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PART TWO

FIELDS AND ATOMS

Prologue to Part Two

1. A REVOLUTION IN SCIENCE

The work of Isaac Newton concluded the scientific revolution that began in large part in A.D. 1549 when Nicholaus Copernicus first argued that the Earth is not stationary at the center of the Universe but rotates on its axis once a day and orbits the Sun once a year, along with the other planets. The revolution in science extended over the work of numerous "giants," as Newton called them—Galileo, Kepler, Descartes, and many others—resulting, by Newton's death in 1724, in the basis for the understanding of the physical world that we have today, what we call modern physics.

Many of the characteristics of modern physics that were established during the scientific revolution actually derived from the work of ancient thinkers, especially the work of the Ancient Greeks. This was because the Greeks were the first influential thinkers to seek explanations of natural events in terms of rational causes, rather than in the actions of supernatural beings. This meant that, for the first time, people regarded nature as accessible to human inquiry and study and governed by humanly understandable, rational principles. Truly scientific research was now possible.

As established by the scientific revolution, scientific research consists of the gathering of data through active experimentation and testing, not just passive observation or no observation at all. Galileo called experimental inquiry the "interrogation" of nature. The experimental evidence and closely related hypotheses are then joined together through rational processes and further experimental testing into a theory about the workings of nature that

Albert Einstein (1879–1955).

is then subject thereafter to revision, or even rejection, as new evidence becomes available.

Two of the main characteristic assumptions about nature that we have today can be traced, through Newton and the scientific revolution, back to the Ancient Greeks. The first is that nature is governed by a few, simple, clear rational laws and principles. From Plato and his followers, Newton and others came to realize that many of these principles can be expressed in mathematical terms and that the basic concepts of nature behave according to the rules of mathematics. Many centuries later, Albert Einstein declared: "the supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction."* In another statement he declared:

> I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena.†

* *Ideas and Opinions*, p. 226.

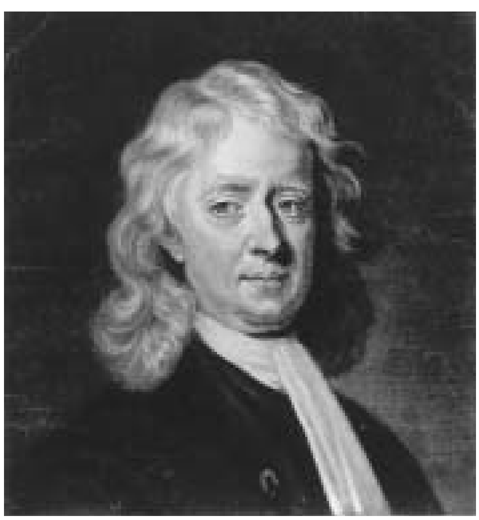
† *Ideas and Opinions*, p. 274.

A second characteristic assumption of contemporary physics goes back even further than Plato to the Greek thinker Democritus. Smelling the baking of bread one day, he reasoned that something must travel from the bread to his nose, even though he could not see anything traveling. He surmised that what traveled were extremely small, invisible "atoms" of bread. These and other considerations led to the hypothesis that the natural world consists of myriads of tiny atoms moving through empty space and clumping together to form the matter we see around us. Although this hypothesis was out of favor for nearly two millennia, it was revived and established as a foundation of physical science during the Scientific Revolution. The reason for the sudden popularity of atoms at that time is that, assuming nature consists of these inert bits of matter, the laws governing the events of nature can be clearly understood by referring to atoms, without having to refer to hidden spirits or other nonmaterial causes.

By assuming that matter consists of inert atoms moving around and clumping together in empty space, the behavior of everyday matter could be easily obtained from the properties of the atoms themselves and the few simple laws that govern their motion. These simple laws were Newton's famous *three laws of motion* (although they are not quite so simple as they may seem). They are:

1. The Law of Inertia:

   Every object continues in its state of rest or of uniform velocity (motion at uniform speed in a straight line) unless acted upon by an unbalanced force (a net force). Conversely, if an object is at rest or in motion with uniform velocity, all forces that may be acting on it must cancel so that the net force is zero.



Isaac Newton (1642–1727).

2. The Force Law:
   The net force acting on an object is numerically equal to, and in the same direction as, the acceleration of the object multiplied by its mass. In symbols: $\mathbf{F}_{net} = m\mathbf{a}$.
3. The Law of Action and Reaction:
   If one object exerts a force on another object, the second object at the same time exerts a force on the first object. These two forces, each acting on one of the two objects, are equal in magnitude and opposite in direction.

