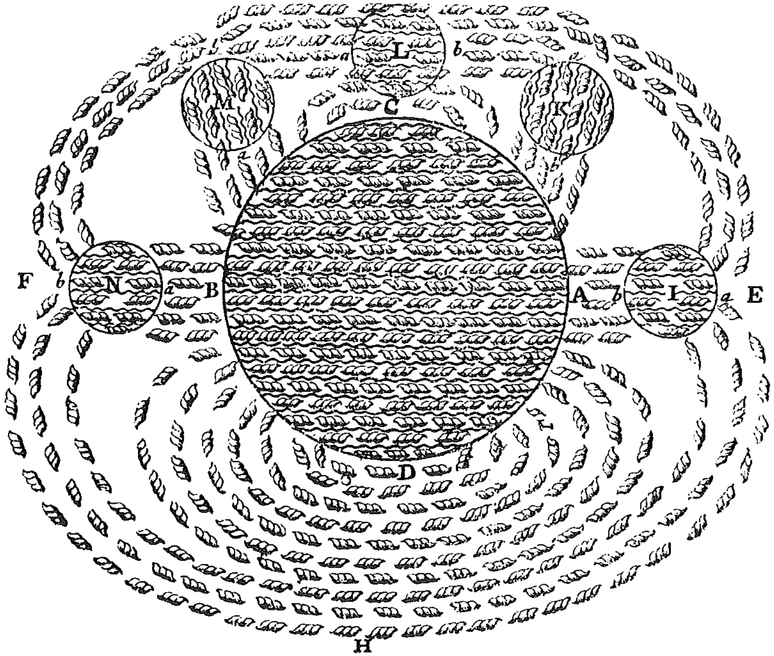

Figure 2.1. The screw-shaped pieces which cause magnetic action pass through the earth and through five loadstones shown in various positions as they align with the earth's magnetic field.

the motion of the particles, which in passing through the pores in magnets and iron, drive the air from between the two and cause them to move together. What about the fact of two magnetic poles? Very simple, Descartes replied; there are left-handed screws and there are right-handed screws.

The treatment of magnetism is revealing of the basic motivations of Cartesian science. In contrast to Gilbert, Descartes did not undertake a detailed investigation of magnetic phenomena. He regarded the phenomena as given; there was no need to confuse himself by searching for more. The problem was not the phenomena but their interpretation, and Descartes' purpose was to demonstrate that there are no magnetic phenomena which cannot be explained in mechanical terms. In the same way, when his *Principles of Philosophy* came to the detailed discussion of nature, Descartes assumed that the phenomena were known. His science was not devoted to careful investigations of nature, not to the discovery of new phenomena, but to the elaboration of a new explanation of those already known. There is no necessity that the physical world be similar in any way to the one our senses depict; it consists solely of particles of matter in motion. Descartes' purpose was to show that for all known phenomena causal mechanisms can be imagined. Since the mechanical philosophy as such offered no criteria of what is possible, some rather strange phenomena found their way into Descartes' universe. Helmont's discussion of blood running when the murderer approaches strikes us as the epitome of absurdity; Descartes accepted the fact and imagined an effluvial mechanism to explain it. The sympathetic unguent did not appear in his work, but Kenelm Digby, a mechanical philosopher of the following generation, duly described the invisible mechanism by which it cures.

Earlier philosophies had seen nature in organic terms. Descartes turned the tables by picturing even organic phenomena as mechanisms. In his universe, man was unique—the one living being which was both soul and body. Even in the case of man, however, the soul was not considered to be the seat of life, and all organic functions were described in purely mechanistic terms. The heart became a tea kettle, its heat analogous to the heat of fermentation (in itself a mechanical process to Descartes), its action the boiling and expansion of the drops of blood which were forced into it from the veins and forced on by the pressure of vaporization. Other animals, lacking a rational soul, were nothing but complicated machines. If there were automata, Descartes asserted, "possessing the organs and outward form of a monkey or some other animal without reason, we should not have had any means of ascertaining that they were not of the same nature as those animals."

Many of Descartes' explanations of phenomena differ so widely from those we now believe to be correct that we are frequently tempted to scoff. We must attempt rather to understand what he was trying to do and how it fit into the work of the scientific revolution. The cornerstone of the entire edifice of his philosophy of nature was the assertion that physical reality is not in any way similar to the appearances of sensation. As Copernicus had rejected the commonsense view of an immovable earth, and Galileo the commonsense view of motion, so Descartes now generalized the reinterpretation of daily experience. He did not intend to conduct the sort of scientific investigation we are familiar with today. Rather his purpose was metaphysical—he proposed a new picture of the reality behind experience. However wild and incredible we find his explanations, we must remember that the whole course of modern science has been run, not by returning to the earlier philosophy of nature, but by following the path he chose.

Certainly the 17th century found the appeal of the mechanical philosophy of nature overwhelming. The mechanical philosophy did not mean solely the Cartesian philosophy, however, and among other mechanical approaches to nature, one at least stood as a viable and attractive alternative, Gassendi's atomism. Inevitably, the atomic philosophy of antiquity had reappeared in western Europe with the general recovery of ancient thought during the Renaissance. Galileo had felt its influence, and its mechanistic treatment of nature probably helped to shape Descartes' system. It remained, however, for a contemporary of Descartes, Pierre Gassendi (1592–1655), to espouse and expound atomism as an alternative mechanical philosophy. As a thinker, Gassendi was utterly unlike Descartes. Where Descartes saw himself as a systematic philosopher rebuilding the philosophic tradition on new principles of his own creation, Gassendi considered himself as a scholar drawing together the best elements that the tradition could offer. His principal work, *Syntagma Philosophicum** (1658), is an unreadable compilation of everything ever said on the topics discussed, a compilation further which intended to exhaust discussable topics. The work grew like Topsy, and was published in its ultimate form only as a posthumous work, when the author was finally beyond the possibility of adding and patching. In a word, Gassendi was the original scissors and paste man, and his book contains all the inconsistencies of eclectic compilations. At least three different conceptions of motion are put forward in it with no effort whatever to reconcile them. From the tradition one system appealed to him above the others, however, and the *Syntagma* was unmistakably an exposition of atomism.

Being an atomist, Gassendi differed from Descartes on certain specific questions. Descartes argued that matter is infinitely divisible; Gassendi of course maintained that there are ultimate units which are never divided. The very word "atom" derives from the Greek word for indivisible. Descartes' universe was a plenum; Gassendi in contrast argued for the existence of voids, spaces empty of all matter. Both issues are important philosophic questions, but the disagreements of the two men pale beside their large areas of agreement. They asserted

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* *Philosophical Treatise.*

alike that physical nature is composed of qualitatively neutral matter, and that all the phenomena of nature are produced by particles of matter in motion.

Far more important for later science was another difference between Descartes and Gassendi which was logically connected with the question of the plenum. Descartes' insistence that nature is a plenum was the necessary consequence of his identification of matter with extension, and the identification of matter with extension in turn made possible the utilization of geometric reasoning in science. Because geometric space is equivalent to matter, natural science might hope to attain the same rigor in its demonstrations that geometry was agreed to have. Indeed his method, four rules to govern investigations, was little more than a restatement of the principles of geometric demonstration. Rebel against the prevailing tradition though he was, Descartes accepted an ideal of science that went back to Aristotle. It held that the name "science" applies, not to conjectures, not to probable explanations, but solely to necessary demonstrations rigorously deduced from necessary principles. If such a degree of certainty could not be attained in the details of causal explanations, where it was possible to imagine more than one satisfactory mechanism, at least the general principles were beyond doubt—the rigorous separation of the corporeal from the spiritual, and the consequent necessity of mechanical causation.

