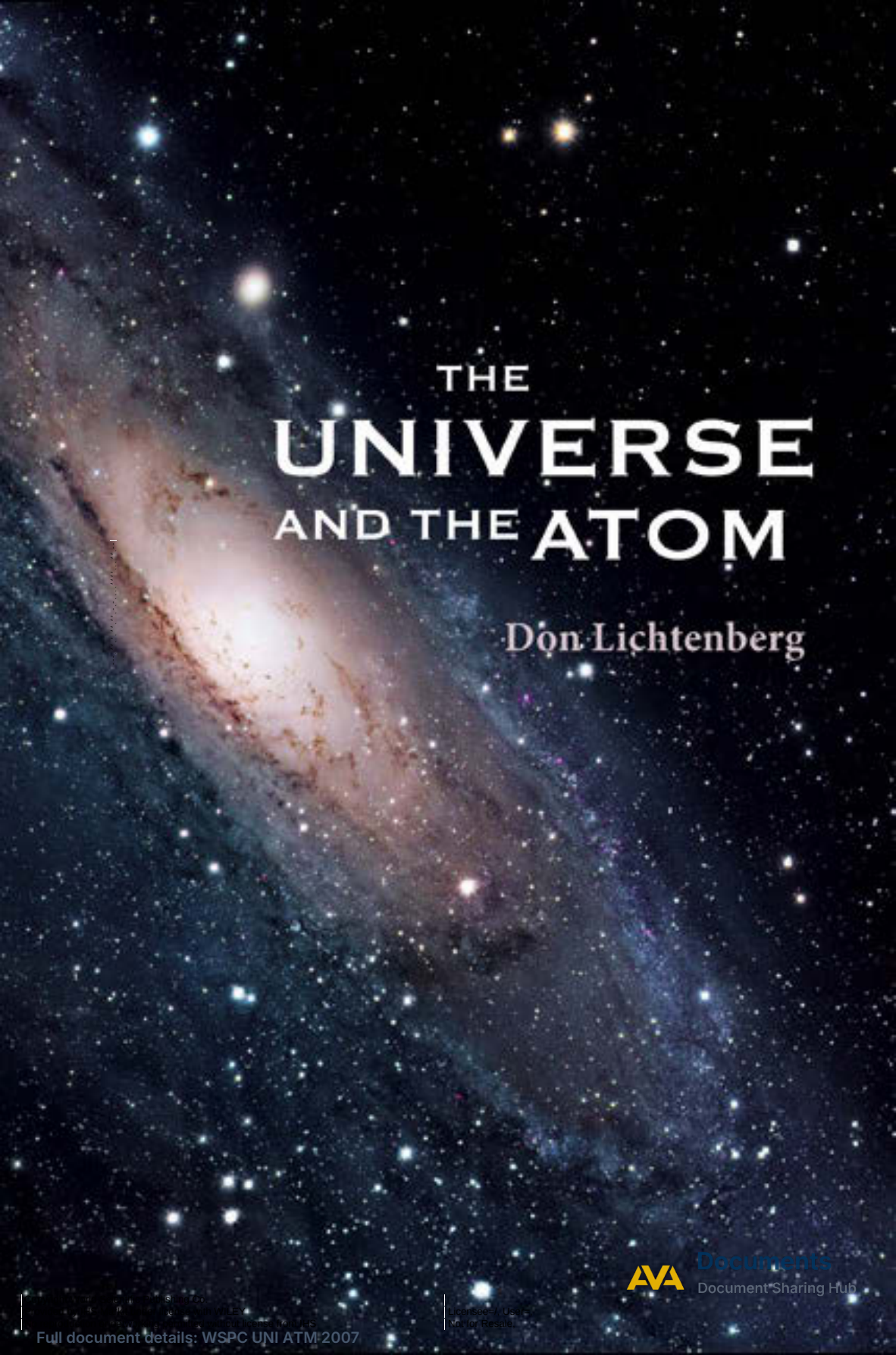




THE UNIVERSE AND THE ATOM

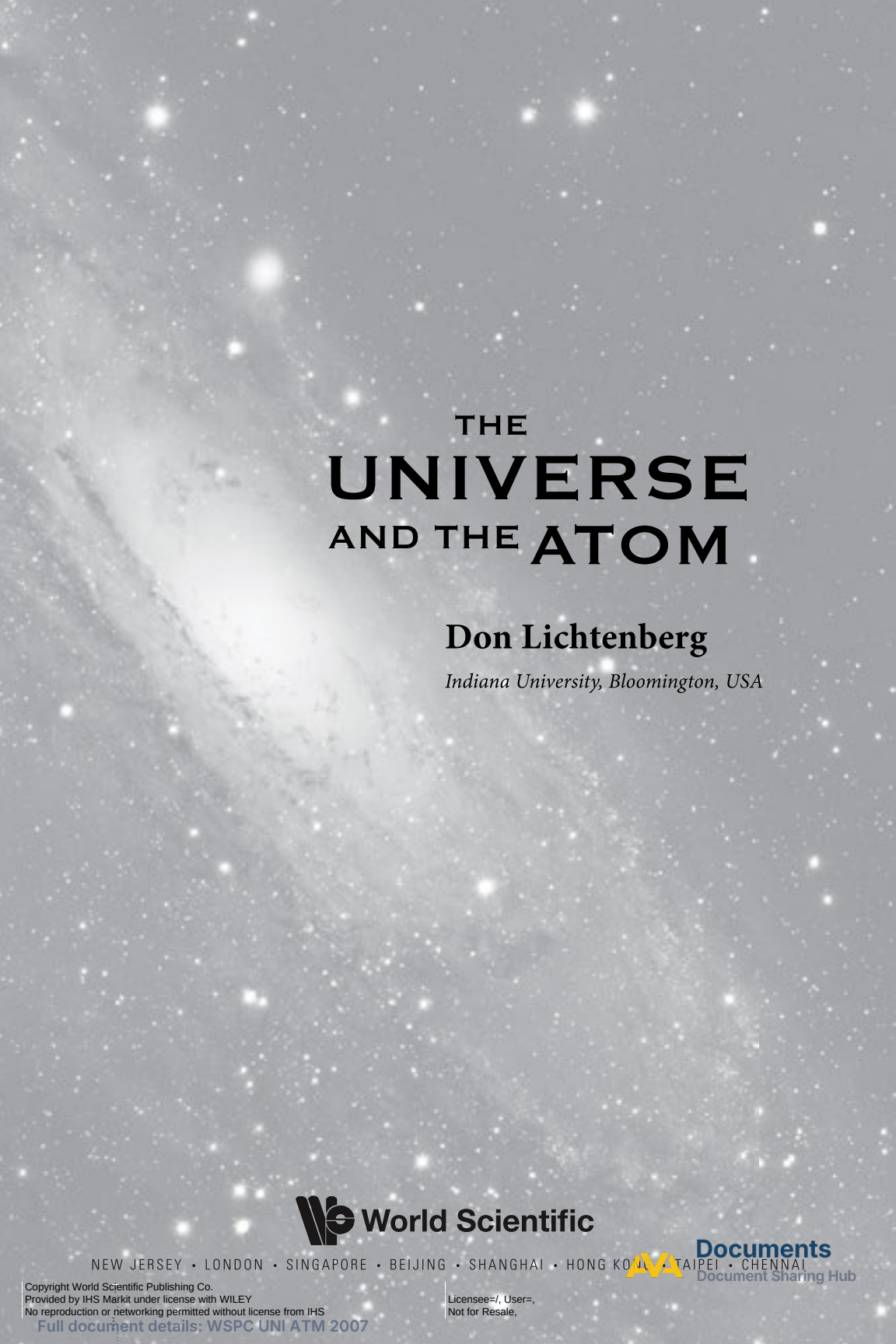
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THE UNIVERSE AND THE ATOM

