

## 2·The Newtonian World-Machine

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The world view and value system that lie at the basis of our culture and that have to be carefully reexamined were formulated in their essential outlines in the sixteenth and seventeenth centuries. Between 1500 and 1700 there was a dramatic shift in the way people pictured the world and in their whole way of thinking. The new mentality and the new perception of the cosmos gave our Western civilization the features that are characteristic of the modern era. They became the basis of the paradigm that has dominated our culture for the past three hundred years and is now about to change.

Before 1500 the dominant world view in Europe, as well as in most other civilizations, was organic. People lived in small, cohesive communities and experienced nature in terms of organic relationships, characterized by the interdependence of spiritual and material phenomena and the subordination of individual needs to those of the community. The scientific framework of this organic world view rested on two authorities—Aristotle and the Church. In the thirteenth century Thomas Aquinas combined Aristotle's comprehensive system of nature with Christian theology and ethics and, in doing so, established the conceptual framework that remained unquestioned throughout the Middle Ages. The nature of medieval science was very different from that of contemporary science. It was based on both reason and faith and its main goal was to understand the meaning and significance of things, rather than prediction and control. Medieval scientists, looking for the purposes underlying various natural phenomena, considered

questions relating to God, the human soul, and ethics to be of the highest significance.

The medieval outlook changed radically in the sixteenth and seventeenth centuries. The notion of an organic, living, and spiritual universe was replaced by that of the world as a machine, and the world-machine became the dominant metaphor of the modern era. This development was brought about by revolutionary changes in physics and astronomy, culminating in the achievements of Copernicus, Galileo, and Newton. The science of the seventeenth century was based on a new method of inquiry, advocated forcefully by Francis Bacon, which involved the mathematical description of nature and the analytic method of reasoning conceived by the genius of Descartes. Acknowledging the crucial role of science in bringing about these far-reaching changes, historians have called the sixteenth and seventeenth centuries the Age of the Scientific Revolution.

The Scientific Revolution began with Nicolas Copernicus, who overthrew the geocentric view of Ptolemy and the Bible that had been accepted dogma for more than a thousand years. After Copernicus, the earth was no longer the center of the universe but merely one of the many planets circling a minor star at the edge of the galaxy, and man was robbed of his proud position as the central figure of God's creation. Copernicus was fully aware that his view would deeply offend the religious consciousness of his time; he delayed its publication until 1543, the year of his death, and even then he presented the heliocentric view merely as a hypothesis.

Copernicus was followed by Johannes Kepler, a scientist and mystic who searched for the harmony of the spheres and was able, through painstaking work with astronomical tables, to formulate his celebrated empirical laws of planetary motion, which gave further support to the Copernican system. But the real change in scientific opinion was brought about by Galileo Galilei, who was already famous for discovering the laws of falling bodies when he turned his attention to astronomy. Directing the newly invented telescope to the skies and applying his extraordinary gift for scientific observation to celestial phenomena, Galileo was able to discredit the old cosmology beyond any doubt and to establish the Copernican hypothesis as a valid scientific theory.

The role of Galileo in the Scientific Revolution goes far beyond his achievements in astronomy, although these are most widely known because of his clash with the Church. Galileo was the first to combine

scientific experimentation with the use of mathematical language to formulate the laws of nature he discovered, and is therefore considered the father of modern science. "Philosophy,"\* he believed, "is written in that great book which ever lies before our eyes; but we cannot understand it if we do not first learn the language and characters in which it is written. This language is mathematics, and the characters are triangles, circles, and other geometrical figures."<sup>1</sup> The two aspects of Galileo's pioneering work—his empirical approach and his use of a mathematical description of nature—became the dominant features of science in the seventeenth century and have remained important criteria of scientific theories up to the present day.

To make it possible for scientists to describe nature mathematically, Galileo postulated that they should restrict themselves to studying the essential properties of material bodies—shapes, numbers, and movement—which could be measured and quantified. Other properties, like color, sound, taste, or smell, were merely subjective mental projections which should be excluded from the domain of science.<sup>2</sup> Galileo's strategy of directing the scientist's attention to the quantifiable properties of matter has proved extremely successful throughout modern science, but it has also exacted a heavy toll, as the psychiatrist R. D. Laing emphatically reminds us: "Out go sight, sound, taste, touch and smell and along with them has since gone aesthetics and ethical sensibility, values, quality, form; all feelings, motives, intentions, soul, consciousness, spirit. Experience as such is cast out of the realm of scientific discourse."<sup>3</sup> According to Laing, hardly anything has changed our world more during the past four hundred years than the obsession of scientists with measurement and quantification.

While Galileo devised ingenious experiments in Italy, Francis Bacon set forth the empirical method of science explicitly in England. Bacon was the first to formulate a clear theory of the inductive procedure—to make experiments and to draw general conclusions from them, to be tested in further experiments—and he became extremely influential by vigorously advocating the new method. He boldly attacked traditional schools of thought and developed a veritable passion for scientific experimentation.

