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PART ONE

MATTER AND MOTION

Prologue to Part One

1. LIVING IDEAS

The purpose of this course is to explore the development and content of the major ideas that have led to our understanding of the physical universe. As in any science course you will learn about many of the important concepts, theories, and laws that make up the content of the science, physics in this case. But this course goes beyond that; it presents science as *experience*, as an integrated and exciting intellectual adventure, as the product of humankind's continual drive to know and to understand our world and our relationship to it.

Not only will you learn about the many ideas and concepts that make up our understanding of the physical world today but, equally important, these ideas will come alive as we look back at how they arose, who the people were who arrived at these ideas in their struggle to understand nature, and how this struggle continues today. Our story has two sides to it: the ideas of physics *and* the people and atmosphere of the times in which these ideas emerged. As you watch the rise and fall of physical theories, you will gain an appreciation of the nature of science, where our current theories came from, the reasons why we accept them today, and the impact of these theories and ideas on the culture in which they arose.

Finally, you will see how physics came to be thought of as it is today: *as an organized body of experimentally tested ideas about the physical world*. Information about this world is accumulating ever more rapidly as we reach out into space, into the interior of matter, and into the subatomic domain. The great achievement of physics has been to find a fairly small number of basic principles which help us to organize and to make sense of key parts of this flood of information.

2. OUR PLACE IN TIME AND SPACE

Since the aim of this course is to understand the physical world in which we live, and the processes that led to that understanding, it will help to begin with some perspective on where we are in the vast ocean of time and space that is our Universe. In fact, the Universe is so vast that we need a new yardstick, the *light year*, to measure the distances involved. Light in empty space moves at the fastest speed possible, about 186,000 miles every second (about 300,000 kilometers every second). A light year is not a measure of time but of distance. A light year is defined as the distance light travels in one year, which is about five trillion miles. The tables that follow provide an overview of our place on this planet in both space and time.

Current Estimates of Our Place in Time and Space

Time	*Years since start*
Age of the Universe	about 15 billion years
Age of our Sun and Earth	5 billion
Beginning of life on Earth	3.5 billion
Extinction of dinosaurs (Jurassic Age)	65 million
First humanoids	5 million
First modern humans	100,000
Rise of civilization	30,000
End of the last Ice Age	12,000
Height of Hellenic Greece	2500
Rise of modern science	400

Distance (from the center of the Earth)	
Edge of the Universe	about 15 billion light years
Nearest spiral galaxy (Andromeda)	2.2 million light years
Radius of our galaxy (Milky Way)	100,000 light years
Nearest star (Alpha Centauri)	4.3 light years, or 25 trillion miles
Distance to the Sun	93 million miles (150 million kilometers)
Distance to the Moon	239,000 miles (384,000 kilometers)
Radius of the Earth	3963 miles (6,370 kilometers) (about 1.5 times the distance between New York and Los Angeles)

You may be amazed to see from these tables that, within this vast ocean of the Universe measuring billions of light years across, a frail species evolved on a ball of mud only about 4000 miles in radius, orbiting an average star, our Sun, in an average corner of an average galaxy—a species that is nevertheless able, or believes it is able, to understand the most fundamental properties of the universe in which it lives. Even more astonishing: this frail species, which first appeared in contemporary form only about 100,000 years ago, invented an enormously successful procedure for focusing its mind and its emotions on the study of nature, and that procedure, modern science, is now only a mere 400 years old! Yet within that brief span of just four centuries science has enabled that species—us—to make gigantic strides toward comprehending nature. For instance, we are now approaching a fairly good understanding of the origins of matter, the structure of space and time, the genetic code of life, the dynamic character of the Earth, and the origins and fate of stars and galaxies and the entire Universe itself. And within that same period we have utilized the knowledge we have gained to provide many members of our species with unparalleled comforts and with a higher standard of living than ever previously achieved.

Take a moment to look around at everything in the room, wherever you are right now. What do you see? Perhaps a table, a chair, lamp, computer, telephone, this book, painted walls, your clothes, a carpet, a half-eaten sandwich . . . . Now think about the technologies that went into making each of these things: the electricity that makes the light work; the chemical processes that generated the synthetic fabrics, dyes, paints, plastics, processed food, and even the paper, ink, and glue of this book; the microtransistors that make a computer work; the solid-state electronics in a television set, radio, phone, CD player; the high-speed networking and software that allows you to read a Web page from the other side of the Earth.