When Gassendi denied the equation of matter with extension, he denied as well the program of Cartesian science. Atoms are extended, but extension is not their essence. He was convinced indeed that knowledge of the essence of things is beyond the reach of finite man. Gassendi accepted a degree of skepticism as an inevitable ingredient of the human condition. God and God alone can know ultimate essences. Hence the ideal of science held by the dominant school of philosophy in the western tradition from Aristotle to the 17th century and reaffirmed by Descartes was labelled an illusion. Thoroughgoing skepticism was not Gassendi's conclusion, however; he offered instead a redefinition of science. Nature is not completely transparent to human reason; man can know her only externally, only as phenomena. It follows that the only science possible to man is the description of phenomena, a new ideal of science which found its earliest statement in Gassendi's logical writings. Implicit already in Galileo's description of the uniform acceleration of free fall whatever its cause, the ideal was stated formally by Gassendi as part of his denial of the traditional one. It was not an easy conception to grasp, and mechanical philosophers in the 17th century continued to imagine microscopic mechanisms to "cause" natural phenomena. In Isaac Newton, however, Gassendi found a follower, and in the work of Newton, his definition of science demonstrated what it could foster. It has become so deeply ingrained in the procedures of modern experimental science that we find it difficult today to comprehend the Cartesian (and Aristotelian) ideal of necessary demonstrations —although that ideal appeared self-evident to men before the 17th century.

Gassendi's discussions of method were one thing; Gassendi's practice was something else. In the bulk of his work, where he took up the details of natural philosophy, fine phrases about restricting science to the description of phenomena could not restrain him from the occupational vice of mechanical philosophers, the imaginary construction of invisible mechanisms to account for phenomena. In many ways, the qualitative philosophy of Aristotle reappeared in disguise in his writings; that is, special particles with special shapes were posited to account for specific qualities. Descartes equated heat with the motion of the parts of bodies and considered coldness as the absence of heat. Gassendi, on the other hand, spoke of calorific and frigorific particles. Nevertheless, by insisting on particles and allowing differences solely in shape and motion, he maintained allegiance to the basic principles of the mechanical philosophy of nature. Robert Boyle, a leading mechanical philosopher as well as chemist of the following generation, treated atomism and Cartesianism as two expressions of the same conception of nature. We owe the name, "mechanical philosophy," to Boyle. As he summed it up, the mechanical philosophy traces all natural phenomena to the "two catholic principles," matter and motion. He might have added that by "matter" the mechanical philosophy means qualitatively neutral stuff, shorn of every active principle and of every vestige of perception. Whatever the crudities of the 17th century's conception of nature, the rigid exclusion of the psychic from physical nature has remained as its permanent legacy.

Meanwhile, in the 17th century, the mechanical philosophy defined the framework in which nearly all creative scientific work was conducted. In its language questions were formulated; in its language answers were given. Since the mechanisms of 17th century thought were relatively crude, areas of science to which they were inappropriate were probably frustrated more than encouraged by its influence. The search for ultimate mechanisms, or perhaps the presumption to imagine them, diverted attention continually from potentially fruitful enquiries and hampered the acceptance of more than one discovery. Above all, the demand for mechanical explanations stood in the way of the other fundamental current of 17th century science, the Pythagorean conviction that nature can be described in exact mathematical terms. Despite its rejection of a qualitative philosophy of nature, the mechanical philosophy in its original form was an obstacle to the full mathematization of nature, and the incompatibility of the two themes of 17th century science was not resolved before the work of Isaac Newton. Meanwhile, virtually no scientific work in the 17th century stood clear of its influence, and most of the work cannot be understood apart from it.

CHAPTER III

Mechanical Science

THE PROMINENCE which a set of long-known phenomena suddenly acquired in the middle of the 17th century can be attributed to the rise of the mechanical philosophy and mechanical modes of explanation. The cupping glass, a glass heated and placed over a sore, was an ancient instrument for drawing infected matter. It was known likewise that water does not run out of a narrow-necked bottle when it is filled and inverted. The operation of pumps and syphons was analogous. In their case, perhaps, an effect appeared that was disturbingly non-analogous. Pumps would not draw water more than about thirty-four feet and syphons would not operate over hills of more than that height. In both cases, however, it was universally agreed that imperfections in the materials caused the failure. Since the pipes in use were of wood, the conclusion was not without apparent justification. In the established philosophy of nature, all of the phenomena were referred to nature's abhorrence of a vacuum, an explanation which embodied the principles the mechanical philosophy had been created to destroy. It implied that nature has sensitive and active faculties by which she perceives threats to her continuity and moves to oppose them. For such phenomena, moreover, alternative mechanical explanations were obvious.

A passage in Galileo's *Discourses,* published in 1638, effectively started the debate. As part of his analysis of the breaking strength of beams, Galileo needed a theory of the cohesion of bodies. The observed fact that a syphon carries water over a maximum height of about thirty-four feet seemed to offer a foundation on which to build. Above all, it provided an exact quantitative factor, the weight of a unit column of water some thirty-four feet high. He attributed the column of water to what he called the attraction of the vacuum; and arguing that bodies

CHAPTER V

Biology and the Mechanical Philosophy

THE RAPID ACCELERATION of scientific enquiry in the 17th century was not confined to the physical sciences. If in the end the proudest achievements were recorded in that area, nevertheless biology (though it was not yet given that name) received an immense investment of attention and witnessed considerable discoveries as well. The concept of a scientific revolution has validity for the organic sciences as well as the inorganic.

During the century, a flood of new information swept over the life sciences. Overseas exploration brought knowledge of a host of new plants and animals; the microscope revealed new realms of life; intensified anatomical research uncovered new information about what had been considered well known. Thomas Moffett's attempt to classify grasshoppers revealed the dangers in too much information.

> "Some are green, some black, some blue. Some fly with one pair of wings, others with more; those that have no wings they leap, those that cannot either fly or leap, they walk; some have longer shanks, some shorter. Some there are that sing, others are silent. And as there are many kinds of them in nature, so their names are almost infinite, which through the neglect of Naturalists are grown out of use."

The deluge of new knowledge beyond the power of biology immediately to assimilate suggests a major difference from physics. The revolution in physical concepts was a matter primarily, not of new facts, but of new ways of looking at old facts. In contrast, biological science witnessed for the most part an enormous expansion of its body of factual information, providing material which a later age employed to reconstruct the categories of biological thought.

In such a situation, taxonomy inevitably assumed great importance. Whereas Gaspard Bauhin described some six thousand different species in his herbal from the early 17th century, John Ray included over eighteen thousand species in his *Historia plantarum generalis,** which appeared at the end of the century. Some system of classification was essential to organize such a body of data. By 1750, when Linnaeus' work marked a turning point in botany, no less than twenty-five systems had been proposed. Most of them were artificial, as botanists are wont to say, seizing arbitrarily on one characteristic as the criterion of classification instead of utilizing the whole plant and its natural affinities to form what is called the natural system. Whatever defects they embodied, the systems did succeed in organizing the immense number of species into manageable patterns, and they did prepare the way for the greater taxonomists of the 18th century.

Botany reached its highest level in the work of the Frenchman, Joseph Pitton de Tournefort (1656–1708), and the Englishman, John Ray (1627–1705). Tournefort was the first systematically to classify the categories higher than genera, dividing all plants into twenty-two classes, which in turn divide into families within which the genera find their place. Ray established the basic distinction of the monocotyledons and dicotyledons (plants which germinate with a single leaf and those which germinate with two). Tournefort contended that the genus is the most important category of classification and reformed nomenclature to express genera with names of one word. Ray insisted equally on the species as the ultimate unit. In the 18th century, Linnaeus drew on both to develop the binomial system of classification, in which plants are divided into genera and species, the two words in their names fully locating them in the system. The systems of both Tournefort and Ray were far from perfect, and botany recognizes Linnaeus above them both as its great taxonomist. The extent of Linnaeus' debt to their work, however, is witness to the contribution of 17th century naturalists.