The "Baconian spirit" profoundly changed the nature and purpose of the scientific quest. From the time of the ancients the goals of sci-

\* From the Middle Ages to the nineteenth century the term "philosophy" was used in a very broad sense and included what we now call "science."

ence had been wisdom, understanding the natural order and living in harmony with it. Science was pursued "for the glory of God," or, as the Chinese put it, to "follow the natural order" and "flow in the current of the Tao."<sup>4</sup> These were yin, or integrative, purposes; the basic attitude of scientists was ecological, as we would say in today's language. In the seventeenth century this attitude changed into its polar opposite; from yin to yang, from integration to self-assertion. Since Bacon, the goal of science has been knowledge that can be used to dominate and control nature, and today both science and technology are used predominantly for purposes that are profoundly antiecological.

The terms in which Bacon advocated his new empirical method of investigation were not only passionate but often outright vicious. Nature, in his view, had to be "hounded in her wanderings," "bound into service," and made a "slave." She was to be "put in constraint," and the aim of the scientist was to "torture nature's secrets from her."<sup>5</sup> Much of this violent imagery seems to have been inspired by the witch trials that were held frequently in Bacon's time. As attorney general for King James I, Bacon was intimately familiar with such prosecutions, and because nature was commonly seen as female, it is not surprising that he should carry over the metaphors used in the courtroom into his scientific writings. Indeed, his view of nature as a female whose secrets have to be tortured from her with the help of mechanical devices is strongly suggestive of the widespread torture of women in the witch trials of the early seventeenth century.<sup>6</sup> Bacon's work thus represents an outstanding example of the influence of patriarchal attitudes on scientific thought.

The ancient concept of the earth as nurturing mother was radically transformed in Bacon's writings, and it disappeared completely as the Scientific Revolution proceeded to replace the organic view of nature with the metaphor of the world as a machine. This shift, which was to become of overwhelming importance for the further development of Western civilization, was initiated and completed by two towering figures of the seventeenth century, Descartes and Newton.

René Descartes is usually regarded as the founder of modern philosophy. He was a brilliant mathematician and his philosophical outlook was profoundly affected by the new physics and astronomy. He did not accept any traditional knowledge, but set out to build a whole new sys-

tem of thought. According to Bertrand Russell, "This had not happened since Aristotle, and is a sign of the new self-confidence that resulted from the progress of science. There is a freshness about his work that is not to be found in any eminent previous philosopher since Plato."<sup>7</sup>

At the age of twenty-three, Descartes experienced an illuminating vision that was to shape his entire life.<sup>8</sup> After several hours of intense concentration, during which he reviewed systematically all the knowledge he had accumulated, he perceived, in a sudden flash of intuition, the "foundations of a marvellous science" which promised the unification of all knowledge. This intuition had been foreshadowed in a letter to a friend in which Descartes announced his ambitious aim: "And so as to not hide anything from you about the nature of my work, I would like to give the public . . . a completely new science which would resolve generally all questions of quantity, continuous or discontinuous."<sup>9</sup> In his vision Descartes perceived how he could realize this plan. He saw a method that would allow him to construct a complete science of nature about which he could have absolute certainty; a science based, like mathematics, on self-evident first principles. Descartes was overwhelmed by this revelation. He felt that he had made the supreme discovery of his life and had no doubt that his vision came from divine inspiration. This conviction was enforced by an extraordinary dream the following night in which the new science was presented to him in symbolic form. Descartes was now certain that God had shown him his mission, and he set out to build a new scientific philosophy.

Descartes' vision had implanted in him the firm belief in the certainty of scientific knowledge, and his vocation in life was to distinguish truth from error in all fields of learning. "All science is certain, evident knowledge," he wrote. "We reject all knowledge which is merely probable and judge that only those things should be believed which are perfectly known and about which there can be no doubts."<sup>10</sup>

The belief in the certainty of scientific knowledge lies at the very basis of Cartesian philosophy and of the world view derived from it, and it was here, at the very outset, that Descartes went wrong. Twentieth-century physics has shown us very forcefully that there is no absolute truth in science, that all our concepts and theories are limited and approximate. The Cartesian belief in scientific truth is still widespread today and is reflected in the scientism that has become typical of our Western culture. Many people in our society, scientists as well as non-

scientists, are convinced that the scientific method is the only valid way of understanding the universe. Descartes' method of thought and his view of nature have influenced all branches of modern science and can still be very useful today. But they will be useful only if their limitations are recognized. The acceptance of the Cartesian view as absolute truth and of Descartes' method as the only valid way to knowledge has played an important role in bringing about our current cultural imbalance.

