CHAPTER 3

Understanding Motion

A. THE THREE LAWS OF MOTION

3.1 NATURAL MOTION

You saw in the previous chapter that the proposal that the Earth moves caused all sorts of problems for the Earth-centered view of the Universe—as well as for theology, philosophy, and just plain common sense. If the Earth really is moving around the Sun, then what keeps the heavy Earth on its orbit? The ground beneath our feet must be moving very fast, so why do heavy objects fall straight down, instead of hitting behind the spot over which they are released?

You probably know that these and other excellent questions can be answered by referring to the law governing the force of gravity. But understanding what gravity is and how it answers these questions requires a further understanding of motion and its causes. We could just list the results for you here in a few paragraphs, but (as usual) we think you will get a much clearer idea of what these concepts really mean, and what goes into them, by seeing where they came from and how people managed to provide the understanding we have today of this complicated thing we so easily call "motion." This understanding, too, began with Galileo, which he discussed in his book *Two New Sciences*, published after his condemnation for religious heresy. At least two other scientists of that era, Descartes and Newton, further enhanced his work and put it into more modern form after his death.

The story begins with what seems to be a very simple concept we have already encountered, the concept of "natural motion"—how an object moves "naturally" without outside help. In Aristotle's physics there were two types of motion: "natural" motion and "violent" motion. Natural motion was the motion of an object on a vertical line directly to the place where it "belonged." For example, a stone falls straight down through the air and further through any water to reach the earth below. On the other hand, an air bubble trapped under water moves upward through the water until it reaches the air above. There was no need to explain why these motions occur—they're just as natural as the movement of an animal making straight for its "home."

In contrast to natural motion Aristotle also defined "violent" motion. This was any motion that is not directly to the place where the object "belonged." Examples are the lifting of a stone upward from the earth, or the motion of a cart across a horizontal tabletop, or the flight of an arrow through the air. This type of motion had to be explained, since it was not natural for an object to move sideways by itself. Something has to *cause* or *force* the object to perform such motion. This was why he called it "vio-

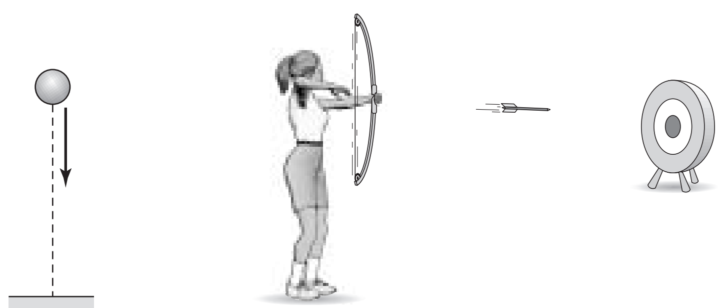


FIGURE 3.1 Examples of Aristotle's notions of natural and violent motion.

FIGURE 3.2

lent" motion. Therefore, according to Aristotle, to maintain these violent motions a *force* had to be applied continuously. As soon as the force ceased, the violent motion ceased. Again, this seems very reasonable at first sight. Anyone who has pushed a heavy cart over a rough pavement knows that it stops moving as soon as you stop pushing. But Galileo showed for the first time that there is more going on here than we realize. The causes and inhibitors to motion are not obvious, and it takes the careful reasoning and experimentation of modern physics that Galileo and others developed to sort this out.

As noted earlier, Galileo was one of the first to realize that he should dispense with less important complications in order to focus on the essential aspects of any motion. He realized that the role of friction and air resistance could be neglected in his thinking in order that the essential properties of the motion itself can be studied. You may recall that when he neglected friction and air resistance for a ball rolling down an inclined plane, he obtained the idea of uniform acceleration. The uniform acceleration increased as the small angle of inclination increased. From this he inferred that the extreme case of a 90° "incline" would also be uniform acceleration. In that case the ball is no longer rolling down the incline, but falling freely to the ground. From this he concluded that free fall must also be an example of uniform acceleration and that all bodies will fall freely at the same uniform acceleration if air resistance is neglected. As a result, heavier objects do *not* fall faster than lighter ones. They all reach the ground at the same time when dropped from the same height (neglecting air resistance).