Don Lichtenberg

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To Rita, Naomi and Rebecca

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Preface

One thing that distinguishes human beings from the other animals is our curiosity about nature. A wolf may look at the moon and howl at it, but only human beings want to know how big it is and how far away, what it is made of and why it changes its appearance. More generally, we want to know the way nature works, even if our knowledge brings no practical benefit. As history has turned out so far, some of the knowledge we have gained about nature has not helped us materially at all, but other knowledge has led to profound changes in our civilization. Unfortunately, not all these changes have been for the good.

Our senses let us perceive nature only at intermediate sizes, but not at the very small and the very large. We can look at a tree but we cannot see the atoms that make up the tree. We can look at a portion of the earth, but our vantage point does not let us see directly that the earth is a sphere.

In this book we shall be principally concerned with nature at both the smallest and the largest scales, from atomic and subatomic particles to the universe as a whole. We want to answer as well we can the questions: “What are we made of?” and “What is the nature of the universe in which we live?”

We are, of course, made of flesh and blood, bones and hair, and we live on the earth. But on a smaller scale our bodies are made of cells, and the cells are made of molecules. In turn, the molecules are made of atoms, and atoms are made of electrons and atomic nuclei. As far as we know, the electrons are elementary in the sense that they are not composed of smaller things. However, atomic nuclei are made of protons and neutrons, which in turn are made of quarks. That is where our present understanding of the nature of matter ends, although there are speculations about even deeper levels. On a larger scale, the earth is the third planet from the sun in our solar system, and the solar system is in our galaxy, the Milky Way, which is a system of more than a hundred billion stars plus dust and other kinds of matter held subject to their mutual gravitational attraction. The Milky Way in turn is only one galaxy (system of stars) of many billions of galaxies that exist in the visible universe. And there have been speculations about what lies beyond the visible universe and whether we can ever know anything about it.

We are about to take a journey into the world of the very small and the world of the very large. What we shall find will be so foreign to our senses and so much against our intuition as to be almost beyond belief. Mankind has long thought about what matter is made of and what the universe is like. However, it was not until the twentieth century that our knowledge has grown so much that today we have a largely coherent picture at what nature is like at both large and small scales.

In order to make sense out of the very large and the very small, we have to devote some of our effort to examining nature on a human

scale. In this way, we learn some of the laws of physics that we need, and we also learn of some laws that seem to satisfy common sense, but have only a limited range of validity. We often take a historical approach and discuss old ideas that seem either quaint or silly today, but it is beneficial to learn what went wrong with earlier scientific ideas.

Scientific knowledge is always provisional. Based on past experience, we can be confident that new discoveries will change the way we look at nature in many ways. However, many of our present ideas are rooted firmly in the results of a large number of observations and experiments, and so we can be confident that much of our present picture will endure.

The bibliography contains a number of books on the topics I treat here. I acknowledge freely consulting several of these books to obtain part of the material I used. I consulted other sources, especially on the web, as well. I have made decisions about what information to include, updated material when necessary, and put my own stamp on the presentation. I also acknowledge beneficial conversations with my good friends and colleagues at Indiana University, Steven Gottlieb and Roger Newton. I am thankful to Bruce Carpenter of Indiana University for doing the drawings and to Andrew Chan Yeu Tong for his assistance with the editing and Alvin Chong of World Scientific for his cooperation in publishing this book.

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Chapter 1

Early Ideas about the Universe

To deride the hope of progress is the ultimate fatuity, the last word in poverty of spirit and meanness of mind.

—Sir Peter Medewar (1915–1987)

1.1 The earth

In early times, most scholars regarded the earth as the center of the universe. This is only natural, as the earth appears huge to our senses. Everything in the heavens looks tiny by comparison, even the sun. In various cultures, the earth was regarded either as a flat disk or as a sphere. It is also understandable why some civilizations thought the earth was flat except for irregularities, such as mountains, on its surface. The reason, of course, is that the earth is so large that we cannot normally see the curvature of its surface. This is the first of many instances in which we shall find that the universe is quite different from the way it appears to our senses.

We can get a clue that the surface of the earth is curved. If we

look at a ship approaching us far away at sea, the top of the ship comes into view first, when the part at the waterline is still below the horizon.

In modern times, we have had ample evidence that the earth is a sphere (to a good approximation). A few hundred years ago explorers circumnavigated the earth with sailing ships. More recently, airplanes and manned artificial satellites have flown around the earth. The fact that the earth looks round from every vantage point shows that it is a sphere. If the earth were some other shape, for example, a round disk, it could be viewed edgewise and appear to be thin. A sphere has more symmetry than any other shape because it is the only shape that looks round no matter from where it is viewed. Of course, the view has to be from far enough away that we can see the earth's roundness. The earth is so large that from its surface it appears flat, or rather, lumpy, with mountains and valleys.