Cartesian certainty is mathematical in its essential nature. Descartes believed that the key to the universe was its mathematical structure, and in his mind science was synonymous with mathematics. Thus he wrote, regarding the properties of physical objects, "I admit nothing as true of them that is not deduced, with the clarity of a mathematical demonstration, from common notions whose truth we cannot doubt. Because all the phenomena of nature can be explained in this way, I think that no other principles of physics need be admitted, nor are to be desired."<sup>11</sup>

Like Galileo, Descartes believed that the language of nature—"that great book which ever lies before our eyes"—was mathematics, and his desire to describe nature in mathematical terms led him to his most celebrated discovery. By applying numerical relations to geometrical figures, he was able to correlate algebra and geometry and, in doing so, founded a new branch of mathematics, now known as analytic geometry. This included the representation of curves by algebraic equations whose solutions he studied in a systematic way. His new method allowed Descartes to apply a very general type of mathematical analysis to the study of moving bodies, in accordance with his grand scheme of reducing all physical phenomena to exact mathematical relationships. Thus he could say, with great pride, "My entire physics is nothing other than geometry."<sup>12</sup>

Descartes' genius was that of a mathematician, and this is apparent also in his philosophy. To carry out his plan of building a complete and exact natural science, he developed a new method of reasoning which he presented in his most famous book, *Discourse on Method*. Although this text has become one of the great philosophical classics, its original purpose was not to teach philosophy but to serve as an introduction to science. Descartes' method was designed to reach scientific truth, as is evident from the book's full title, *Discourse on the*

*Method of Rightly Conducting One's Reason and Searching the Truth in the Sciences.*

The crux of Descartes' method is radical doubt. He doubts everything he can manage to doubt—all traditional knowledge, the impressions of his senses, and even the fact that he has a body—until he reaches one thing he cannot doubt, the existence of himself as a thinker. Thus he arrives at his celebrated statement, "*Cogito, ergo sum*," "I think, therefore I exist." From this Descartes deduces that the essence of human nature lies in thought, and that all the things we conceive clearly and distinctly are true. Such clear and distinct conception—"the conception of the pure and attentive mind"<sup>13</sup>—he calls "intuition," and he affirms that "there are no paths to the certain knowledge of truth open to man except evident intuition and necessary deduction."<sup>14</sup> Certain knowledge, then, is achieved through intuition and deduction, and these are the tools Descartes uses in his attempt to rebuild the edifice of knowledge on firm foundations.

Descartes' method is analytic. It consists in breaking up thoughts and problems into pieces and in arranging these in their logical order. This analytic method of reasoning is probably Descartes' greatest contribution to science. It has become an essential characteristic of modern scientific thought and has proved extremely useful in the development of scientific theories and the realization of complex technological projects. It was Descartes' method that made it possible for NASA to put a man on the moon. On the other hand, overemphasis on the Cartesian method has led to the fragmentation that is characteristic of both our general thinking and our academic disciplines, and to the widespread attitude of reductionism in science—the belief that all aspects of complex phenomena can be understood by reducing them to their constituent parts.

Descartes' *cogito*, as it has come to be called, made mind more certain for him than matter and led him to the conclusion that the two were separate and fundamentally different. Thus he asserted that "there is nothing included in the concept of body that belongs to the mind; and nothing in that of mind that belongs to the body"<sup>15</sup> The Cartesian division between mind and matter has had a profound effect on Western thought. It has taught us to be aware of ourselves as isolated egos existing "inside" our bodies; it has led us to set a higher value on mental than manual work; it has enabled huge industries to

sell products—especially to women—that would make us owners of the “ideal body”; it has kept doctors from seriously considering the psychological dimensions of illness, and psychotherapists from dealing with their patients’ bodies. In the life sciences, the Cartesian division has led to endless confusion about the relation between mind and brain, and in physics it made it extremely difficult for the founders of quantum theory to interpret their observations of atomic phenomena. According to Heisenberg, who struggled with the problem for many years, “This partition has penetrated deeply into the human mind during the three centuries following Descartes and it will take a long time for it to be replaced by a really different attitude toward the problem of reality.”<sup>16</sup>

Descartes based his whole view of nature on this fundamental division between two independent and separate realms; that of mind, or *res cogitans*, the “thinking thing,” and that of matter, or *res extensa*, the “extended thing.” Both mind and matter were the creations of God, who represented their common point of reference, being the source of the exact natural order and of the light of reason that enabled the human mind to recognize this order. For Descartes, the existence of God was essential to his scientific philosophy, but in subsequent centuries scientists omitted any explicit reference to God and developed their theories according to the Cartesian division, the humanities concentrating on the *res cogitans* and the natural sciences on the *res extensa*.

To Descartes the material universe was a machine and nothing but a machine. There was no purpose, life, or spirituality in matter. Nature worked according to mechanical laws, and everything in the material world could be explained in terms of the arrangement and movement of its parts. This mechanical picture of nature became the dominant paradigm of science in the period following Descartes. It guided all scientific observation and the formulation of all theories of natural phenomena until twentieth-century physics brought about radical change. The whole elaboration of mechanistic science in the seventeenth, eighteenth and nineteenth centuries, including Newton’s grand synthesis, was but the development of the Cartesian idea. Descartes gave scientific thought its general framework—the view of nature as a perfect machine, governed by exact mathematical laws.