All of these are based upon scientific principles obtained only within the past few centuries, and all of these are based upon technologies invented within just the past 100 years or so. This gives you an idea of how much our lives are influenced by the knowledge we have gained through science. One hardly dares to imagine what life will be like in another century, or even within a mere 50, or 25, or 10 years!

Some Discoveries and Inventions of the Past 100 Years

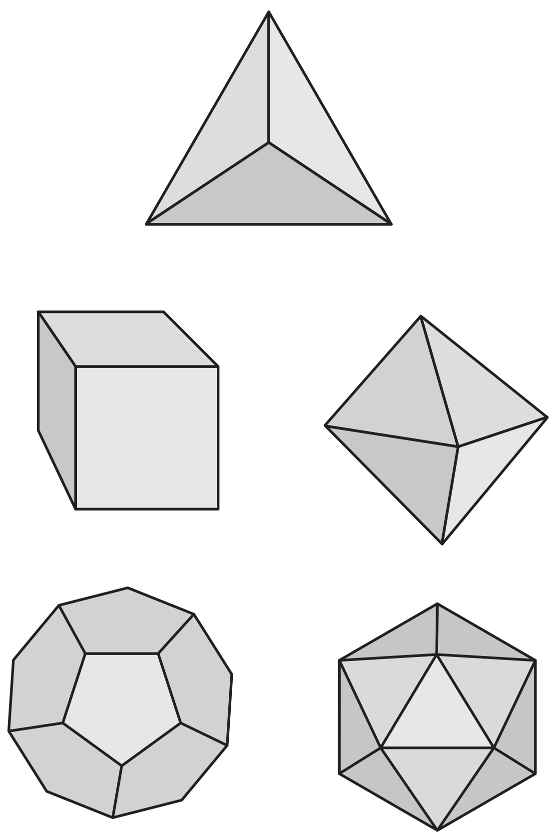
airplane	structure of DNA
automobile	microchip
expansion of the Universe	organ transplants
penicillin	first human landing on the Moon
motion picture with sound	laser
elementary particles	MRI and CT scan
plate tectonics	personal computers
nuclear weapons	Internet
polio vaccine	planets around stars other than our Sun
first artificial satellite (Sputnik)	human genome

Let's look at some of the fundamental ideas of modern physics that made many of these inventions and discoveries possible.

3. FIRST THINGS FIRST

The basic assumptions about nature, the procedures employed in research today, and even some of our theories have at bottom not changed much since the rise of modern physics. Some of these assumptions originated even earlier, deriving from the ancient world, especially the work of such Greek thinkers as Plato, Aristotle, and Democritus.

What set the Greeks apart from other ancients was their effort to seek nonanimistic, natural explanations for the natural events they observed and to subject these explanations to rational criticism and debate. They were



The five "regular solids" (also called "Pythagorean figures" or "Platonic solids") that appear in Kepler's *Harmonices Mundi (Harmony of the World)*. The *cube* is a regular solid with six square faces. The *dodecahedron* has 12 five-sided faces. The other three regular solids have faces that are equilateral triangles. The *tetrahedron* has four triangular faces, the *octahedron* has eight triangular faces, and the *icosahedron* has 20 triangular faces.

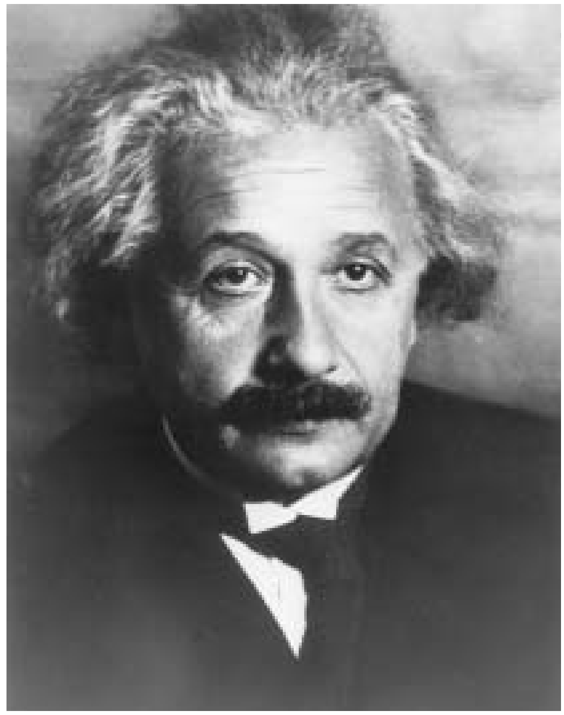
also the first to look for rational, universal first principles behind the events and phenomena they perceived in nature. On the other hand, the use of experimental investigation, now a fundamental tool of modern science, was invoked by only a few of the Greek thinkers, instead of being built in as an indispensable part of their research.