These laws are valid for all matter everywhere in the Universe, and they apply to matter in any form it takes, from planets and galaxies to space satellites and moving electrons in computers. They are still valid today.

We will not go into the details of these laws here (see Section 3.3), but you should be aware that for some concepts in these laws, such as force, acceleration, and velocity, the direction of the force or acceleration is as important as how large they are, their "magnitude." Concepts in which the direction and the magnitude are important are given a special name. They are called *vectors*. They are represented in this text in boldface. Other quantities that do not have a direction—such as mass and temperature—are called *scalars*. They are usually given in this text in italics, as are symbols representing only magnitudes of vectors.

You should also be aware that all quantities that can be measured are measured in carefully defined units. Although the American–English system of pounds, feet, and gallons is common in the United States, the metric system is used in science, since it is a decimal system. In this system, distance is usually measured in meters (m) or centimeters (cm), time in seconds (s), and force in newtons (N). Here

$$1 \text{ N} = 1 \text{ kg m/s}^2.$$

(See the *Student Guide* for further details. Your instructor may go over these units with you in class.)

Newton's crowning achievement was his discovery of the law of universal gravitation. According to this law, every massive object in the Universe attracts any other massive object with a force that can be given by a mathematical expression. This expression says that the force is equal to a constant times the product of the two masses, divided by the square of the distance between their centers, or in symbols:

$$F = \frac{Gm_1m_2}{R^2}.$$

This law is still valid today. For instance, it guides the launching of satellites from Earth or the fall of apples to the ground. However, while it is simple, it is not very clear. What exactly is this force and how does it operate? Newton was unable to provide an explanation in terms of only atoms moving through space; and it is still a problem today. But that does not prevent us from using the concept and equation for gravitational force today.

In the end atoms moving through space and time and clumping together by gravitation and other forces formed the basic conception of the entire Universe known as the "mechanical world view."

2. THE MECHANICAL WORLD VIEW

Once scientists realized the usefulness of the combination of the atomic hypothesis with the laws of motion and the force laws, all of which are based on experimental evidence, they were convinced that they had found the ultimate principles by which we can understand events in the physical world. This was an extremely important discovery. Since in physics the science of mechanics has to do with the study of matter in motion, this point of view became known as the "mechanical world view," which dominated physical science until well into the twentieth century. It is still prevalent today for everyday events on the human scales of distance, time, and speed, but not in situations where relativity and the quantum theory are important.

According to the mechanical world view, or the "mechanical philosophy," the physical world—the Earth, planets, and the entire Universe—can be understood in terms of atoms of matter interacting with each other as they move through space and time according to Newton's laws of motion and the pushes and pulls of gravitation and other forces. These mechanical principles were considered to be so fundamental that for centuries most scientists believed that a rational divine being must have established the Universe and everything in it according to mechanical principles.

In the mechanical view, atoms moved around and clumped together against the background of a flat, fixed, infinite space and in an unending linear unfolding of time. In an era when the first mechanical "grandfather" clocks were being invented, the Universe seemed to these scientists a clockwork universe, one that operates like a gigantic mechanical clock, constructed and set in motion by God in the beginning, and running smoothly against the backdrop of space and time ever since.

3. ENERGY AND ATOMS

The idea of a clockwork universe, based on the mechanical world view, enabled physical scientists to make enormous progress toward understanding the physical Universe. With this outlook scientists could be confident that all of the complex phenomena and their numerous unanswered questions about their world and the entire Universe would eventually be understood in terms of the basic, well-known principles of mechanical philosophy. Fired with the new confidence engendered by Newton's success, scientists turned to new areas of research in an attempt to discover the mechanical principles underlying these as yet unexplained phenomena, such as the behavior of heat, light, and electricity and magnetism. The first two of these are discussed in Part One of this text; we will start with electricity and magnetism in this part of the course.

Applying the mechanical world view to these fields led to great scientific progress in the centuries ahead. They also led to such important technological inventions as the steam engine, the electric generator, and the electric motor, which together helped to unleash the Industrial Revolution and the electric age, transforming the economic and social fabric of the world in which we live today. But, in the end, as you will see in the following chapters, these sciences also pointed to the limitations of the mechanical philosophy, leading ultimately to the contemporary theories of relativity theory and quantum mechanics. Part One of this text, which focuses on the study of motion, ended with relativity theory. This part, in which we investigate atoms and electromagnetism, will lead us into the strange and exciting world of quantum mechanics. We include the discussion of electromagnetism with that of atoms, because the structure and behavior of the atom itself involves electrical forces, while many properties of matter in the everyday world arise from the electrical behavior of atoms.