The drastic change in the image of nature from organism to machine had a strong effect on people’s attitudes toward the natural en-

vironment. The organic world view of the Middle Ages had implied a value system conducive to ecological behavior. In the words of Carolyn Merchant:

The image of the earth as a living organism and nurturing mother served as a cultural constraint restricting the actions of human beings. One does not readily slay a mother, dig into her entrails for gold, or mutilate her body . . . As long as the earth was considered to be alive and sensitive, it could be considered a breach of human ethical behavior to carry out destructive acts against it.<sup>17</sup>

These cultural constraints disappeared as the mechanization of science took place. The Cartesian view of the universe as a mechanical system provided a “scientific” sanction for the manipulation and exploitation of nature that has become typical of Western culture. In fact, Descartes himself shared Bacon’s view that the aim of science was the domination and control of nature, affirming that scientific knowledge could be used to “render ourselves the masters and possessors of nature.”<sup>18</sup>

In his attempt to build a complete natural science, Descartes extended his mechanistic view of matter to living organisms. Plants and animals were considered simply machines; human beings were inhabited by a rational soul that was connected with the body through the pineal gland in the center of the brain. As far as the human body was concerned, it was indistinguishable from an animal-machine. Descartes explained at great length how the motions and various biological functions of the body could be reduced to mechanical operations, in order to show that living organisms were nothing but automata. In doing so he was strongly influenced by the preoccupation of the baroque seventeenth century with artful, “lifelike” machinery that delighted people with the magic of its seemingly spontaneous movements. Like most of his contemporaries, Descartes was fascinated by these automata and even constructed a few of them himself. Inevitably, he compared their functioning to that of living organisms: “We see clocks, artificial fountains, mills and other similar machines which, though merely man-made, have nonetheless the power to move by themselves in several different ways . . . I do not recognize any difference between the machines made by craftsmen and the various bodies that nature alone composes.”<sup>19</sup>

Clockmaking in particular had attained a high degree of perfection by Descartes' time, and the clock was thus a privileged model for other automatic machines. Descartes compared animals to a "clock . . . composed . . . of wheels and springs," and he extended this comparison to the human body: "I consider the human body as a machine . . . My thought . . . compares a sick man and an ill-made clock with my idea of a healthy man and a well-made clock."<sup>20</sup>

Descartes' view of living organisms has had a decisive influence on the development of the life sciences. The careful description of the mechanisms that make up living organisms has been the major task of biologists, physicians, and psychologists for the past three hundred years. The Cartesian approach has been very successful, especially in biology, but it has also limited the directions of scientific research. The problem is that scientists, encouraged by their success in treating living organisms as machines, tend to believe that they are *nothing but* machines. The adverse consequences of this reductionist fallacy have become especially apparent in medicine, where the adherence to the Cartesian model of the human body as a clockwork has prevented doctors from understanding many of today's major illnesses.

This, then, was Descartes' "marvellous science." Using his method of analytic thought, he attempted to give a precise account of all natural phenomena in one single system of mechanical principles. His science was to be complete, and the knowledge it gave was to provide absolute mathematical certainty. Descartes, of course, was not able to carry out this ambitious plan, and he himself recognized that his science was incomplete. But his method of reasoning and the general outline of the theory of natural phenomena he provided have shaped Western scientific thought for three centuries.

Today, although the severe limitations of the Cartesian world view are becoming apparent in all the sciences, Descartes' general method of approaching intellectual problems and his clarity of thought remain immensely valuable. I was vividly reminded of this after a lecture on modern physics in which I emphasized the limitations of the mechanistic world view in quantum theory and the necessity of overcoming this view in other fields, when a Frenchwoman complimented me on my "Cartesian clarity." As Montesquieu wrote in the eighteenth century, "Descartes has taught those who came after him how to discover his own errors."<sup>21</sup>

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Descartes created the conceptual framework for seventeenth-century science, but his view of nature as a perfect machine, governed by exact mathematical laws, had to remain a vision during his lifetime. He could not do more than sketch the outlines of his theory of natural phenomena. The man who realized the Cartesian dream and completed the Scientific Revolution was Isaac Newton, born in England in 1642, the year of Galileo's death. Newton developed a complete mathematical formulation of the mechanistic view of nature, and thus accomplished a grand synthesis of the works of Copernicus and Kepler, Bacon, Galileo, and Descartes. Newtonian physics, the crowning achievement of seventeenth-century science, provided a consistent mathematical theory of the world that remained the solid foundation of scientific thought well into the twentieth century. Newton's grasp of mathematics was far more powerful than that of his contemporaries. He invented a completely new method, known today as differential calculus, to describe the motion of solid bodies; a method that went far beyond the mathematical techniques of Galileo and Descartes. This tremendous intellectual achievement has been praised by Einstein as "perhaps the greatest advance in thought that a single individual was ever privileged to make."<sup>22</sup>

Kepler had derived empirical laws of planetary motion by studying astronomical tables, and Galileo had performed ingenious experiments to discover the laws of falling bodies. Newton combined those two discoveries by formulating the general laws of motion governing all objects in the solar system, from stones to planets.