In seeking the first principles, Greek thinkers utilized the notion that all things are made up of four basic "elements," which they called earth, water, air, and fire. In many ways they viewed these elements the way we might view the three states of matter: solid, liquid, and gas, with heat (fire) serving as the source of change. (Some added a fifth element, called "quintessence," constituting the celestial objects.) The Greek philosopher Plato (427?–347 B.C.), regarded mathematical relationships as constituting the permanent first principles behind the constantly changing world that we observe around us. As such, Plato associated the five elements with the five Platonic solids in solid geometry. (Refer to pg. 6.) Although we no longer hold this view, scientists today often do express physical events, laws, and theories in terms of mathematical relationships. For instance, the physicist Albert Einstein wrote in 1933:

> 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. . . . Experience remains, of course, the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.*

The Greek thinker Democritus (fl. c. 420 B.C.) and his followers offered a quite different account of the permanent first principles constituting the elements that give rise to observed phenomena. For them, the elements are not made up of abstract geometrical figures but of individual particles of matter that they called "atomos," Greek for "indivisible." Democritus is said to have thought of the idea of atoms when smelling the aroma of freshly baked bread. He surmised that, in order to detect the smell, something had to travel from the bread to his nose. He concluded that the "something" must be tiny, invisible particles that leave the bread carrying the smell of the bread to his nose—an explanation that is quite similar to the one we have today! For the "atomists" down through the centuries, all of reality

* A. Einstein, *Ideas and Opinions* (New York: Crown, 1982), p. 274.



Albert Einstein (1879–1955).

and everything that can be perceived with their senses could be explained in terms of an infinite number of eternally existing indivisible atoms, moving about and clumping together in infinite empty space to form stars, planets, and people.

Like Plato's notions, the views of the ancient atomists bore some striking similarities to our current views. We too have a relatively small number of "elements" (92 naturally occurring elements) which we associate with different types of atoms, as you can see from the periodic table. And we too attribute the properties of everyday matter to the combinations and interactions of the atoms that constitute the matter. However, our atoms have been shown to be divisible, and they, along with the elements, behave quite differently from Greek atoms and elements. Moreover, our atomic idea is no longer just a speculation but an accepted theory based firmly upon experimental evidence. Since the days of Plato and Democritus, we have learned how to bring reason and experiment together into the much more powerful tool of research for exploring and comprehending atomic properties underlying the phenomena we observe in nature.

Unfortunately, both Plato and Aristotle rejected the atomic hypothesis of Democritus and his followers. Aristotle, Plato's pupil, also rejected Plato's

PLATO'S PROBLEM

Like many ancient thinkers, Plato believed that the celestial bodies must be perfect and divine, since they and their motions are eternal and unchanging, while the components of the earthly, terrestrial world are constantly changing. Thus, for him, analysis of the motions of the heavenly bodies according to mathematical principles became a quest for divine truth and goodness. This was the beginning of modern mathematical astronomy—although of course we no longer seek divine truth and goodness in celestial motions. But his idea was also the beginning of a split in the physical world between the Earth on the one hand and the rest of the Universe on the other, a split that was healed only with the rise of modern science.

It is said that Plato defined an astronomical problem for his students, a problem that lasted for centuries until the time of Johannes Kepler and Galileo Galilei, over 350 years ago. Because of their supposed perfection, Plato believed that the celestial objects move around the Earth (which he regarded as the center of the Universe) at a perfectly uniform, unchanging speed in what he regarded as the most "perfect" of all geometrical figures, the circle. He chose the circle because it is unending yet bounded, and encompasses the largest area inside a given perimeter. The problem Plato set for his followers was to reduce the complicated motions of the Sun, Moon, planets, and stars to simple circular motions, and to show how the complexity of their observed motions can arise from the interaction of mathematically simple perfect circles rotating with constant speeds.