In the case of zoology, the multiplicity of life forms combined with the very availability of a seemingly satisfactory system to inhibit similar progress. Success in botany was confined largely to plants with the familiar pattern of roots, stems, and leaves; difficult forms such as alga and moss presented unsolved enigmas and were put to the side as imperfect herbs. In contrast, zoology faced a multiplicity of forms which could not be avoided, such as quadrupeds, birds, reptiles, fish, shell-fish

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* *General History of Plants.*

and insects, to which microscopical life was added during the century. By apparent good fortune, however, the ancient world had provided in Aristotle a systematizer who reduced the bewildering variety to order. Undoubtedly the existence of the Aristotelian system helps to explain the fact that the 17th century devoted far less attention to zoological taxonomy than to botanical, and another century was to pass before zoology burst out of Aristotelian classification.

How heavily tradition weighed on zoology may be seen in the massive works of Aldrovandi which appeared between 1599 and 1616—in all ten folio volumes with more than seven thousand pages. Alas, most of the erudition was derivative. Of 294 pages devoted to the horse, three or four concerned themselves with its zoological characteristics while the rest presented a compilation of everything that had even been said about the temperament of horses, their use in war, their sympathies and antipathies, and so on. Aldrovandi followed the Aristotelian classification without question. Even though John Ray tried to reform the classification of sanguineous animals (we would say vertebrates) by using comparative studies of the circulatory and respiratory systems, he ended up with five classes virtually identical to Aristotle's. For all the defects it would later reveal, Aristotle's zoological classification did organize knowledge into coherent patterns—like the botanical systems, which were more original because they inherited less.

Taxonomy provided the broad framework within which biological knowledge was organized. Within the framework, detailed investigation of a wide variety of biological problems was carried on. Studies of individual organs filled in the outlines of human anatomy which Vesalius and his successors established during the 16th century. Anatomy today is full of names which commemorate the labors of 17th century investigators—Glisson's capsule, the Malpighian bodies, Wharton's duct, the aqueduct of Sylvius, Brunner's glands. The fact that few laymen have ever heard of the parts thus named testifies to the depth of the 17th century anatomy. Nor was anatomical research confined to the human body. During the second half of the century, similar detailed studies by Claude Perrault, Edward Tyson, and others were devoted to other species. Marcello Malpighi's *Dissertatio de bombyce** (1669) contained the first successful study of the internal organization of insect life. It is true that comparative anatomy did little more than suggest its own possibility during the 17th century, as the failure of taxonomists seriously to refine Aristotle's classification demonstrates. A beginning, however hesitant, is still a beginning, and comparative anatomy traces its history to the age of the scientific revolution.

No single thing contributed more to biological research during the century than the invention of the microscope, apparently in 1624. What the telescope was to astronomy the microscope was to biology. If Galileo's discovery of new planets (as he called the satellites of Jupiter) excited the imagination of Europe, the revelation of the microscope, that wholly unsuspected levels of life exist, not above us, but about us and within us, stimulated it more. "I have used the Microscope to examine bees and all their parts," Francesco Stelluti exclaimed in the first publication of microscopical observations. "I have also figured separately all members thus discovered by me, to my no less joy than marvel, since they are unknown to Aristotle and to every other naturalist." Stelluti got magnification of roughly five diameters. By the end of the century Anthony van Leeuwenhoek realized magnifications approaching three hundred diameters and observed forms of life Stelluti had not dreamed of. (See Fig. 5.1.) Even the cynicism of Jonathan Swift reflects the sensation he caused.

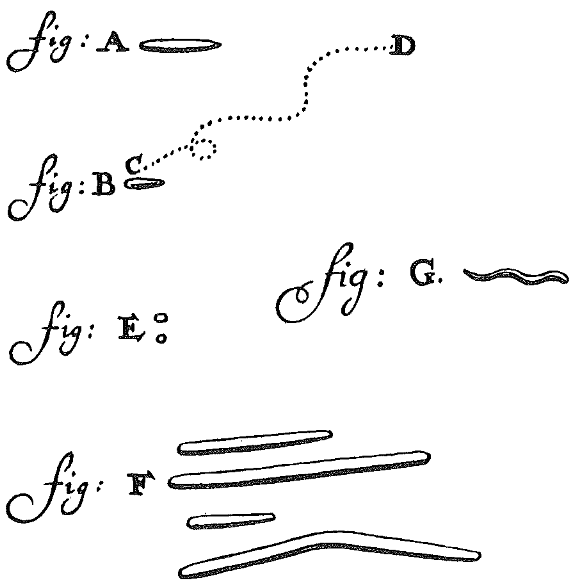

Figure 5.1. Leeuwenhoek's figures of bacteria from the human mouth.

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* *Treatise on the Silkworm.*

"Fleas, so naturalists say,
Have smaller fleas that on them prey.
These have smaller still to bite 'em,
And so proceed ad infinitum."

The second half of the 17th century was the heroic age of microscopy; the early observations were not improved on and seldom equaled before the 1830s. Leeuwenhoek (1632–1723) stands out as a giant even among the heroes. Using single lenses, more magnifying beads than microscopes, he achieved magnifications not repeated for over a century. Swift's fleas on fleas referred to Leeuwenhoek's little animals, infusoria and rotatoria observed in rain water. "When these *animalcula* or living Atoms did move, they put forth two little horns, continually moving themselves. The place between these two horns was flat, though the rest of the body was roundish, sharpning a little towards the end, where they had a tayl, near four times the length of the whole body, of the thickness (by my Microscope) of a Spiders-web; at the end of which appear'd a globul, of the bigness of one of those which made up the body." He observed spermatozoa, and he discovered the corpuscles of the blood,—"flat oval particles, swiming in a clear liquor." Just as more than a century had to pass before the observations were improved upon, so an equal period had to pass before their full significance was realized. Meanwhile they constituted a magnificent addition to the corpus of biological knowledge.

The immense expansion of biological knowledge—an expansion quite unequalled by the expansion of physical knowledge—was accompanied by a reconsideration of the nature of life as the mechanical philosophy extended its influence over the last stronghold of Aristotelianism. A comparison of two contemporaries, William Harvey and René Descartes, both of whom played major roles in the biological thought of the 17th century, reveals something of the complexities of the relationship between biology and the mechanical philosophy.

In an age when English medical education remained primitive, William Harvey (1578–1657) travelled to Padua in 1600 to study for his medical degree. Padua was the foremost center of medical science in Europe. There Vesalius had dissected and lectured, and there the succession of eminent anatomists who followed him was represented by Fabricius of Aquapendente during the period of Harvey's stay. The result of half a century's careful study conspired to raise doubts in Harvey's mind about the function and operation of the heart.

According to prevailing Galenic physiology, the liver is the primary organ of the body. (See Fig. 5.2.) Here food receives its first elaboration, being converted to blood. Imbued with natural spirits, blood flows from the liver through the system of veins to the organs and parts of the body, where it is absorbed as food. Part of the blood enters the right ventricle of the heart and seeps through pores in the septum, the partition separating the two ventricles, to enter the left ventricle where it undergoes a second elaboration in the presence of air, which enters from the lungs. What emerges from the left ventricle to be carried throughout the body by the arterial system is vital spirits, a fluid as different from blood as blood is from food. Part of the vital spirits that ascend to the brain undergo a third elaboration there and are converted to animal spirits, which are distributed through the nerves.