According to legend, the decisive insight occurred to Newton in a sudden flash of inspiration when he saw an apple fall from a tree. He realized that the apple was pulled toward the earth by the same force that pulled the planets toward the sun, and thus found the key to his grand synthesis. He then used his new mathematical method to formulate the exact laws of motion for all bodies under the influence of the force of gravity. The significance of these laws lay in their universal application. They were found to be valid throughout the solar system and thus seemed to confirm the Cartesian view of nature. The Newtonian universe was, indeed, one huge mechanical system, operating according to exact mathematical laws.

Newton presented his theory of the world in great detail in his *Mathematical Principles of Natural Philosophy*. The *Principia*, as the work is usually called for short after its original Latin title, comprises a

comprehensive system of definitions, propositions, and proofs which scientists regarded as the correct description of nature for more than two hundred years. It also contains an explicit discussion of Newton's experimental method, which he saw as a systematic procedure whereby the mathematical description is based, at every step, on critical evaluation of experimental evidence:

Whatever is not deduced from the phenomena is to be called a hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy. In this philosophy, particular propositions are inferred from the phenomena, and afterwards rendered general by induction.<sup>23</sup>

Before Newton there had been two opposing trends in seventeenth-century science; the empirical, inductive method represented by Bacon and the rational, deductive method represented by Descartes. Newton, in his *Principia*, introduced the proper mixture of both methods, emphasizing that neither experiments without systematic interpretation nor deduction from first principles without experimental evidence will lead to a reliable theory. Going beyond Bacon in his systematic experimentation and beyond Descartes in his mathematical analysis, Newton unified the two trends and developed the methodology upon which natural science has been based ever since.

Isaac Newton was a much more complex personality than one would think from a reading of his scientific writings. He excelled not only as a scientist and mathematician but also, at various stages of his life, as a lawyer, historian, and theologian, and he was deeply involved in research into occult and esoteric knowledge. He looked at the world as a riddle and believed that its clues could be found not only through scientific experiments but also in the cryptic revelations of esoteric traditions. Newton was tempted to think, like Descartes, that his powerful mind could unravel all the secrets of the universe, and he applied it with equal intensity to the study of natural and esoteric science. While working at Trinity College, Cambridge, on the *Principia*, he accumulated, during the very same years, voluminous notes on alchemy, apocalyptic texts, unorthodox theological theories, and various occult matters. Most of these esoteric writings have never been published, but what is known of them indicates that Newton, the great genius of the

Scientific Revolution, was at the same time the "last of the magicians."<sup>24</sup>

The stage of the Newtonian universe, on which all physical phenomena took place, was the three-dimensional space of classical Euclidean geometry. It was an absolute space, an empty container that was independent of the physical phenomena occurring in it. In Newton's own words, "Absolute space, in its own nature, without regard to anything external, remains always similar and immovable."<sup>25</sup> All changes in the physical world were described in terms of a separate dimension, time, which again was absolute, having no connection with the material world and flowing smoothly from the past through the present to the future. "Absolute, true, and mathematical time," wrote Newton, "of itself and by its own nature, flows uniformly, without regard to anything external."<sup>26</sup>

The elements of the Newtonian world which moved in this absolute space and absolute time were material particles; small, solid and indestructible objects out of which all matter was made. The Newtonian model of matter was atomistic, but it differed from the modern notion of atoms in that the Newtonian particles were all thought to be made of the same material substance. Newton assumed matter to be homogeneous; he explained the difference between one type of matter and another not in terms of atoms of different weights or densities but in terms of more or less dense packing of atoms. The basic building blocks of matter could be of different sizes but consisted of the same "stuff," and the total amount of material substance in an object was given by the object's mass.

The motion of the particles was caused by the force of gravity, which, in Newton's view, acted instantaneously over a distance. The material particles and the forces between them were of a fundamentally different nature, the inner constitution of the particles being independent of their mutual interaction. Newton saw both the particles and the force of gravity as created by God and thus not subject to further analysis. In his *Opticks*, Newton gave a clear picture of how he imagined God's creation of the material world:

It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles, of such sizes and

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figures, and with such other properties, and in such proportion to space, as most conduced to the end for which he formed them; and that these primitive particles being solids, are incomparably harder than any porous bodies compounded of them; even so very hard, as never to wear or break in pieces; no ordinary power being able to divide what God himself made one in the first creation.<sup>27</sup>

In Newtonian mechanics all physical phenomena are reduced to the motion of material particles, caused by their mutual attraction, that is, by the force of gravity. The effect of this force on a particle or any other material object is described mathematically by Newton's equations of motion, which form the basis of classical mechanics. These were considered fixed laws according to which material objects moved, and were thought to account for all changes observed in the physical world. In the Newtonian view, God created in the beginning the material particles, the forces between them, and the fundamental laws of motion. In this way the whole universe was set in motion, and it has continued to run ever since, like a machine, governed by immutable laws. The mechanistic view of nature is thus closely related to a rigorous determinism, with the giant cosmic machine completely causal and determinate. All that happened had a definite cause and gave rise to a definite effect, and the future of any part of the system could—in principle—be predicted with absolute certainty if its state at any time was known in all details.