Before we enter the atomic world, you should know about the concepts of energy and atoms, which are more fully treated in Part One.

Energy

Energy is closely tied to forces. It is transported or transformed into different forms by the action of forces. For instance, a force exerted by a hand on a ball can transform the chemical energy in your muscles into the energy of motion of the ball. The energy of motion is called *kinetic energy*. This action is called *work*, and it is in the performance of useful work that machines are used in industrial processes. Like the arm throwing a ball, the work done by a machine represents the transformation of one form of energy, such as heat energy or electrical energy, into another form of energy, such as the spinning of a wheel.

During the 1800s researchers came to recognize many different forms of energy—heat energy, electrical energy, chemical energy, mechanical energy, and others. After careful studies they came to recognize that all of these forms of energy are different manifestations of one underlying entity—

energy—which can appear in the different forms that we observe. Further study, along with the encouragement of some philosophical notions about energy, led to the idea that in all energy-conversion processes occurring anywhere in nature—on Earth, in the Sun, inside an electric generating plant, etc.—the total amount of energy in the Universe, is never changed, it always stays the same—that is, the total amount of energy in the Universe is "conserved," although it can be transferred into different forms. This is the *Law of Conservation Energy*. It is still a fundamental law of nature today. It states:

> All natural events involve a transformation of energy from one form to another, but the total quantity of energy does not change during the transformation.

How Do We Know that Atoms Really Exist?

Since at least the time of the Ancient Greeks, many thinkers have postulated the existence of atoms. By "atoms" the Greeks meant invisibly small, hard, unbreakable balls of matter that make up the different elements constituting the material objects in the physical world. Such an idea was disregarded for many centuries until it was revived during the Scientific Revolution of the seventeenth century by such esteemed thinkers as Descartes, Boyle, Newton, and Gassendi. Studies of heat and chemistry during the nineteenth century lent strong support for this existence of the supposed atoms which, of course, no one could actually see (and which we can only barely see with today's apparatus). But not until about 1916 were the last doubters finally satisfied.

There are now several answers to the question: How do we know that atoms really exist? The *first answer* is that in *chemistry during the nineteenth century the work of John Dalton and many others showed that the elements combine in definite integral proportions to form chemical compounds*. This indicated that the atoms of the different elements combined in whole-number ratios to form molecules. These combinations never occurred in fractions of amounts, suggesting that there are indivisible integral units of each element, which we can call atoms. For instance, 1 unit of sodium combined with 1 unit of chlorine to produce 1 unit of salt, but never 1.5 units of sodium and 1.1 units of chlorine.

Second, *we know that atoms exist because the atomic theory of matter is highly successful in accounting for properties of matter that cannot be easily explained in any other way*. During the late nineteenth century, the properties of gases and the behavior of heat as a form of energy in different situations were all shown to be comprehensible in terms of the motions and interactions of the atoms, according to Newton's laws of motion.

But still some suggested that, although the atomic hypothesis was helpful and convenient, that did not make it necessarily valid. The third answer to the question proved to be decisive: in 1905 Albert Einstein showed that the *atomic theory provides the only detailed account of the purely random motion of large-scale molecules or microscopic pollen grains suspended in a stationary liquid.* The phenomenon, known as "Brownian motion" when pollen is involved, could be explained only by assuming that the suspended grains are subjected to random collisions by the much smaller molecules of the liquid, colliding randomly with each grain from different directions. Careful comparisons over the next few years resulted in complete agreement between Einstein's predictions and the observed random motion of Brown's pollen grains. Since then scientists have never seriously doubted the existence of atoms as the fundamental building blocks of all the forms of matter that we observe around us. Today, scanning tunneling microscopes and other high-resolution processes enable us, at last, to see direct evidence of individual atoms.

SOME NEW IDEAS AND CONCEPTS

atoms
Brownian motion
clockwork universe
conservation of energy
laws of motion
mechanical world view
scalars
vectors

STUDY GUIDE QUESTIONS

1. A Revolution in Science

1. What was the Scientific Revolution, and why is it important for us today?
2. What were some of the consequences of the scientific revolution for physics?
3. What was Newton's "crowning achievement?" How would you express it in your own words?

2. The Mechanical World View

1. Describe the mechanical world view in your own words.
2. What were some of the consequences of this world view for science?

3. Energy and Atoms

1. What is energy?
2. What is meant by the conservation of energy?
3. How do we know that atoms really exist?
4. How does Brownian motion relate to the existence of atoms?