Galenic physiology, thus briefly summarized, held its ascendance partly because it expressed itself in conceptions acceptable to a premechanical age and partly because the functions it assigned to organs conformed to the facts of dissection. Rather, they conformed to the facts until Vesalius tried to find the pores in the septum and failed. Others

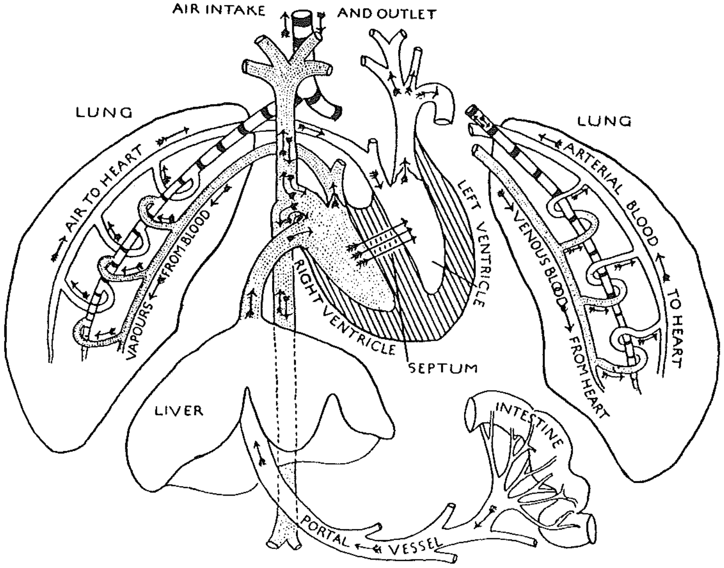

Figure 5.2. Diagram of action of heart and blood vessels according to Galen. Inset on right is a diagram of the circulation in the lung according to Servetus.

after him failed equally to find them. Fortunately, however, a second discovery made it possible to salvage Galenic physiology with minor revisions. Anatomists found that blood passes from the right ventricle to the left through the lungs. Those who established it considered the pulmonary transit as an alternate route now that passage through the septum was acknowledged to be closed. The venous and the arterial systems continued to be separate, each conveying a unique fluid throughout the body. Galenic physiology remained essentially intact.

Nor was it challenged by Fabricius' discovery of membranous pockets in the veins. We call the membranes "valves" and say that they prevent flow toward the extremities. Fabricius called them *"ostiola,"* little doors, and held that they merely obstruct flow in that direction, mitigating its excessive force so that the soft walls of the veins are not ruptured, slowing its rate sufficiently to allow the members to be nourished.

One further influence of Padua, its prevailing Aristotelianism, exerted itself on Harvey. In physiology, Aristotle had asserted the primacy of the heart in contrast to the primacy of the liver in Galenic physiology. Early in the 17th century, there was a great deal of talk among Aristotelians likening the heart in the body to the sun in the cosmos. Life-giving heat flows from both. The circular motion of the sun around the earth plays a significant role in cosmic processes. Should there not be a similar circulation of the heart? The association of a circulation with the heart was common in the literature of the period, although the word "circulation" held various meanings. One equated it with a cyclical repeating motion, such as systole and diastole. A chemical meaning, connected with distillation, suggested that blood is heated in the heart and condensed in the lungs.

The essential insight of Harvey was to apply the concept of circulation to the now established facts of anatomy and to insist that a mechanical meaning of circulation also be recognized. He began by reversing the accepted understanding of the heart's motion. Observing dogs in vivisection, (as one reads the 17th century physiologists, one is sometimes surprised that the canine species managed to survive) especially when the heart slowed down with approaching death so that its motion could be discerned more easily, he decided that the active motion of the heart is its contraction, the systole. In systole, he could feel the heart tense, and as it drew together its apex was thrust out striking the wall of the chest. Galenic physiology, in contrast, had considered expansion, diastole, to be the motion of the heart. When it expanded, the heart attracted, or "drew" a quantity of blood into it. The attraction was understood, not in mechanical terms analogous to a vacuum pump, but in terms reminiscent of the sympathies of Renaissance Naturalism. This conception, Harvey insisted, was wrong. The "intrinsic motion of the heart is not the diastole but the systole."

The further question immediately arose: what happens to the blood in the heart? Valves at the entrance to each ventricle are arranged in such a way that the blood cannot flow out through the passage by which it enters; valves at the exits prevent its re-entering again once it has left. (See Fig. 5.3.) Over and over, the same action repeats, each stroke thrusting a new quantity of blood after the one before. Blood from the right ventricle, of course, is driven through the lungs and into the left. What happens to that forced out of the left? To his insistence on the mechanical necessities of the heart, Harvey now added another argument wholly typical of 17th century science. By measuring the capacity of a dissected heart, he determined that a ventricle holds more than two ounces of blood; to be on the safe side, he assumed a maximum capacity of two ounces. Suppose that a fourth of it is driven out by each contraction; to be on the safe side, he set it as low as an eighth. And suppose the heart beats a thousand times in half an hour —again a figure deliberately too low. According to our present information, Harvey's calculation of the blood discharged by the heart was less than three percent of the true quantity. Never mind; his purpose was not measurement as such, but the polemic value of a quantitative argument deliberately understated. By a simple calculation, he showed that even with the underestimates the heart discharges more blood into the arteries in half an hour than the entire body contains. Where can it possibly go, but back to the heart by another route?

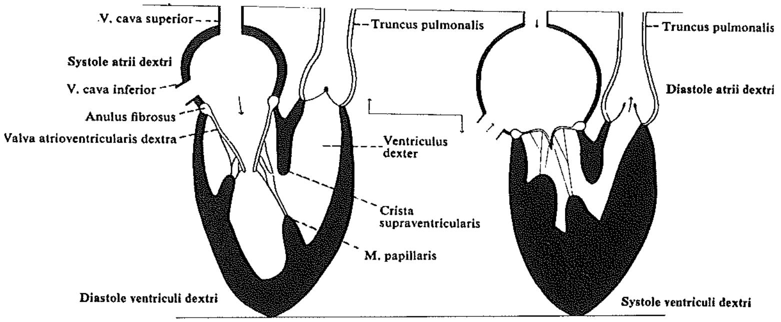

Figure 5.3. A modern diagram shows the action of the valves of the right ventricle in diastole and systole.

Harvey had demonstrated the necessity of circulation. The problem was to demonstrate as well that circulation is a fact. Without a microscope, he was unable to observe the capillaries which connect the arterial system to the venous. Nevertheless, by an ingenious experiment on himself, Harvey was able to show that the blood does pass from the arteries to the veins. Applying what was called a perfect ligature to his arm, he cut off both the veins and the artery. The arm gradually grew cold but did not change color; above the ligature the artery filled and throbbed. Loosening the ligature enough to free the artery while the veins remained blocked, he felt the surge of warmth as fresh blood was forced through his arm. Immediately, the arm became purple and the veins swelled visibly below the ligature. They had not been filled from the venous system which remained cut off; the blood had to reach them from the arteries.

The essence of Harvey's demonstration of the circulation of the blood lay in his attention to the mechanical necessities of the vascular system. On this question, the mechanical mode of thought, so spontaneous to the 17th century mind, could offer assistance to biological science. The heart functions as a pump moving a fluid through a closed circuit of conduits, a system reminiscent of the waterworks which ran the elaborate fountains admired by 17th century monarchs. As a paragraph among his lecture notes says,

> "From the structure of the heart it is clear that the blood is constantly carried through the lungs into the aorta *as by two clacks* [valves] *of a water bellows to rayse water.*"

The same William Harvey in the same book which expounded the circulation of the blood also called the heart "the beginning of life."