This picture of a perfect world-machine implied an external creator; a monarchical god who ruled the world from above by imposing his divine law on it. The physical phenomena themselves were not thought to be divine in any sense, and when science made it more and more difficult to believe in such a god, the divine disappeared completely from the scientific world view, leaving behind the spiritual vacuum that has become characteristic of the mainstream of our culture. The philosophical basis of this secularization of nature was the Cartesian division between spirit and matter. As a consequence of this division, the world was believed to be a mechanical system that could be described objectively, without ever mentioning the human observer, and such an objective description of nature became the ideal of all science.

The eighteenth and nineteenth centuries used Newtonian mechanics with tremendous success. The Newtonian theory was able to

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explain the motion of the planets, moons, and comets down to the smallest details, as well as the flow of the tides and various other phenomena related to gravity. Newton's mathematical system of the world established itself quickly as the correct theory of reality and generated enormous enthusiasm among scientists and the lay public alike. The picture of the world as a perfect machine, which had been introduced by Descartes, was now considered a proved fact and Newton became its symbol. During the last twenty years of his life Sir Isaac Newton reigned in eighteenth-century London as the most famous man of his time, the great white-haired sage of the Scientific Revolution. Accounts of this period of Newton's life sound quite familiar to us because of our memories and photographs of Albert Einstein, who played a very similar role in our century.

Encouraged by the brilliant success of Newtonian mechanics in astronomy, physicists extended it to the continuous motion of fluids and to the vibrations of elastic bodies, and again it worked. Finally, even the theory of heat could be reduced to mechanics when it was realized that heat was the energy generated by a complicated "jiggling" motion of atoms and molecules. Thus many thermal phenomena, such as the evaporation of a liquid, or the temperature and pressure of a gas, could be understood quite well from a purely mechanistic point of view.

The study of the physical behavior of gases led John Dalton to the formulation of his celebrated atomic hypothesis, which was probably the most important step in the entire history of chemistry. Dalton had a vivid pictorial imagination and tried to explain the properties of gas mixtures with the help of elaborate drawings of geometric and mechanical models of atoms. His main assumptions were that all chemical elements are made up of atoms, and that the atoms of a given element are all alike but differ from those of every other element in mass, size, and properties. Using Dalton's hypothesis, chemists of the nineteenth century developed a precise atomic theory of chemistry which paved the way for the conceptual unification of physics and chemistry in the twentieth century. Thus Newtonian mechanics was extended far beyond the description of macroscopic bodies. The behavior of solids, liquids, and gases, including the phenomena of heat and sound, was explained successfully in terms of the motion of elementary material particles. For the scientists of the eighteenth and nineteenth centuries this tremendous success of the mechanistic model confirmed their belief that the universe was indeed a huge mechanical system, running

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according to the Newtonian laws of motion, and that Newton's mechanics was the ultimate theory of natural phenomena.

Although the properties of atoms were studied by chemists rather than physicists throughout the nineteenth century, classical physics was based on the Newtonian idea of atoms as hard and solid building blocks of matter. This image no doubt contributed to the reputation of physics as a "hard science," and to the development of the "hard technology" based upon it. The overwhelming success of Newtonian physics and the Cartesian belief in the certainty of scientific knowledge led directly to the emphasis on hard science and hard technology in our culture. Not until the mid-twentieth century would it become clear that the idea of a hard science was part of the Cartesian-Newtonian paradigm, a paradigm that would be transcended.

With the firm establishment of the mechanistic world view in the eighteenth century, physics naturally became the basis of all the sciences. If the world is really a machine, the best way to find out how it works is to turn to Newtonian mechanics. It was thus an inevitable consequence of the Cartesian world view that the sciences of the eighteenth and nineteenth centuries modeled themselves after Newtonian physics. In fact, Descartes was well aware of the basic role of physics in his view of nature. "All philosophy," he wrote, "is like a tree. The roots are metaphysics, the trunk is physics, and the branches are all the other sciences."<sup>28</sup>

Descartes himself had sketched the outlines of a mechanistic approach to physics, astronomy, biology, psychology, and medicine. The thinkers of the eighteenth century carried this program further by applying the principles of Newtonian mechanics to the sciences of human nature and human society. The newly created social sciences generated great enthusiasm, and some of their proponents even claimed to have discovered a "social physics." The Newtonian theory of the universe and the belief in the rational approach to human problems spread so rapidly among the middle classes of the eighteenth century that the whole era became the "Age of Enlightenment." The dominant figure in this development was the philosopher John Locke, whose most important writings were published late in the seventeenth century. Strongly influenced by Descartes and Newton, Locke's work had a decisive impact on eighteenth-century thought.