It is interesting that many people who thought the earth was flat regarded it as a disk rather than a square or some irregular shape. Also, most of the flat-earth people thought they stood on the top side of the earth, the top being toward the heavens. What was below was only guessed at. People who believed in a flat earth thought that it was possible to fall off its edge, but, somehow, nobody ever saw the edge, and so they must have thought that they were always far away from it. The alternative view, that the flat earth was infinite in size (in other words, that there was no end to the earth in any direction) does not seem to have been seriously considered by most flat-earth advocates.

Those who regarded the earth as a sphere (apart from irregular-

ities such as mountains) knew that it could be finite in size without having an edge. We now know that the earth is not quite a sphere, as it bulges outward at the equator because it is rotating on its axis once a day. With a spherical or almost spherical earth, the direction “down” is toward the center of the earth. People thought either that it was “natural” for bodies to fall toward the earth or that bodies fell because of some “influence” (later called gravity). There is not as much difference between these two points of view as appears, because gravity is a natural influence. Today we realize that a quantitative description of how bodies fall is very useful.

1.2 The heavens

According to many of the ancients, the heavens are what we see above the earth. These consist of the sun, the moon, the planets, the stars, and other objects occasionally, like comets and meteors. Even in early times, the planets were distinguished from the stars by their motion. They moved relative to the stars, and the name “planet” in Greek means “wanderer.”

One of the earliest civilizations to have ideas about the universe was the Babylonian, located in what is now Iraq. We know from ancient writings that by 1700 BCE the Babylonians knew the length of a year to within a few minutes. The Babylonians divided the year into twelve lunar months. A lunar month is the time for the moon to go from full moon to full moon, as observed on earth, a time of somewhat more than 29 days. Because a year is a little longer than 12 lunar months, the Babylonians included a leap month every few

years.

The Babylonians divided the circle into 360 degrees, each degree into 60 minutes, and each minute into 60 seconds. We still use these units of angular measurement, but we also use others. In Figure 1.1 we show a circle with angles of 30 degrees and 90 degrees marked off. A degree is abbreviated $^{\circ}$.

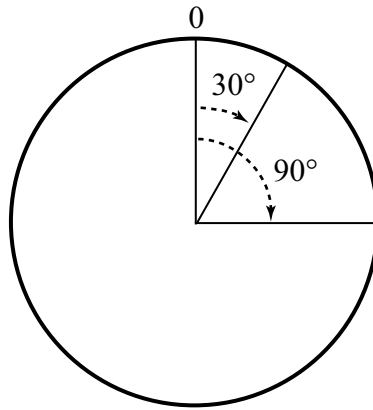


Figure 1.1: A circle, showing angles of 30 degrees and 90 degrees.

1.3 The views of Aristotle and Aristarchus

We skip over the accomplishments of the Chinese and Indian astronomers and pass directly to the Greeks. The most influential Greek philosopher was Aristotle (384–322 BCE). He proclaimed that knowledge of nature should be based on observation, an idea that was a great advance over that of Plato, who insisted that knowledge should come primarily from pure reason. However, Aristotle did not always follow his own precepts, often slipping into the patterns of thought

of Plato. Furthermore, Aristotle often drew wrong conclusions from his observations.

Aristotle regarded the earth, the sun, and the moon as spherical, and said that the heavenly bodies move in circles around the earth, which is stationary and at the center of the universe. In this scheme, the sun and the stars go around the earth once every day, whereas we now know that the earth rotates around its axis once a day, giving rise to the apparent motion of the sun and stars.

Aristotle took over most of his ideas about the earth and the heavens from earlier Greek philosophers, including Pythagoras and Plato. Who can blame Aristotle? From our vantage point it certainly looks like the earth is the center of the universe.

The first Greek I know of who claimed the earth is spherical was Pythagoras (d. 497 BCE). Pythagoras did not give any evidence for his belief, but made his claim on esthetic grounds. On the other hand, Aristotle had several reasons for believing that the earth is spherical, the most compelling one being that during a lunar eclipse, the shadow of the earth appears as part of a circle as it moves across the surface of the moon.

Somewhat later, Eratosthenes (b. around 276 BCE, d. ?), who was born in what is now Libya and lived in Athens and Alexandria, made a measurement that enabled him to estimate the circumference of the earth. He had heard that on the summer solstice (June 21), the sun was directly overhead at noon in a place called Syene, now Aswan, Egypt. Eratosthenes, then living in Alexandria (which is north of Syene), found that the shadow of a stick made an angle of about 7 degrees, or about 1/50th of a complete circle. (The angle is the

one made between the vertical and the line connecting the top of the stick to the end of the shadow.) He was able to find out the distance between Syene and Alexandria, and calculated that the circumference of the earth was about 50 times as great. We are not sure of the exact size of the units of distance used by Eratosthenes, but he came pretty close to determining the circumference of the earth to be around 25,000 miles, its present value.

We return to Aristotle. In his view, the earth and its neighborhood are made of four elements: earth, air, water, and fire. The heavens are made of a fifth substance, which he called “ether” or “quintessence.” Today we know that Aristotle was naive in his assertions. For example, there are many different substances in what he called “earth,” as it is easy to tell by just looking at the large variety of different objects on the earth. We now know that these different objects are made of fewer than 100 naturally occurring substances called “elements.” We shall discuss the elements in much more detail in later chapters.

The Greek astronomer Aristarchus of Samos (310–230 BCE), deduced the relative sizes of the earth, sun, and moon by geometrical means. Finding that the sun is much larger than the earth, he concluded that the earth must move around the sun, because he could not believe that the greater body moves around the lesser one. The notion that the earth revolves around the sun is called the “heliocentric” view.

Aristarchus also believed that the earth rotates on its axis, causing day and night, and that the earth’s axis is tilted with respect to the ecliptic (the name given to the plane of the earth’s orbit around the sun). We do not have the writings of Aristarchus to support his con-

clusions, but he is quoted by the great Greek physicist Archimedes (287–212 BCE).

In the following centuries, Aristarchus's ideas were not widely appreciated, in part owing to the influence of the Aristotle, who had common sense on his side. If the earth is moving, why do we not feel that it is moving? Why do we not fall off? The Greeks at the time of Aristotle had no answers to these questions because they did not understand the ideas of inertia and of gravity. These concepts were understood only after the sixteenth century and will be discussed in later chapters.

After Aristarchus, the greatest Greek astronomer was Hipparchus, who lived in the second century BCE. Using trigonometry, he refined Aristarchus's work, obtaining the relative sizes of the earth, sun, and moon more accurately. Nevertheless, Hipparchus accepted Aristotle's view that the sun moves around the earth, rather than the reverse.