> "The heart is the sun of the microcosm, even as the sun in his turn might well be designated the heart of the world; for it is the heart by whose virtue and pulse the blood is moved, perfected, and made apt to nourish, and is preserved from corruption and coagulation; it is the household divinity which, discharging its function, nourishes, cherishes, quickens the whole body, and is indeed the foundation of life, the source of all action."

Although Harvey saw the heart as a pump, he did not see it solely as a pump, or even primarily as a pump. The circulation of the blood, the mechanical effect of a machine neatly contrived, exists to serve an end which is not mechanical. Its circulation recalls the cycle of evaporation and rain which emulates, as it is caused by, the "circular motion of the superior bodies" by which the generation of all living things is produced.

> "And so, in all likelihood, does it come to pass in the body, through the motion of the blood, that the various parts are nourished, cherished, quickened by the warmer, more perfect, vaporous, spirituous, and, as I may say, alimentive blood; which, on the contrary, in contact with these parts, becomes cooled, coagulated, and, so to speak, effete; whence it returns to its sovereign the heart, as if to its source, or to the inmost home of the body, there to recover its state of excellence or perfection. Here it resumes its due fluidity, and receives an infusion of natural heat—powerful, fervid, a kind of treasury of life, and is impregnated with spirits, it might be said with balsam, and thence it is again dispersed."

Harvey was a thorough-going Aristotelian who saw in the circulation of the blood one aspect of the primacy of the heart. Unlike his master, he insisted on the role of the blood as well, heart and blood together forming a single functioning unit which is the very seat of life, a basis which has nothing whatever to do with mechanisms and matter. The blood is a spiritual substance.

> "It is also celestial, for nature, the soul, that which answers to the essence of the stars, is the inmate of the spirit, in other words, it is something analogous to heaven, the instrument of heaven, vicarious of heaven."

In his study of the generation of animals, Harvey had observed a pulsing point of blood as the first sign of life in the embryo. In death, a palpitation of the blood was the last living act—"nature in death, retracing her steps, reverts to whence she had set out, returns at the end of her course to the goal whence she had started."

For Harvey as for Aristotle, then, circulation had manifold meaning, reproducing the cyclical regeneration which is the means to the preservation of the cosmos and all it contains. In the cyclic alteration of birth, reproduction, and death, he saw another reflection and embodiment of the eternal orbits which determine the generation and corruption of terrestrial beings. By describing the circuit, the species achieves immortality;

> "now pullet, now egg, the series is continued in perpetuity; from frail

> and perishing individuals an immortal species is engendered. By these, and means like to these, do we see many inferior or terrestrial things brought to emulate the perpetuity of superior or celestial things. And whether we say, or do not say, that the vital principle inheres in the egg, it still plainly appears, from the circuit indicated, that there must be some principle influencing this revolution from the fowl to the egg and from the egg back to the fowl, which gives them perpetuity."

So also some principle must govern the circulation of the blood. The mechanical necessity of circulation expresses only its material conditions. But blood is a spiritual fluid, the bearer of the vital principle on which life depends. Its true circulation is the cycle of renewal and decline. It leaves the heart warm and vital, bearing life to the extremities, and returns coagulated and effete to be restored. In its circulation, the blood repeats in the microcosm the cosmic cycle of generation and corruption, and in its repetition preserves the life of the individual.

When Harvey's *De motu cordis et sanguinis** was published in 1628, Descartes was already at work on the reconstruction of natural philosophy. Inevitably, Harvey's discovery interested him; inevitably, he comprehended it in his own terms. The notion that blood moves in a closed circuit, an idea that corresponded to his exposition of motion in a plenum, did not fail to catch his eye. Consequently, when his *Discourse on Method* appeared ten years after Harvey's book, it included an exposition of the circulation of the blood as an example of a purely mechanical physiological process.

"And that there may be less difficulty in understanding what I am about to say on this subject," he counselled as he began, "I advise those who are not versed in Anatomy, before they commence the perusal of these observations, to take the trouble of getting dissected in their presence the heart of some large animal possessed of lungs, (for this is throughout sufficiently like the human)." The advice probably fell as incongruously on the ears of the 17th century reader as it does on those of the 20th century one. For the benefit of those readers who had no one to cut open a heart for them and preferred not to do it themselves, Descartes described its structure, laying stress on the valves which "readily permit the blood to pass, but preclude its return." He remarked as well that the heart has more heat than the rest of the body. In it there is kindled what he called "one of those fires without light, not different from the heat in hay that has been heaped together before it is dry, or that which causes fermentation in new wines." He understood such a fermentation as a mechanical process, of course.

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* *On the Motion of the Heart and Blood.*

When portions of blood enter the two ventricles, they "are immediately rarefied, and dilated by the heat they meet with."

> "In this way they cause the whole heart to expand, and at the same time press home and shut the five small valves that are at the entrances of the two vessels from which they flow, and thus prevent any more blood from coming down into the heart, and becoming more and more rarefied, they push open the six small valves that are in the orifices of the other two vessels, through which they pass out, causing in this way all the branches of the arterial vein and of the grand artery to expand almost simultaneously with the heart—which immediately thereafter begins to contract, as do also the arteries, because the blood that has entered them has cooled, and the six small valves close, and the five of the hollow vein and of the venous artery open anew and allow a passage to other two drops of blood, which cause the heart and the arteries again to expand as before."

Those who do not appreciate the force of mathematical demonstrations, he added, must be warned "that the motion which I have now explained follows as necessarily from the very arrangement of the parts, which may be observed in the heart by the eye alone, and from the heat which may be felt with the fingers, and from the nature of the blood as learned from experience, as does the motion of a clock from the power, the situation, and shape of its counterweights and wheels."

What Descartes had done was to appropriate Harvey's discovery but systematically to eliminate Harvey's vitalism which he regarded as occult. In his *Traité de l'homme** he described a machine that performs all the physiological functions of man—circulation, digestion, nourishment and growth, perception.

> "I want you to consider [he concluded] that all these functions in this machine follow naturally from the disposition of its organs alone, just as the movements of a clock or another automat follow from the disposition of its counterweights and wheels; so that to explain its functions it is not necessary to imagine a vegetative or sensitive soul in the machine, or any other principle of movement and life other than its blood and spirits agitated by the fire which burns continually in its heart and which differs in nothing from all the fires in inanimate bodies."

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* *Treatise on Man.*

It is not necessary to imagine a principle of life—here was the crux of Cartesian physiology. Life itself was an alien presence in a mechanical world. Indeed, it was not a presence at all, but a mere appearance to be explained away with other occult properties.

To say that Descartes appropriated Harvey's discovery is only half true until we add that he bowdlerized it egregiously in the process. Determined to eliminate any mysterious entity such as life, he insisted on deriving the motion of the heart from known physical processes; in doing so, he turned the heart into a teakettle. More than that, the physiology of the radical innovator represented a reactionary step backward in comparison to that of Harvey, the conservative Aristotelian. Whereas Harvey established the fundamental role of the systole, Descartes' vaporization returned to the Galenic diastole. He accepted circulation, it is true, but the vaporized blood which leaves the heart in his system recalls Galen's vital spirits, and he described a separation in the brain of the most subtle particles of the blood to form the animal spirits which circulate through the nerves. Cartesian physiology was basically Galenic physiology reattired in the robes of mechanical philosophy. A lifetime's contemplation of vital phenomena left Harvey convinced that they could not be reduced to material explanations. For a priori reasons that did not derive in any way from biological considerations, Descartes vulgarized Harvey's work in order more easily to mechanize it. In the process, he even lost the principal elements of Harvey's mechanical treatment of cardiac motion. It was not a happy augury for the contribution of mechanical philosophy to biological science.