Following Newtonian physics, Locke developed an atomistic view of

## THE NEWTONIAN WORLD-MACHINE

society, describing it in terms of its basic building block, the human being. As physicists reduced the properties of gases to the motion of their atoms, or molecules, so Locke attempted to reduce the patterns observed in society to the behavior of its individuals. Thus he proceeded to study first the nature of the individual human being, and then tried to apply the principles of human nature to economic and political problems. Locke's analysis of human nature was based on that of an earlier philosopher, Thomas Hobbes, who had declared that all knowledge was based on sensory perception. Locke adopted this theory of knowledge and, in a famous metaphor, compared the human mind at birth to a *tabula rasa*, a completely blank tablet on which knowledge is imprinted once it is acquired through sensory experience. This image was to have a strong influence on two major schools of classical psychology, behaviorism and psychoanalysis, as well as on political philosophy. According to Locke, all human beings—"all men," as he would say—were equal at birth and depended in their development entirely on their environment. Their actions, Locke believed, were always motivated by what they assumed to be their own interest.

When Locke applied his theory of human nature to social phenomena, he was guided by the belief that there were laws of nature governing human society similar to those governing the physical universe. As the atoms in a gas would establish a balanced state, so human individuals would settle down in a society in a "state of nature." Thus the function of government was not to impose its laws on the people, but rather to discover and enforce the natural laws that existed before any government was formed. According to Locke, these natural laws included the freedom and equality of all individuals as well as the right to property, which represented the fruits of one's labor.

Locke's ideas became the basis for the value system of the Enlightenment and had a strong influence on the development of modern economic and political thought. The ideals of individualism, property rights, free markets, and representative government, all of which can be traced back to Locke, contributed significantly to the thinking of Thomas Jefferson and are reflected in the Declaration of Independence and the American Constitution.

During the nineteenth century scientists continued to elaborate the mechanistic model of the universe in physics, chemistry, biology, psychology, and the social sciences. As a result the Newtonian world-ma-

chine became a much more complex and subtle structure. At the same time, new discoveries and new ways of thinking made the limitations of the Newtonian model apparent and prepared the way for the scientific revolutions of the twentieth century.

One of these nineteenth-century developments was the discovery and investigation of electric and magnetic phenomena that involved a new type of force and could not be described appropriately by the mechanistic model. The important step was taken by Michael Faraday and completed by Clerk Maxwell—the first one of the greatest experimenters in the history of science, the second a brilliant theorist. Faraday and Maxwell not only studied the effects of the electric and magnetic forces, but made the forces themselves the primary object of their investigation. By replacing the concept of a force with the much subtler concept of a force field they were the first to go beyond Newtonian physics,<sup>29</sup> showing that the fields had their own reality and could be studied without any reference to material bodies. This theory, called electrodynamics, culminated in the realization that light was in fact a rapidly alternating electromagnetic field traveling through space in the form of waves.

In spite of these far-reaching changes, Newtonian mechanics still held its position as the basis of all physics. Maxwell himself tried to explain his results in mechanical terms, interpreting the fields as states of mechanical stress in a very light, all-pervasive medium, called ether, and the electromagnetic waves as elastic waves of this ether. However, he used several mechanical interpretations of his theory at the same time and apparently took none of them really seriously, knowing intuitively that the fundamental entities in his theory were the fields and not the mechanical models. It remained for Einstein to clearly recognize this fact in our century, when he declared that no ether existed, and that the electromagnetic fields were physical entities in their own right which could travel through empty space and could not be explained mechanically.

While electromagnetism dethroned Newtonian mechanics as the ultimate theory of natural phenomena, a new trend of thinking arose that went beyond the image of the Newtonian world-machine and was to dominate not only the nineteenth century but all future scientific thinking. It involved the idea of evolution; of change, growth, and development. The notion of evolution had arisen in geology, where careful studies of fossils led scientists to the idea that the present state of

the earth was the result of a continuous development caused by the action of natural forces over immense periods of time. But geologists were not the only ones who thought in those terms. The theory of the solar system proposed by both Immanuel Kant and Pierre Laplace was based on evolutionary, or developmental, thinking; evolutionary concepts were crucial to the political philosophies of Hegel and Engels; poets and philosophers alike, throughout the nineteenth century, were deeply concerned with the problem of becoming.

These ideas formed the intellectual background to the most precise and most far-reaching formulation of evolutionary thought—the theory of the evolution of species in biology. Ever since antiquity natural philosophers had entertained the idea of a “great chain of being.” This chain, however, was conceived as a static hierarchy, starting with God at the top and descending through angels, human beings, and animals, to ever lower forms of life. The number of species was fixed; it had not changed since the day of their creation. As Linnaeus, the great botanist and classifier, put it: “We reckon as many species as issued in pairs from the hands of the Creator.”<sup>30</sup> This view of biological species was in complete agreement with Judeo-Christian doctrine and was well suited for the Newtonian world.