Plato's problem, applied to the observed motions of the planets, as well as to the other celestial objects, was a problem that occupied most of the best mathematical astronomers for centuries. During the Renaissance, people found that Plato's assumption of perfectly circular motions at constant speed was no longer useful and did not agree with more precise observations.

theory. Instead, he offered a much more appealing and more fully worked-out system as an alternative to both Plato and the atomists. As a result, Aristotle's views dominated scientific thought for centuries, and Plato's penchant for mathematics and Democritus's atomic hypothesis were set aside for centuries.

4. ARISTOTLE'S UNIVERSE

The Greek philosopher Aristotle (384–322 B.C.) argued that we should rely on sense perceptions and the qualitative properties of bodies, which seem far more real and plausible than abstract atoms or mathematical formulas.

After all, we can see and touch a glob of earth, and feel the wetness of water or the heat of fire, but we can't see or touch an atom or a triangle. The result was an amazingly plausible, coherent, and common-sense system that naturally appealed to people for centuries.

As did Plato, Aristotle divided the Universe into two separate spheres: the celestial sphere, the heavens above where unchanging perfection resides; and the terrestrial sphere here below, where all change and imperfection and corruption and death are found. The upper boundary of the terrestrial sphere is the Moon, which is obviously imperfect, since one can see dark blotches on it. All change, such as comets, novae (exploding stars), and meteors, must occur below the Moon, which is also the limit of the reign of the four basic elements. Above the Moon are the perfect celestial bodies. These, to the naked eye, display no markings at all. So Aristotle attributed to them Plato's fifth element, quintessence, which fills all of space above the Moon. One of the assumed properties of quintessence was that it moves by itself in a circle. (In one of Aristotle's other writings he further argued that since every motion requires a mover, there must be a divine being—an "unmoved mover"—outside the whole system, who keeps it spinning.)

Aristotle argued that the spinning motion of the heavens around the Earth at the center caused a spinning motion of the terrestrial sphere—like an object in a giant washing machine—which in turn caused the four elements to separate out according to their weight (or density). In this system the "heaviest" element, Earth, coalesced in the center. On top of that came the next heaviest element, water, which covers much of the Earth in the form of oceans, lakes, and rivers. Then comes air, and finally fire, the lightest element. The terrestrial sphere is completely filled with these four elements, while the celestial sphere from the Moon outward is completely filled with quintessence. There is no empty space, or vacuum, anywhere.

Aristotle's system seemed quite plausible. A natural vacuum is extremely rare in daily experience, while in the whirling motion of a system of tiny objects of different densities (representing different elements) the objects actually do separate as he indicated. Einstein later explained that the pressure in a fluid mixture during rotation of materials of various densities forces the most dense material to the center, followed by the next dense material, and so on—resulting in layers of materials according to density, just as Aristotle had argued!

Aristotle applied his arrangement of the elements to explanations of practically everything. According to Aristotle, as a result of the whirling motion of the cosmos, each of the four elements ended up in a special place where it "belongs" according to its "weight" (really density): earth at the center, followed by water, then air, then fire, just as we see around us. However, because of imperfections in the system below the celestial objects, the

The four ancient "elements," shown superimposed on the Earth at the center of the whole Ptolemaic Universe.

separation of the four terrestrial elements was not quite complete, trapping some of the elements in the "wrong" place. If they are freed, they will head straight "home," meaning to the place where they belong—straight being in a vertical direction, either straight up or straight down. Such motions require no explanation; they are simply natural. (This is discussed further in Section 3.1.)

Mixing the elements and their natural motions helped to explain some of the changes and events one can see all around us. For instance, a stone lifted from the earth and released will drop straight down through air and water to reach the earth where it "belongs" at the bottom of a pond. A flame lit in air will move straight upward, as does a bubble of air trapped under water. Water trapped in the Earth will emerge onto the surface as springs or geysers; air emerges from the Earth by causing earthquakes; fire trapped in the Earth breaks forth in volcanoes. Oil, he believed, contains air in addition to earth and water, so it floats on water. Clouds, according to Aristotle, are condensed air mixed with water. They are densest at the top, Aristotle claimed, because they are closest to the source of heat, the Sun. Wind and fire squeezed out of the cloud produce thunder and lightning—a far cry from an angry Zeus hurling thunderbolts!