Nevertheless, Descartes determined the tone of biological studies in the later 17th century far more than Harvey did, and there developed a school of mechanical biology known as iatromechanics. Biology remained more richly varied than chemistry, and iatromechanics never dominated it to the extent that mechanism came to dominate chemistry. Iatromechanism was more than a factor in the biological science of the late 17th century, however; it was the distinctive feature.

De motu animalium (1680–1) by Giovanni Alfonso Borelli (1608–1679) ranks among the best products of iatromechanics. First for man, and then for other animals including birds and fish, Borelli applied the principles of simple machines to the analysis of various movements. (See Fig. 5.4.) Consider, for example, a man crouched and ready to spring into the air. Borelli examined the position of the muscles that must contract and their connection to the skeleton. His basic insight, both here and in other cases, was that the muscles work always at a considerable mechanical disadvantage. Treating the bone as a lever with the joint as its fulcrum, he showed that the muscle which supplies the motive force connects very close to the fulcrum, whereas the load is generally placed near the other end of a bone with a lever arm ten

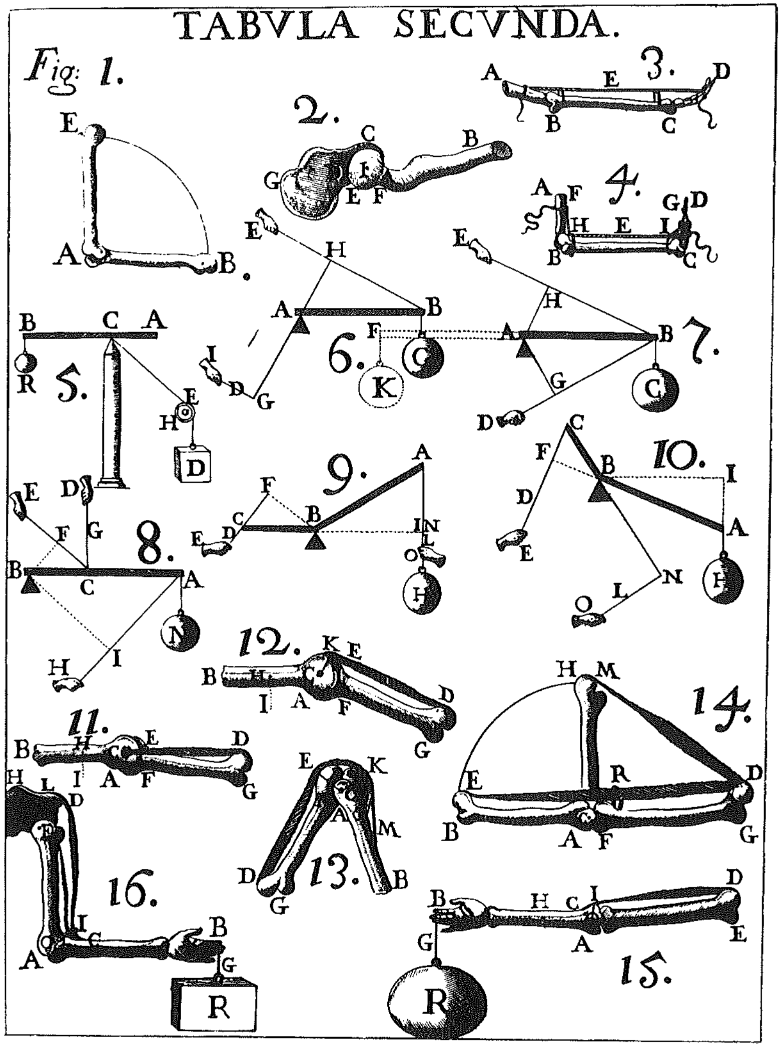

Figure 5.4. A set of diagrams from Borelli's work illustrates the mechanical principles that he applied to the operation of muscles and joints.

times and more that of the muscle. Complicated motions involving several joints compound the disadvantage. Thus in the case of the leap, he concluded that the muscles must exert a force over four hundred and twenty times the weight of the man just to pull him erect, and by an argument which will not bear close scrutiny, he concluded further that a force seven times greater is required to project the man into the air. In all, then, a man must exert a force twenty-nine hundred times his weight in order to leap into the air. As in the case of leaping, all of Borelli's analyses were vitiated by his use of static equilibrium to examine motion. Beyond that, however, his willingness to apply the principles of statics to the human frame was a sound, if minor, addition to biological understanding.

Neither Borelli nor iatromechanists in general were satisfied to stop with such limited problems. Harvey's discovery of circulation opened a broad field for mechanical investigations. Iatromechanists calculated the velocity of the blood and the resistance which vessels of various dimensions offer to it. They proposed to explain animal heat, not by Descartes' fire without flame, but by the friction of the blood with the walls of the arteries. They constructed a theory of secretions based on the velocity of circulating fluids, and they filled the body with porous filters which separated particles by sizes and shapes. It is generally recognized, proclaimed Dr. Richard Mead, that the body of man is "a hydraulic machine contrived with the most exquisite art, in which there are numberless tubes properly adjusted and disposed for the conveyance of fluids of different kinds. Upon the whole, health consists of regular motions of the fluids, together with a proper state of the solids, and diseases are their aberrations."

Such a view of life could not fail to color the observations of the observing naturalist. In at least two areas of biology, it helped to obstruct the appreciation of discoveries of major importance. The early microscopists observed the cellular structure of wood. Our very word "cell," which plays such a fundamental role in biological science, was first used as a biological term by Robert Hooke (1635–1703) in *Micrographia,* (1665). Observing a piece of cork under a microscope, he was reminded of a honeycomb and referred to what he saw as pores or cells. The word "pores" was more expressive of Hooke's interpretation. They seem, he said, "to be the channels or pipes through which the *Succus nutritius,* or natural juices of Vegetables are convey'd and seem to correspond to the veins, arteries, and other Vessels in sensible creatures." He even looked for valves to control the direction of flow, and though he failed to observe them, he thought it probable nevertheless that nature had not failed to provide such "appropriated Instruments and contrivances" to achieve her purposes.

The whole tenor of 17th century thought inclined the microscopists to see in this discovery, not the ultimate unit of life, but pipes suitable to carry fluids. As Nehemiah Grew, who extended Hooke's initial observations into a complete theory of vegetable physiology, asked: "to what end are Vessels, but for the conveyance of Liquor?" Additional irony derives from the fact that microscopists also observed unicellular creatures such as spermatozoa. They could not even dream that their "little animals" bore any relation to the pores observed in plants.

A much more complicated story revolves about the study of embryology. From the ancient world the 17th century did not inherit a unified theory of generation, but rather different theories for different classes of beings. The generation of viviparous quadrupeds (and man) obviously differed from that of oviparous animals. Insects were held to generate spontaneously from decaying material, and the reproduction of plants was another matter altogether. It was the work of William Harvey, one of the first great embryologists of the modern world, as well as the discoverer of circulation, which attempted to comprehend the generation of all animals in common terms. The frontispiece of his book, *De generatione animalium** (1651), shows Zeus opening an egg from which animals of all sorts, including a human, emerge, and on the egg appears the legend "Ex ovo omnia" or, as he stated the same idea in the treatise, "An egg is the common origin of all animals." On close examination, the word "egg" turns out to be highly ambiguous. In the case of oviparous animals, it is definite enough. Harvey never comprehended the function of the organs that we call ovaries in viviparous animals, however. What he called the egg of the deer was the amniotic sac, in which an embryo had been developing for several weeks. In the case of insects, it was the cocoon from which the butterfly emerges. By egg then, he meant, not a product of a female ovary, but what he also called a "primordium," a first matter or first beginning however produced. It was a broad enough concept to embrace even the spontaneous generation of insects, which Harvey did not question.