The reason for Hipparchus's conclusion is that if the earth moves around the sun, then the stars should appear to shift their positions as seen from the earth. This shifting is known as "stellar parallax," and Hipparchus did not observe it. To understand parallax, hold a finger a foot in front of your face, and look at the finger, alternately with one eye closed and then with the other eye closed. The finger appears to be in different positions relative to the background in the two cases. The reason is that the two eyes, being separated, view the finger from different angles. The angular separation of the two apparent positions of the finger is known as parallax. Knowing the separation of the eyes, one can calculate the distance of the finger

from the difference in observed angle. The farther away an object is from us, the smaller the angular separation when we view it from different positions. We are not confined to the different angles seen by our two eyes. For far-off objects, we can move to different places on earth, and see how the angle changes. Then we can calculate the distance of the object by how much the angle differs when viewed from the two places.

If the earth moves around the sun, then the positions of stars should appear different in winter and summer, when the earth is at opposite sides of its orbit. The difference in observed position relative to more distant stars is called “stellar parallax.” We illustrate stellar parallax in Figure 1.2.

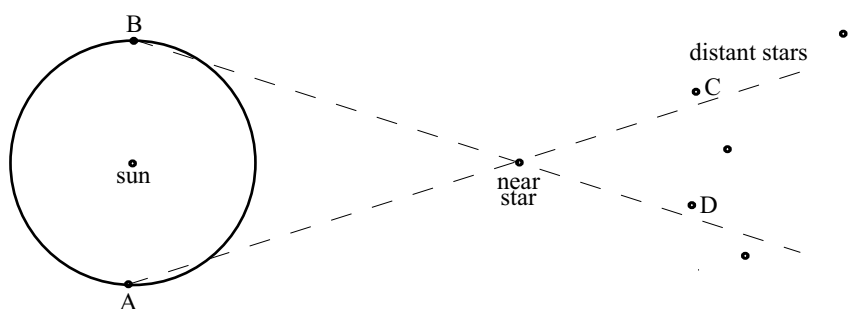


Figure 1.2: Stellar parallax. When the earth is at A in its orbit, a nearby star seems near distant star C, but when the earth is at B, the nearby star seems near distant star D. So the nearby star apparently moves with respect to distant stars. The figure is not drawn to scale.

But Hipparchus did not observe stellar parallax and so concluded that the earth did not move. Hipparchus’s idea to look for stellar parallax was a good one, and with telescopes we can observe stellar parallax for the closer stars. But the amount of parallax decreases with

distance of the observed object, and even the closest stars are too far away for Hipparchus to have observed parallax with the measuring instrument he had at his disposal: namely, his eyes. So Hipparchus missed the heliocentric view of the sun and planets because he could not believe that stars were so far away from us.

The astronomer Claudius Ptolemy of Alexandria, who flourished in the second century CE, codified the prevailing ideas of his time and added ideas of his own as a result of his observations. According to the Ptolomaic system, the earth is a stationary globe at the center of the universe. The basic motions of the sun, moon, stars, and planets are circles around the earth. The stars are fixed on a "celestial sphere," which rotates once every twenty-four hours. The planets could not be stationary on the same celestial sphere because they move with respect to the stars.

In order for the picture to agree with careful observations, Ptolemy had to assume that the planets move in small circles, called "epicycles," whose centers move in large circles around the earth. Epicycles were first proposed some four hundred years before Ptolemy, when it was realized by observation that the planets do not move in Aristotelian circles. However, the circle was supposed to be a "perfect" curve, and therefore, the description of the motion of the planets was described by circles within circles.

After the Ptolomaic system was explained to King Alfonso X of Castile and Leon (1221–1284), the king is supposed to have said, "If the Lord Almighty had consulted me before embarking upon Creation, I should have recommended something simpler."

1.4 The Copernican revolution

Despite the skepticism of King Alfonso and others, the Ptolomaic system was widely believed until the Polish astronomer, Nicolaus Copernicus (1473–1543) revived the Aristarchan heliocentric view of the sun and planets. All the planets, according to Copernicus, revolve around the sun. He boldly explained the absence of stellar parallax by assuming that the stars were too distant for parallax to be observed. Copernicus completed his treatise around 1530, but it was not published until just before he died. It appeared under the title, *De Revolutionibus Orbium Coelestium* (*On the Revolution of the Celestial Sphere*). The title, which seems to contradict the main ideas of the book, was the choice of the publisher.

Because Copernicus assumed that the planets go around the sun in circles (their paths are actually approximate ellipses), he also had to postulate the existence of epicycles. In fact, the Copernican model was almost as complicated as the Ptolemaian model, and the predictions were not much more accurate. However, Copernicus was able to calculate the relative speeds and distances of the planets from the sun, something that did not seem possible in the earth-centered model.

We speak of the “Copernican revolution” because his work began a profound change in the way we look upon the universe. Copernicus shifted our point of view from the earth to the sun, but later it was realized that the sun is just one star in a vast collection of stars known as the Milky Way. Still later it was understood that the Milky Way is just one huge collection of stars (called a galaxy) out of many.

For complicated reasons (which we do not care to go into), the Catholic Church had adopted the Aristotelian view that the earth is the center of the universe. At the time of Copernicus, the Church took the view that not only religion but science came under its purview, and it tried to suppress the ideas of Copernicus. Despite these attempts, Copernicus's work survived and was the first in a series of great scientific revolutions that deeply changed the way we think about the universe.

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Chapter 2

The Solar System and Beyond

Philosophy is written in a great book which is always open in front of our eyes (I mean: the universe), but one cannot understand it without first applying himself to understanding its language and knowing the characters in which it is written. It is written in the mathematical language.

—Galileo Galilei (1564–1642)

2.1 Elliptical orbits

The Copernican picture of the sun and planets (the solar system) was a great advance over the Ptolomaic picture, but the Copernican idea suffered from the false assumption that the planets go around the sun in circles. About a century later the German astronomer and mathematician, Johannes Kepler (1571–1630), took the next big step. Using records of the precise observations of the planets by the Danish astronomer Tycho Brahe (1546–1601), Kepler concluded that the planets do not go around the sun in circles but rather in oval-shaped orbits called ellipses.