The decisive change came with Jean Baptiste Lamarck, at the beginning of the nineteenth century; a change that was so dramatic that Gregory Bateson, one of the deepest and broadest thinkers of our time, has compared it to the Copernican Revolution:

Lamarck, probably the greatest biologist in history, turned that ladder of explanation upside down. He was the man who said it starts with the infusoria and that there were changes leading up to man. His turning the taxonomy upside down is one of the most astonishing feats that has ever happened. It was the equivalent in biology of the Copernican revolution in astronomy.<sup>31</sup>

Lamarck was the first to propose a coherent theory of evolution, according to which all living beings have evolved from earlier, simpler forms under the pressure of their environment. Although the details of the Lamarckian theory had to be abandoned later on, it was nevertheless the important first step.

Several decades later Charles Darwin presented an overwhelming mass of evidence in favor of biological evolution, establishing the phe-

nomenon for scientists beyond any doubt. He also proposed an explanation, based on the concepts of chance variation—now known as random mutation—and natural selection, which were to remain the cornerstones of modern evolutionary thought. Darwin's monumental *Origin of Species* synthesized the ideas of previous thinkers and has shaped all subsequent biological thought. Its role in the life sciences was similar to that of Newton's *Principia* in physics and astronomy two centuries earlier.

The discovery of evolution in biology forced scientists to abandon the Cartesian conception of the world as a machine that had emerged fully constructed from the hands of its Creator. Instead, the universe had to be pictured as an evolving and ever changing system in which complex structures developed from simpler forms. While this new way of thinking was elaborated in the life sciences, evolutionary concepts also emerged in physics. However, whereas in biology evolution meant a movement toward increasing order and complexity, in physics it came to mean just the opposite—a movement toward increasing disorder.

The application of Newtonian mechanics to the study of thermal phenomena, which involved treating liquids and gases as complicated mechanical systems, led physicists to the formulation of thermodynamics, the "science of complexity." The first great achievement of this new science was the discovery of one of the most fundamental laws of physics, the law of the conservation of energy. It states that the total energy involved in a process is always conserved. It may change its form in the most complicated way, but none of it is lost. This law, which physicists discovered in their study of steam engines and other heat-producing machines, is also known as the first law of thermodynamics.

It was followed by the second law of thermodynamics, that of the dissipation of energy. While the total energy involved in a process is always constant, the amount of useful energy is diminishing, dissipating into heat, friction, and so on. The second law was formulated first by Sadi Carnot in terms of the technology of thermal engines, but was soon recognized to be of much broader significance. It introduced into physics the idea of irreversible processes, of an "arrow of time." According to the second law, there is a certain trend in physical phenomena. Mechanical energy is dissipated into heat and cannot be completely recovered; when hot and cold water are brought together, the

result will be lukewarm water and the two liquids will not separate. Similarly, when a bag of white sand and a bag of black sand are mixed, the result will be gray sand, and the more we shake the mixture the more uniform the gray will be; we will not see the two kinds of sand separate spontaneously.

What all these processes have in common is that they proceed in a certain direction—from order to disorder—and this is the most general formulation of the second law of thermodynamics: Any isolated physical system will proceed spontaneously in the direction of ever increasing disorder. In mid-century, to express this direction in the evolution of physical systems in precise mathematical form, Rudolf Clausius introduced a new quantity which he called "entropy." The term represents a combination of "energy" and "tropos," the Greek word for transformation, or evolution. Thus entropy is a quantity that measures the degree of evolution of a physical system. According to the second law, the entropy of an isolated physical system will keep increasing, and because this evolution is accompanied by increasing disorder, entropy can also be seen as a measure of disorder.

The formulation of the concept of entropy and the second law of thermodynamics was one of the most important contributions to physics in the nineteenth century. The increase of entropy in physical systems, which marks the direction of time, could not be explained by the laws of Newtonian mechanics and remained mysterious until Ludwig Boltzmann clarified the situation by introducing an additional idea, the concept of probability. With the help of probability theory, the behavior of complex mechanical systems could be described in terms of statistical laws, and thermodynamics could be put on a solid Newtonian basis, known as statistical mechanics.

Boltzmann showed that the second law of thermodynamics is a statistical law. Its affirmation that certain processes do not occur—for example, the spontaneous conversion of heat energy into mechanical energy—does not mean that they are impossible but merely that they are extremely unlikely. In microscopic systems, consisting of only a few molecules, the second law is violated regularly, but in macroscopic systems, which consist of vast numbers of molecules,\* the probability that the total entropy of the system will increase becomes virtual certainty. Thus in any isolated system, made up of a large number of mol-

\* For example, every cubic centimeter of air contains some ten billion billion ( $10^{19}$ ) molecules.