Nevertheless, Harvey's formula embodied a considerable generalization. Whatever the ambiguity in his meaning of egg, he had attempted to comprehend all generation under one common pattern. Even the seed

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* *On the Generation of Animals.*

of a plant could be considered a *primordium.* The details of generation may vary from species to species, but in all of them the egg represents one point in the eternal cycle of reproduction by which the species is preserved.

An egg, the origin of every being, was to Harvey an homogeneous point of matter which an indwelling formative principle molds and converts into an articulated individual able to produce, as its ultimate act, an homogeneous point of matter, the primordium of another generation. In his examination of a doe, Harvey could find no trace of male semen in the uterus, and the egg of the deer was first visible to him seven weeks after coition. Obviously, the male semen cannot play a material part in generation. Harvey described its action by the word "contagion," an immaterial influence which lingers and stimulates the dormant egg. Once stimulated and awakened to activity, the egg had within it both an indwelling principle and material for it to work on. Harvey coined the word "epigenesis" to describe the process he observed in the generation of chickens. In an egg opened three days after it was laid, he saw a pulsing point of blood which became the heart, the first organ to be formed and the center from which the rest of the chicken was generated. Epigenesis was the natural expression of Harvey's vitalism, a creative generation under the guidance of the formative virtue which embodies the divine idea of the species.

Descartes was ready to mechanize epigenesis along with the rest of life. In *La description du corps humain,** he described how male and female semen ferment when joined, and how the resulting motions, by mechanical necessity, build the heart, the circulatory system, and so on. The 17th century considered the account to be arrant nonsense, just as we do, and an alternative embryology suggested by Gassendi won a wider audience. To Gassendi, the fundamental act of generation was the production of a seed. Both in plants and in animals, the seed is a tiny body containing particles from all parts of the individual. He spoke sometimes of a soul in the seed, but since the soul was itself composed of aethereal matter, it did not dilute the essential mechanism of the account. The controlling factor in generation is the attraction of like for like, an idea uncomfortably reminiscent of Renaissance Naturalism but seemingly capable of translation into harmonious shapes and motions. In a seed, like particles (deriving from the same parts) come together, and they attract other like particles from the

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* *The Description of the Human Body.*

food available. Hence, in some sense, the product of generation is already present in the seed. As Gassendi declared, "the seed contains the thing itself, but contains it as rudiments not yet unfolded."

The term "preformation" is attached to this conception of generation. Epigenesis considered generation as a creative process in which the formative virtue molds and alters the material present to it, evoking heterogeneity from homogeneity. Preformation, on the other hand, asserted that heterogeneity must be present from the beginning and that generation is merely the process of its evolution (literally, unfolding) or development (literally, emerging from envelopes, or uncovering). "Heterogeneity" was a term readily understood by atomists, who likewise believed that it is present from the beginning in the form of particles of different shapes. Not merely in embryology but in general the mechanical philosophy regarded the formation of all individual things as a process by which suitable pre-existing particles are fitted together. Descartes' attempt to mechanize epigenesis had been an obvious failure, but preformation offered a mechanical alternative to the unacceptable idea of a formative virtue.

Marcello Malpighi (1628–1694), perhaps the greatest embryologist of the century, elaborated Gassendi's account. By perfecting a technique of removing the cicatrix from a freshly opened egg and spreading it on glass, Malpighi was able to introduce the microscope into embryology. Just six hours after the egg was laid, he discerned the cephalic region and the spine. Outlines of vertebrae appeared after twelve hours. On the second day, he saw the beating heart, which Harvey, without a microscope, had seen only on the fourth. With the heart, he saw the head and the beginnings of eyes. Naturalists, he declared, have sought to discover the genesis of separate parts in different stages; "while we are studying attentively the genesis of animals from the egg, lo! in the egg itself we behold the animal already almost formed."

When Malpighi came to study the generation of chickens, he was already an experienced investigator both of plants and of silkworms. In the silkworm, he had found the wings and the antennae of the butterfly already existing as rudiments in the body of the caterpillar, and in a bud, he had discovered "a compendium of the not yet unfolded plant." His mind was thus prepared to find the chicken present in the egg from the beginning. It was present, however, as rudiments. He spoke of sacules and vesicles within which different parts develop. Walled off from the rest of the egg by membranes which acts as sieves, the vesicles "admit appropriate matter, which is consumed in the construction of the parts," and when the vesicles are joined together, the structure of the animal appears. Clearly, the filtering action of the porous membrane was a rendition of Gassendi's attraction of like for like, just as his term "rudiments" repeated Gassendi's phrase.

Whereas Malpighi was primarily a skillful observer, others were more concerned with systematizing, and in them the subtlety of Malpighi's preformationism was cast to the winds. Eggs, Swammerdam pronounced, are not transformed into chickens, "but grow to be such by the expansion of parts already formed." "There is never any generation in nature," he added, "but only a stretching or a growth of parts." If there is never any generation in nature, then eggs themselves cannot be generated. In the chicken, preformed in the egg, there are preformed eggs as well, and of course in those eggs preformed chickens with their preformed eggs.

> "In eggs, so naturalists say . . ."

At the end of the 17th century, embryology produced the theory of *emboîtement* which held, for example, that the entire human race was present already in Eve.

That the theory of *emboîtement* included Eve and the human race as well as chickens was due to further discoveries which seemed at the time to confirm preformationism. In 1667, Nicholas Steno discovered the ovaries, filled with eggs, in the dog fish, a viviparous creature. Five years later, Regnier de Graaf (1641–1673) discovered vesicles on the female testicles (as they were then called) of rabbits, dogs, cows, and humans. He took the vesicles to be eggs and asserted that the so-called testicles are in fact ovaries. In a brilliant set of experiments with pregnant rabbits, he found a constant numerical identity between the number of embryos in the uterus and the number of yellow bodies on the ovaries—the *corpora lutea* left by the vesicles after ovulation. Although de Graaf mistook the vesicle for the egg, (the mammalian egg is so small that it was not observed until the 19th century), his interpretation of what he discovered was essentially correct, and we continue to commemorate it with the name Graafian follicle. Harvey's dictum now acquired a new and more exact meaning; viviparous mammals are indeed born of eggs. Preformationism had established itself on the study of generation in eggs; ovism, as the doctrine of the universality of generation from eggs was called, appeared to lend it powerful support.

The uncontested reign of ovism lasted exactly five years. What the

microscope gave the microscope took away. In 1677, Leeuwenhoek observed spermatozoa. (See Fig. 5.5.)

> "These *animalicula* were smaller than the corpuscles that make the blood red, so that I estimate a million of them are not equal in size to a large grain of sand. They had roundish bodies, blunt in front, but ending in a point at the rear; they were endowed with a thin transparent tail five or six times as long as the body and about one twenty-fifth as thick, so that I can best compare their shape to a small radish with a long root. They moved forward with a serpentine motion of the tail, like eels swimming in water."