In the interior of an ellipse are two points, called foci (the singular is focus), on opposite sides of the center. The sum of the distances from the curve of the ellipse to the two foci is a constant. The closer together the two foci are relative to the size of the ellipse, the closer the ellipse is to a circle. In the limit that the two foci coincide, the curve is a circle. The orbits of the planets known at the time of Kepler are very nearly circles. A drawing of an ellipse is given in Figure 2.1. The ellipse is very elongated compared to the orbits of the planets.

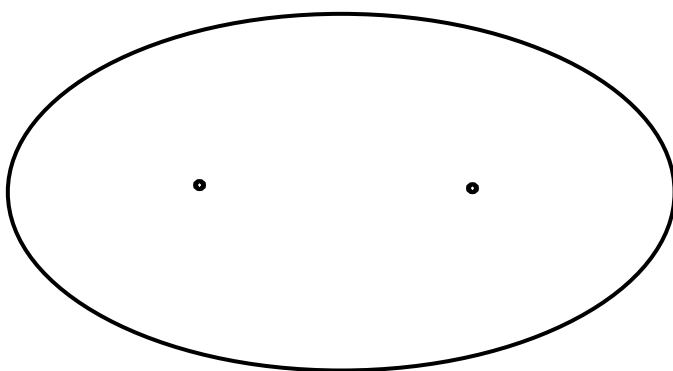


Figure 2.1: An ellipse, showing the two foci.

Kepler concluded from Brahe's observations that the sun is not located at the center of the ellipse but at one of the two foci. Nothing at all is at the other focus. The statement that the planets move in ellipses around the sun with the sun at one focus is known as Kepler's first law. From Tycho Brahe's observations, Kepler deduced two other laws of planetary motion.

Kepler's second law says that as a planet moves around the sun, an imaginary line from the sun to the planet sweeps out equal areas in equal times. As a consequence, the planet moves fastest when

it is closest to the sun (the “perihelion”) and moves slowest when it is farthest from the sun (the “aphelion”). A drawing illustrating Kepler’s second law is given in Figure 2.2. The two shaded areas shown in the figure are equal, so that it takes the same amount of time for a planet to go from A to B as it takes for the planet to go from C to D. The actual planetary orbits are more nearly circular than the drawing shows.

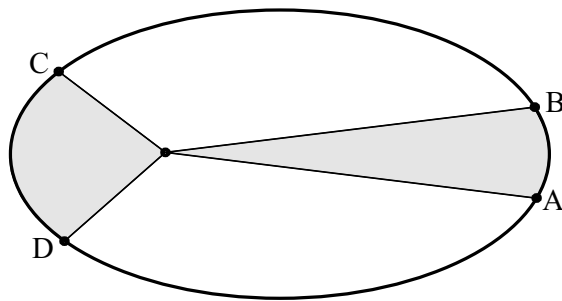


Figure 2.2: Illustration of Kepler’s second law.

The third law says that the square of the period of a planet (the period is the time it takes the planet to make one complete orbit) is proportional to the cube of the semimajor axis (the line from the center of the ellipse through one focus to the curve of the ellipse). (The square of a number is the number multiplied by itself, while the cube of a number is the number multiplied twice by itself.) Kepler’s third law makes quantitative the observed fact that the larger the orbit of a planet, the slower it moves.

Kepler’s three laws are very accurate, but we now know that they are not exact. For example, a very slight discrepancy in the orbit of Mercury was discovered in the nineteenth century, showing that the

orbit is not exactly an ellipse. Part of the discrepancy in Mercury's orbit could be attributed to perturbations from the gravity of other planets, but a residual deviation remained. This deviation was not explained until the general theory of relativity was proposed in the early twentieth century, discussed in Chapter 10.

While Kepler was doing the work that led to his three laws of planetary motion, he decided that the reason the planets move around the sun is that the sun exerts some influence over the planets. This idea was a precursor of the theory of gravitation of Isaac Newton (1642–1727), an English physicist.

Kepler observed that all the planets revolve around the sun in the same direction. In ancient times it was believed that the planets revolve around the earth in the same direction. However, at times during their orbits, the planets are observed to undergo what is known as retrograde motion—that is, they temporarily reverse direction as observed from earth. Retrograde motion was originally explained in terms of epicycles, but Kepler understood the motion from his three laws. A planet farther from the sun than the earth moves more slowly than the earth. When the earth and the planet are moving on the same side of the sun, because the earth is moving faster, the planet moves in the opposite direction *relative to the earth*. Of course, when planets are moving on the opposite side of the sun, they are moving in a direction opposite to that of the earth.

Our present understanding of why the planets revolve around the sun in the same direction is that the solar system evolved from a rotating cloud of gas. As the cloud condensed into the sun and the planets, the rotary motion persisted. That is why the sun spins

around its axis in the same direction as the planets revolve around the sun. The sun and the planets are said to have “angular momentum,” a concept discussed in Chapter 7.

2.2 Galileo's contributions

Galileo Galilei (1564–1642), an Italian, was a contemporary of Kepler and the first great “modern” physicist. (At that time physics was called philosophy.) Galileo made revolutionary changes in our ideas of motion as well as our ideas about astronomy. He and Kepler both observed the supernova of 1604, an object that suddenly brightened in the sky. From the absence of parallax, Galileo realized that the object was at stellar distances and therefore exceedingly bright. We now know that a supernova is an exploding star. We shall have more to say about supernovae in Chapter 18.

Galileo did not invent the telescope but as soon as he heard about it he built one of his own and was the first person to use it to look at the sky. One of his most significant discoveries was the first observation of four of the moons of Jupiter. By observing these satellites at different times, Galileo established that they were orbiting Jupiter and not the earth. This was the first instance to be established that heavenly bodies orbited an object other than the earth. Of course, Kepler's work showed it was much simpler to assume that the planets orbit the sun rather than the earth, but many astronomers still held the earth-centered point of view.

Galileo also studied sunspots, which are relatively dark spots on the surface of the sun. Before Galileo, astronomers believed that the

spots were not on the sun but moved in front of it. Galileo, however, noted that the spots apparently move slower when near the edge of the sun than when near the center. He explained this behavior by assuming that the sun rotates at constant angular speed. When a spot is near the edge of the sun the spot moves mostly toward the earth or away from it as the sun rotates, making the spot's sideways motion appear slower. Galileo's observation scandalized those astronomers who believed the sun must be unblemished and must not rotate.