As you can see, Aristotle's explanations are all "commonsensical"—plausible, and reasonable, if you don't ask too many questions. Everything fit together into a single, rational cosmic scheme that could explain almost everything—from the behavior of the cosmos to the appearance of springs of water. Although the wide acceptance of Aristotle's system discouraged the consideration of more fruitful alternatives, such as those of Plato and the atomists, the dominance of his views for centuries encouraged the domination of the search for rational explanations of natural events in plausible, human terms that is one of the hallmarks of modern science. Aristotle was considered such an authority on the rational workings of nature that he was called for centuries simply "the Philosopher."

But This Is Not What We Today Would Call Science

Seen from today's perspective, the problem is not chiefly with the content but with the approach. For Aristotle, a theory was acceptable if it was logically sound, if all of the ideas were consistent with each other, and if the result was plausible. That is fine as far as it goes, and it is found in all theories today. But he did not take a necessary step further. He could not provide precise, perhaps even *quantitative*, explanations of the observed events that could be tested and confirmed, for example, in a laboratory. He offered only *qualitative* descriptions. For instance, things are not just hot or cold, but they have a precise temperature, say $-16°C$ or $+71°C$. Nor did Aristotle think of explanations of events, no matter how logically sound, as being tentative hypotheses that must be tested, debated, and compared with the experimental evidence. Also, he rejected the approach of Plato and the atomists in which explanations of phenomena should involve the motions and interactions of invisible individual elements. Without resting on experimental research or more general underlying principles, Aristotle's philosophy lacked the capability of modern science, in which experiment, mathematics, and the atomic hypothesis are brought together into a powerful instrument for the study of nature.

WHAT IS SCIENCE?

The American Physical Society, the leading society of professional physicists, has issued the following statement in answer to the question "What is Science?":

> Science extends and enriches our lives, expands our imagination, and liberates us from the bonds of ignorance and superstition. The American Physical Society affirms the precepts of modern science that are responsible for its success.
>
> Science is the systematic enterprise of gathering knowledge about the Universe and organizing and condensing that knowledge into testable laws and theories.
>
> The success and credibility of science are anchored in the willingness of scientists to:
>
> 1. Expose their ideas and results to independent testing and replication by other scientists. This requires the complete and open exchange of data, procedures, and materials.
> 2. Abandon or modify accepted conclusions when confronted with more complete or reliable experimental evidence.
>
> Adherence to these principles provides a mechanism for self-correction that is the foundation of the credibility of science.

And when these elements were brought together, especially in the study of motion, modern physics emerged.

SOME NEW IDEAS AND CONCEPTS

animism
atoms
elements
first principles
terrestrial sphere

FURTHER READING

G. Holton and S.G. Brush, *Physics, The Human Adventure, From Copernicus to Einstein and Beyond* (Piscataway, NJ: Rutgers University Press, 2001), Chapters 1 and 3.

D.C. Lindberg, *The Beginnings of Western Science* (Chicago: University of Chicago Press, 1992).

K. Ferguson, *Measuring the Universe: Our Historic Quest to Chart the Horizons of Space and Time* (New York: Walker, 1999).

STUDY GUIDE QUESTIONS

1. Living Ideas

1. What are the "living ideas"? What makes them alive?
2. What is the twofold purpose of this course?
3. Why did the authors of this book choose this approach, instead of the standard emphasis on laws, formulas, and theories that you may have encountered in other science courses?
4. What is your reaction to this approach?

2. Our Place in Time and Space

1. How would you summarize our place in time and space?
2. In what ways is technology different from science? In what ways is it the same?

3. First Things First

1. Why, in this chapter, did we look back at the Ancient Greeks before introducing contemporary physics?
2. What was so special about the Ancient Greeks, as far as physics is concerned?
3. What types of answers were they seeking?
4. What did the word "elements" mean to the Greeks?
5. What are the two proposed solutions to the problem of change and diversity examined in this section?

4. Aristotle's Universe

1. What did Aristotle think was the best way to find the first principles?
2. What types of principles did he expect to find?
3. Describe Aristotle's cosmology.
4. Why is Aristotle's system not yet what we call science? What are the characteristics of science as presently understood?
5. Describe how Aristotle explained one of the everyday observations.
6. How would you evaluate Aristotle's physics in comparison with physics today?
7. A researcher claims to have reasoned that under certain circumstances heavy objects should actually rise upward, rather than fall downward on the surface of the Earth. As a good scientist, what would be your reaction?