Ovism, it now appeared, was a monstrous mistake. The passive egg could be nothing but food for the true agents of reproduction, the manifestly vital animacules or, as he also called them, the "spermatic worms" of the male semen. A Swedish doctor found the new doctrine

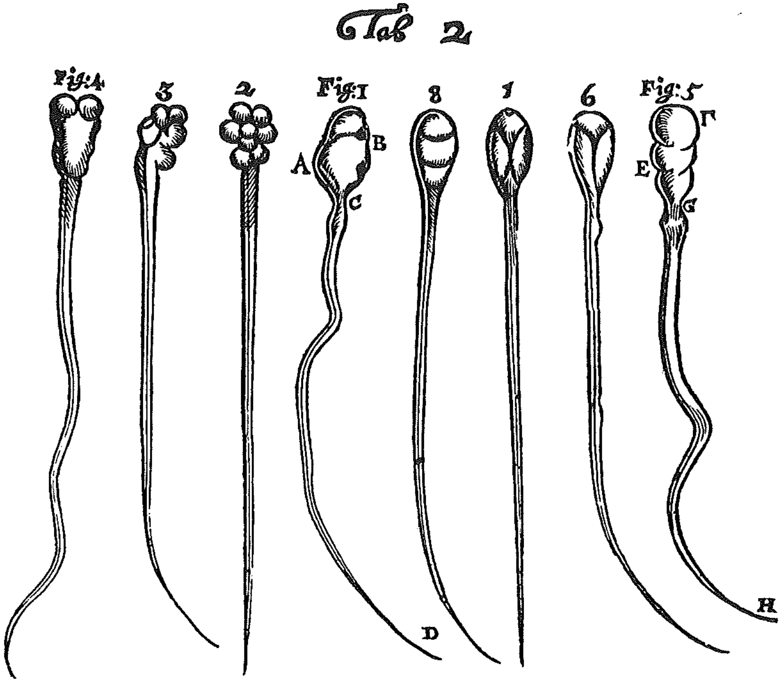

Figure 5.5. Leeuwenhoek's drawing of spermatozoa. 1–4 represent human spermatozoa, 5–8 canine spermatozoa.

more conformable to the dignity of man. Niklaas Hartsoeker (1656–1725) showed the absurdity of ovism by calculating that an original egg would be larger than one destined for fertilization sixty centuries later (since the creation of the world was popularly placed in 4004 B.C., he was comparing Eve with his own generation) by a factor of $10^{30,000}$.

One might suspect then that animaculism (as the new doctrine was called) rejected preformation. Nothing could be further from the truth. The same factors that made preformation attractive to the ovists made it attractive to the animaculists. The same Hartsoeker who demonstrated the absurdity of ovism failed to see that animaculism suffered from the identical problem.

> "It can be said that each animal, actually and in miniature, contains and shields in a delicate and tender membrane a male or female animal of the same species, as that in the semen of which it is found."

He even published a picture of an homunculus all curled up in the head of a spermatozoon. (See Fig. 5.6.) As a satirical reply, a French doctor, François de Plantade, published a similar figure and told how he had observed an homunculus in the act of sloughing off its envelope.

> "He clearly showed, bare and exposed, his two legs, his thighs, his belly, his two arms; the membrane drawn toward the top coiffured him like a capuchin. He paused as he stripped himself."

Alas, the irony was lost, and Plantade's drawing was received as confirmation of Hartsoeker's.

It is difficult to read the embryologists of the late 17th century without a sense of bewilderment. Their contribution to the knowledge of generation was immense. To the discovery of spermatozoa and the virtual discovery of mammalian eggs, they added the effective disproof of the prevailing notion that worms, insects, and small animals are products of spontaneous generation and the demonstration of sexuality in plants. Francesco Redi conducted controlled experiments in which worms appeared in decaying meat open to flies whereas none appeared in samples carefully screened. He concluded that the worms, far from generating spontaneously, are larvae which grow from eggs laid in the flesh. In the case of plants, R. J. Camerarius demonstrated that seeds require pollen from the stamens in order to reach maturity. He recognized that pollen is analogous to male semen. Thus biological science was placed within reach of a general theory of generation embracing all living forms. What was actually produced in preformationism, however, was a theory unable to account satisfactorily for the most obvious fact of generation, that offspring can and do inherit characteristics from both parents.

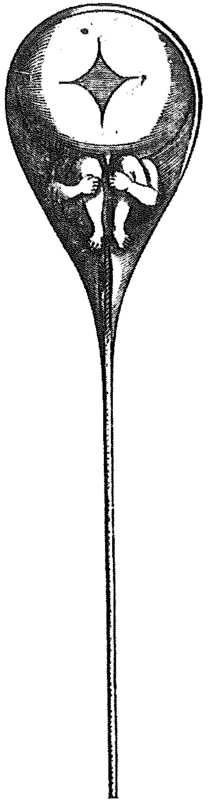

Figure 5.6. Hartsoeker's conception of how an homunculus ought to look in an animacula in the sperm.

It is tempting to conclude that the mechanical philosophy, with its inability to recognize in generation anything but an unfolding of preexistent parts, stood between 17th century embryology and the comprehension of its own discoveries. Before we accept such a conclusion, we should recall that Harvey the vitalist, the exponent of epigenesis, was also an ovist who denied any contribution of the male semen to the embryo. For reasons almost diametrically opposed to those of mechanical philosophers, that is, to assert the nonmateriality of generation, Harvey rejected the possibility of material contact between the semen and the egg. More than the mechanical philosophy obstructed comprehension of the new discoveries. A vast range of additional knowledge and understanding of vital processes, not available until the 19th century, was needed before the full import of 17th century discoveries could be realized. We need to remember as well that the discoveries in embryology, as well as many others in the whole field of biology, were in fact made during an age when the mechanical philosophy held sway over scientific thought. However inappropriate its categories for biological understanding, it did not prevent the great expansion of biological knowledge.

Another temptation must equally be resisted—the temptation to greet the iatromechanists as early biophysicists and biochemists. Iatromechanism did not arise from the demands of biological study; it was far more the puppet regime set up by the mechanical philosophy's invasion. In isolated problems—the circulation of the blood is the classic example—mechanical modes of thought, the ability to see the mechanical necessity in a vital process, could lead to new insights. Harvey himself, however, was a vitalist, not a mechanist. For the most part, iatromechanics was simply irrelevant to biology. It did not prevent the vital work of detailed observations; it contributed almost nothing toward understanding what was seen. Beside the subtlety of biological processes, the 17th century's mechanical philosophy was crudity itself. Above all, it lacked a sophisticated chemistry which has turned out to be a prerequisite for the rapprochement of the physical and biological sciences. One can only wonder in amazement that the mechanical explanations were considered adequate to the biological facts, and in fact iatromechanics made no significant discovery whatever.

CHAPTER VI

Organization of the Scientific Enterprise

MORE THAN SIMPLY a reformulation of scientific conceptions occurred in the 17th century, even though the reformulation of conceptions was radical enough to warrant the name "revolution" that is frequently applied to it. Science as an organized social activity also appeared. Obviously, earlier periods had witnessed a great deal of scientific activity. It is difficult to distinguish science from philosophy before the 17th century, however, and it is equally difficult to describe many men primarily as scientists. The existence of a Leibniz indicates that the compartmentalization of what we now call science was far from complete at the end of the 17th century. Nevertheless, by that time, Western Europe contained, not just a few, but whole groups of men whom we label without hesitation as scientists. Moreover, they were not working in isolation as individuals, but had organized societies which placed them in effective communication with large numbers of men engaged in the same pursuit. On the ground once trod by prophets an organized church now stood.

The 20th century learns with surprise that the word "university" did not appear in the title of that church. We are accustomed to think of universities as the principal centers, or at least as being among the principal centers, of scientific research. A similar situation had existed in the Middle Ages, when virtually all intellectual activity, including science, had been located within university walls. A radically different situation obtained during the 17th century. Not only were the universities of Europe not the foci of scientific activity, not only did natural science have to develop its own centers of activity independent of the universities, but the universities were the principal centers of opposition to the new conception of nature which modern science constructed.