In his great work, *Dialogue on the Two Chief World Systems*, Galileo argued for the heliocentric picture of the sun and planets. He did not directly advocate the Copernican picture because it was forbidden by the church. Instead, he introduced three characters: Salviati, Simplicio, and Sagredo. Salviati gave arguments for the heliocentric view, based on Galileo's observations. Simplicio argued for the Aristotelian view, and Sagredo listened to both Salviati and Simplicio but was persuaded by the superior arguments of Salviati. Despite Galileo's saying in his preface that he did not personally believe in the Copernican system, the Church banned the book (as it had banned the works of Copernicus and Kepler) and put Galileo under house arrest for the rest of his life.

2.3 The stars

The Copernican revolution was the beginning of a profound change in the way we look at the universe. Copernicus's work led to the abandonment of the idea that the earth is the center of the universe, to be replaced by the newer idea that it is the sun. Later astronomers

came to the conclusion that the sun is not at the center of the universe but is only one star in a huge collection of perhaps about two hundred billion stars known as the Milky Way galaxy. Still later, other astronomers discovered that the Milky Way is only one of many billions of galaxies in our visible universe. It has been estimated that as many as a trillion (1000 billion) galaxies are in the visible universe.

Copernicus knew that the stars are not part of the solar system. The stars apparently rotate around the earth once every twenty-four hours, but the reason for this apparent rotation is that the earth rotates once a day around an axis that goes through the north and south poles of the earth and through its center. The stars seemed to Copernicus and Galileo to be fixed in space. We now know that the stars also move, but because they are so far away they appear to be stationary in space.

Let us discuss the reason why we do not see stars move, except for their apparent motion caused by the rotation of the earth. If you look at a stationary car in the distance, light from the front and back ends will enter your eyes at different angles. The difference in angles gives you the perception that the car has a length. If the car is twice as far away, the angle is only half the size (to a good approximation), and so the apparent length is only half as much. Our brains compensate for this decrease in apparent length and so we realize that the car has not changed size. With a star, which looks very much like a point of light, our brains have no way of compensating, so we do not have any idea how far away a star is just by looking at it. Now imagine a person walking from one end of the car to the other end in a certain time. If the car and the person are twice as far away, the person apparently

walks half the distance (because the car seems half as long) in the same amount of time, and so seems to move only half as fast. The farther away a person is, the more slowly he seems to walk. This same effect holds for other moving things as well, so, for example, an airplane high in the sky seems to move more slowly than an airplane close to the ground. The stars are so far away that their apparent motion is too slow for us to observe. As we shall see in Chapter 9, we can deduce some information about the speed of stars by observing how the frequency of the light emitted by the stars changes because of their motion. (The effect is called the Doppler effect.)

The information astronomers obtain from observation must be interpreted in terms of physical laws of nature, or, more accurately, in terms of our theories about the way nature behaves. It is theory that tells us, for example, why stars shine, as we shall discuss in Chapter 15.

Chapter 3

Newton's Ideas about Space and Time

God in his wisdom made the fly, and then forgot to tell us why.

—Ogden Nash (1902-1971)

In order to discuss the universe in a useful way, we need to know something about the forces of nature. It is also essential to have some knowledge about the concepts of space, time, and motion. We devote a number of chapters to these topics. We begin with ideas about space and time that are useful to describe ordinary happenings on earth but that need to be modified if we are to understand nature at a deeper level. In subsequent chapters we describe other topics that will help us understand the universe.

3.1 Infinite space

For more than 200 years, Isaac Newton's ideas of space and time were generally accepted by the physics community, but were overthrown in the 20th century by the theories of relativity and quantum

mechanics. The special and general theories of relativity were by Albert Einstein (1879–1955), a German-born physicist who fled Germany in 1933 when Hitler came to power, and who then became an American. The ideas of quantum physics began in 1900, the last year of the 19th century, with the work of Max Planck, and developed over the years by many physicists, culminating in the 1920s with the invention of quantum mechanics.

Newton's concept of space is that it exists independently of matter, and stretches out to infinity in three mutually perpendicular directions. The number of mutually perpendicular lines one can draw through a point is called the *dimension* of the space. To our eyes, space is three-dimensional, although there have been speculations that space contains additional dimensions that we are unaware of.

We can never measure an infinite distance, or measure anything infinite directly. So the statement that space is infinite is a theoretical idea that can never be tested. However, we may be able to test certain consequences of the idea that space is infinite. If the consequences are found to be correct (within the errors of our measurements), we gain confidence in the soundness of the idea. But this confidence is always subject to revision, for it is possible that a future measurement may show a contradiction to a prediction of the theory.

Newton's space has additional properties. First of all, it is “flat,” which means that it obeys Euclidean geometry. With such a geometry, (straight) parallel lines never meet (or, what essentially amounts to the same thing, parallel lines meet only at infinity). In Euclidean geometry, this statement about parallel lines is sometimes taken as a definition of what parallel means. In flat or Euclidean geometry,

only one line can be drawn through a point external to a given line which is parallel to the given line. This statement (taken together with the definition of parallel lines) is equivalent to one of the axioms on which Euclidean geometry rests. The statement cannot be proved from the other axioms of Euclidean geometry. In Figure 3.1 we illustrate parallel lines in Euclidean geometry.

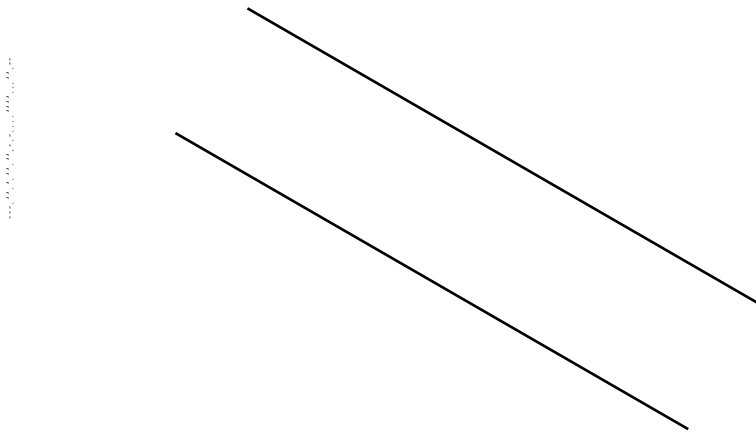


Figure 3.1: Parallel lines in Euclidean geometry. The lines may be extended (in principle) indefinitely in both directions without intersecting.

In later mathematical developments, it became clear that the definition and/or the axiom could be given up and the resulting “non-Euclidean” geometry could still be consistent. An axiom is something that is supposed to be “self-evident.” With these developments, it is more appropriate to call the statements that Euclid accepted without proof “postulates.” Postulates are initial assumptions for a mathematical system, and do not need to be self-evident or true in nature. Instead of calling the statement about parallel lines not

intersecting a definition, we may call it a postulate. Then another definition has to be given of what makes two lines parallel. In the case of non-Euclidean geometry, the definition is complicated, and to give such a definition would take us too far afield.

A “straight line” between two points on a curved surface is defined to be the shortest distance between those two points on the surface. As an example of a non-Euclidean geometry, consider the surface of a sphere, which is curved. A “straight line” on the surface of a sphere is a *great circle*, which is a circle whose center is at the center of the sphere. On a sphere, parallel lines do intersect. For example, the lines of longitude on the surface of the earth are great circles. They are all parallel locally at the equator and all intersect at the north and south poles. In Figure 3.2 we illustrate great circles.

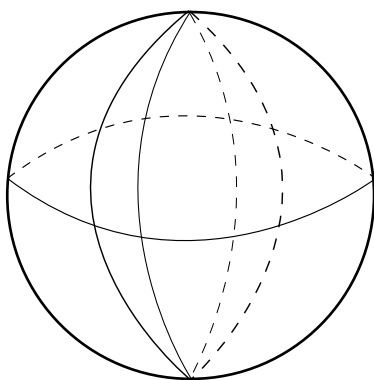


Figure 3.2: Great circles on a sphere.

On the other hand, the lines of latitude do not intersect, but, except for the equator itself, are not great circles. Therefore, the lines of latitude are considered to be curved. Because parallel lines mean

parallel “straight” lines, the lines of latitude are not considered to be parallel.

We must distinguish a flat three-dimensional space from a flat space in two dimensions. Imagine beings confined to live on a plane and unaware of a third dimension. Actually, life as we know it cannot exist in two dimensions but needs a third. We can see this as follows: In three dimensions we take in food in a cavity which runs through the body in a continuous fashion so that we can eliminate waste at the other end of the cavity. But in two dimensions a cavity running through the body and open to the outside in two places divides the individual into two distinct separated parts. This is unlike the situation in three dimensions, in which a long hole can run through a body while the body remains connected. Of course, in principle a long hole can exist in a two-dimensional body, but it can have only one opening to the outside so that the waste must be eliminated through the same opening in which food is taken in.

Ignoring the problem of how life can exist in two dimensions (we believe it can't), let us examine the perception of a two-dimensional being observing a sphere passing through his plane. The sphere looks like a point as it just touches the plane, then becomes a small circle which grows to a maximum size, shrinks again to a point, and then disappears. The two-dimensional being observing the sphere from the outside will not see a point become a circle but will see it become a line, grow, and then shrink again until it disappears.

If a circle rotates, it looks to the viewer as a line that doesn't change in size. We say that the circle has a symmetry that leaves it looking invariant under any rotation between zero and 360 degrees.

No other two-dimensional curve has as much symmetry. For example, a square has a symmetry through a rotation of 90 degrees and multiples thereof, but under a rotation of less than 90 degrees, the length of the externally observed line will change.

We in three dimensions cannot really see a whole sphere, but it appears to us only as a disk. It is our depth perception that gives our brains information that allows us to interpret a disk as a sphere, and depth perception does not work with far-off objects like the moon. We have other evidence that the moon is a sphere rather than a disk. The most direct evidence comes from artificial satellites sent to the moon that revolve around the moon.

A sphere has more symmetry than any other shaped object because it doesn't change its apparent shape no matter how it rotates. Of course, the bright part of the moon does change its shape because the bright part is the part illuminated by the sun that is observable on earth, and that part changes as the moon goes around the earth. But sometimes the part of the moon in shadow can be faintly observed from the earth, and then it is seen that the bright part plus the part in shadow appear to make a full disk.

If a four-dimensional analogy of a sphere passed through our space of three dimensions, we would perceive it as a point becoming an apparent disk which grows to a maximum, then shrinks, and disappears. With depth perception, we could observe in principle that the disk was really a sphere.

We return to three-dimensional space. According to Newton, empty space (called a vacuum) exists independently of any matter that happens to be located within it. (How empty space could be observed is

a question that Newton could not answer.) In any case, according to Newton, space has the property that it can transmit the gravitational force between distant objects. However, empty space cannot transmit sound, which needs a medium, such as air, in which to travel. Newton was uncomfortable with this so-called gravitational “action at a distance,” but he had no other satisfactory explanation for how gravity worked. Implicit in Newton’s idea of action at a distance is that the gravitational force between separated bodies acts instantaneously, no matter how far apart the bodies are from each other. This idea, which implies that the speed of action of the gravitational force is infinite, has turned out to be wrong, as we shall discuss in later chapters. Nevertheless, in many commonly occurring situations, the idea is a sufficiently good approximation to be very useful. That is why we still use Newton’s law of gravity.

3.2 Infinite time

According to Newton, time is also infinite, but it differs from space in several crucial respects. Time is one dimensional, extending from the infinite past to the infinite future. Although we can move at will in any direction in space, moving up or down, forward or backward, or side to side, in time we move inexorably forward. Furthermore, Newton believed that we all move forward at the same rate, helpless to affect our passage through time. These ideas of Newton also turned out to be wrong, but a very useful approximation in most ordinary situations.

Some, but not all, of the equations of modern physics look the

same whether time moves forward or backward. For example, if time were to go backward, the earth would spin in the opposite direction and would also go around the sun in the opposite direction. A distant observer of the earth and the sun would not be able to tell by these motions whether time was going forward or backward.

However, most observations enable us to tell that time is going forward. Consider a film of an egg falling to the floor and breaking. Run backwards, such a film would show the broken egg put itself together and rise to the table from which it fell. Anyone familiar with the way things happen in real life would know that the film was running backwards and that such an event would not happen in reality.

The ways in which Newton's ideas about space and time go wrong are subtle and not at all apparent in our daily activities on earth. Newton was one of the greatest scientists and mathematicians in history, and he would not have made obvious blunders about the nature of space and time. His subtle errors arose primarily because he did not have at his disposal modern precise experiments, which show deviations from his assumptions. He also could not know of the future invention of electromagnetic theory in the nineteenth century by James Clerk Maxwell (1831–79), which had implications (discovered by Einstein early in the twentieth century) that contradicted Newton's ideas. We discuss these developments in later chapters.

3.3 Scalars and vectors

It is obvious that we can discuss space and time only because we

exist. Obviously many things exist in space. Newton discussed the properties of space and time in empty space because he assumed that the presence of things in space did not influence those properties. As we have remarked, he was not strictly correct in his assumption. But for the present, we shall ignore how space and time are affected by matter and motion, and shall discuss objects moving in Newton's space and time. It is clear that motion depends on time as well as space because motion in space takes place during time. To discuss motion we need to make precise the familiar ideas of distance, velocity, and acceleration.

But first we need to introduce the ideas of scalars and vectors. If something we measure can be specified by a single number (a magnitude) along with its appropriate unit, that something is called a *scalar*. The temperature of a glass of water is a scalar because it is specified by a magnitude, for example, 20 and a unit, for example, degrees Celsius, abbreviated $^{\circ}\text{C}$). In other units, the same temperature will have a different magnitude, for example, 20°C is the same as 68 degrees Fahrenheit (68°F).

However, something may require more than one number for its specification. For example, if we say that Boston is about 330 kilometers (a little over 200 miles) from New York, we have not supplied enough information to a traveler who wants to go from New York to Boston. We must also specify the direction the traveler has to go, in this case, approximately northeast. The direction one has to go may also be specified by a number, which may be chosen to be the angle that the direction makes with north. In this example, only one angle is sufficient to specify the direction because the motion is confined to

the surface of the earth. If we were talking about the distance to a bird in a tree, we would need a second angle, which would specify the angle made with the horizontal. A quantity that has both *magnitude* and *direction* is called a *vector*. The magnitude of a vector is sometimes called a scalar.

The *distance* between two points is a scalar. The distance between New York and Washington, DC, is about the same as the distance between New York and Boston. But to get to Washington from New York, a traveler must go in almost the opposite direction as to get to Boston. Physicists use the technical term *displacement* for the vector which gives both the distance and direction from one point to another.

Scientists often use a shorthand notation by denoting frequently-used quantities by symbols rather than words. The symbol for a quantity is often a single letter. Use of symbols instead of words to denote frequently-used concepts not only saves time but also often aids in thinking about the subject. Also, when scientists use symbols, they are better able to employ the powerful tools of mathematics to manipulate the symbols in order to shed additional light on the subject.

We usually denote a scalar by a single italic letter and a vector by a letter in bold face. We often denote the distance between two points by the letter s and displacement by the letter $\mathbf{s}$. The quantity s is the magnitude of the vector $\mathbf{s}$. Sometimes we have to deal with more than one distance (or other quantity) in the same problem, and then we denote the different distances either by different letters or by the same letter with different subscripts. It does not matter what

symbol we use for any quantity so long as we define it so that we know what we are talking about.

In discussing the distance between two places, say Boston and New York, we have to distinguish between two different quantities. The first is the straight-line distance (as the crow flies), which is also the magnitude of the displacement. The second quantity is the distance we might travel if we went by car on curved roads. When we use the word distance without any qualification, we mean the straight-line distance unless it is clear from the context that we mean some other distance. If you walk in a circle until you return to your starting place, the distance you have walked is obviously not zero. However, your (vector) displacement is zero, and therefore the magnitude of your displacement is also zero. If a vector has magnitude zero, its direction is not defined.

When we talk about the straight-line distance between Boston and New York, we gloss over an important fact. A really straight line between those two cities will take us through the interior of the earth. (This is even more obvious of a straight-line path between New York and Tokyo.) As we have said, what we mean by a straight line distance on a curved surface is the shortest distance between two points on the surface in question. If we idealize the earth as a smooth sphere (without mountains and without flattening at the poles), then the shortest distance between two points on the earth's surface is part of a great circle containing the two points. Given any two points on the earth's surface, there is only one great circle through them except if the points are half way around the world from each other. If the points are not half way around the world, then, starting from one of

the points, there are two ways one can get to the other point along a great circle. Either of these paths is considered a “straight line” on the sphere, and the shorter of the two paths is the shortest distance between the two points. If the points are half way around the world, then there are infinitely many great circles through the points, and it is the same distance between the points on any of those great circles. Any path on the surface between two points which is not along a great circle is considered “curved.”

As an example, Los Angeles and Atlanta are both approximately at the same latitude of 34° north of the equator. (Actually, Atlanta is slightly south of Los Angeles by less than a degree of latitude.) However, if an airplane wanted to fly from Los Angeles to Atlanta by the shortest route, it would not fly along 34° latitude but along a great circle connecting the two cities, which would take the airplane *north* of 34° latitude for all of its route except for the two ends.

In many problems, the curvature of the surface in question is so small that it does not need to be considered. When this is the case, we shall not mention curvature, and the surface will be considered to be flat.

Let us return to vectors. We can describe a vector in an alternative way to giving its magnitude and direction by giving numbers called the *components* of the vector. For example, suppose you see a woodpecker on a pole. You can describe the displacement of the bird from your own position by giving two numbers to locate the position of the pole and then a third number to locate the position of the bird on the pole. To reach the pole you might have to walk 30 meters north and then 40 meters west. Then, to reach the bird, you

might have to climb 10 meters up the pole. (A meter is a little longer than three feet.) To describe the vector displacement, we use three numbers, each with its unit, which in our example is the meter, abbreviated m: 30 m north, 40 m west, 10 m up. These three numbers are called the *components* of the vector displacement.

Specifying the components of the displacement serves as a useful alternative to specifying its magnitude and direction. However, if we want to use the magnitude and direction, we still must specify three numbers. This is because in general *two* angles are necessary to specify the direction, for example, the angle with respect to north and the angle above the horizontal. The magnitude of the vector is the third number required for its specification.

In order to make a measurement of the displacement, it is useful to imagine three mutually perpendicular lines, called “axes,” which emerge from any convenient place, called the “origin.” The axes may be called the x , y , and z axes. The directions of the lines are any convenient perpendicular directions. For example, the x axis might be east, the y axis north, and the z axis up. We can measure the displacement, or any other vector in space, by measuring its components along the three axes.

Consider a vector, which we call $\mathbf{F}$. We have in mind that $\mathbf{F}$ stands for the force on an object, which is loosely defined as a push or pull on the object. A force not only has a magnitude but a direction in which it acts, and so it meets the definition of a vector. (We could equally well have considered an arbitrary vector and given it another name.) Then we denote its components in the x , y , and z directions by F_x , F_y , and F_z respectively.