Now Galileo decided to look at the other extreme. What happens when the angle of the incline becomes smaller and smaller, down to zero? As

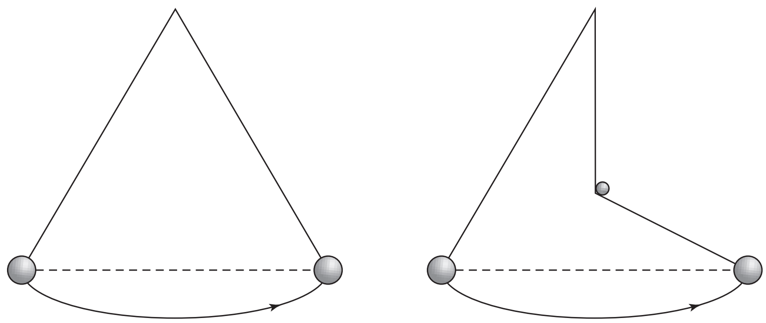


FIGURE 3.3 A swinging pendulum bob returns to its initial height, even if there is an impediment.

usual, he decided to try a "thought experiment" (which can also be done as a real experiment). This thought experiment is based on an actual observation. If a pendulum bob on the end of a string is pulled back and released from rest, it will swing through an arc and rise to very nearly the same height. Indeed, as Galileo showed, the pendulum bob will rise almost to its starting level even if a peg is used to change the path, as shown in the illustration above. Try it yourself!

From this observation Galileo went on to his thought experiment. He predicted that a ball released from a height on a ramp would roll up to the same height on a similar ramp, neglecting all resistances. Consider the following diagram. As the ramp on the right is changed from position A to B and then to C, the ball must roll farther along the upward incline in each case in order to reach its original height.

Now let's look at the extreme case, the limit in which the angle of inclination of the second ramp is zero, and the path is level, as shown in D. In this case the ball never reaches its original height. Therefore, Galileo reasoned, the moving ball on this surface, with no air resistance and no barriers in its way, would continue to roll on and on at uniform speed forever. (Actually, he thought that if the ball continued on long enough, it would

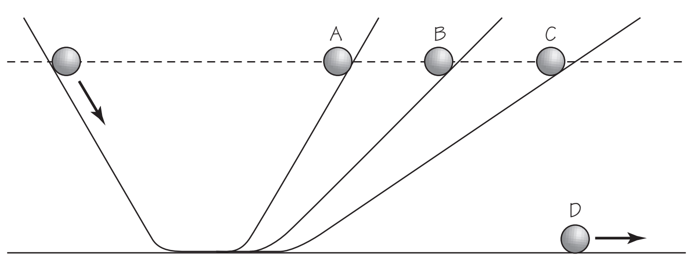


FIGURE 3.4 Ball rolling up ramps of different inclination returning each time to the height, except in D.

For a ball rolling without friction, there is no detectable difference between motion in a straight (horizontal) line in a laboratory on Earth or at a constant height above the Earth. But on a larger scale, Galileo held that eternal rolling would become motion in a circle around the Earth. Newton made clear what is really more important: In the absence of the Earth's gravitational pull or other external forces, the ball's undisturbed path would extend straight out into space without end.

eventually go into a circular orbit around the Earth. However, without the gravity of the Earth, the ball would continue in a straight line forever.) *What Galileo discovered is that, within any reasonable large space—say, a laboratory—it is "natural" for the ball to continue to roll horizontally in a straight line at uniform speed until it is forced by a push or other means to change its motion.* Even though it is not moving vertically, no force is required to keep the ball rolling horizontally, as Aristotle had believed. A force is needed only to stop it from rolling, or to divert it in another direction. Contrary to Aristotle's arguments, the motion of a moving ball at uniform velocity (constant speed in a straight line) is quite "natural." It needs no explanation. What must be explained is why it ever *changes* that motion. And *this* is where the action of a force comes in. The departure from motion with uniform velocity, now called "accelerated motion," occurs only when an object is acted on by a force.

The same holds when objects are at rest. They stay at rest, which can be thought of as a state where the velocity is zero, until they are "forced" to move.

Since objects stay in uniform motion or at rest until they are forced to do otherwise, they behave as if they are "inert," literally unable to change their state by themselves. It takes a force applied from outside themselves to get them to change their motion, either to speed up, or to slow down, or to change direction. When they are at rest, it takes a force to get them to move; otherwise they "naturally" tend to maintain their state of rest or motion. This tendency of all material objects to maintain their state of motion is called *inertia*. Newton elevated this tendency of material objects into the first of his three basic laws of nature governing all motion. These laws are so universal that Newton applied them to all motion everywhere, including throughout the entire Universe. And they are part of the foundation of modern physics. So far, no contradiction to these laws has been found, either on Earth or anywhere else in the Universe—although, as you will see in Chapter 9, modifications become increasingly necessary for events occurring at extremely high speeds approaching the speed of light.

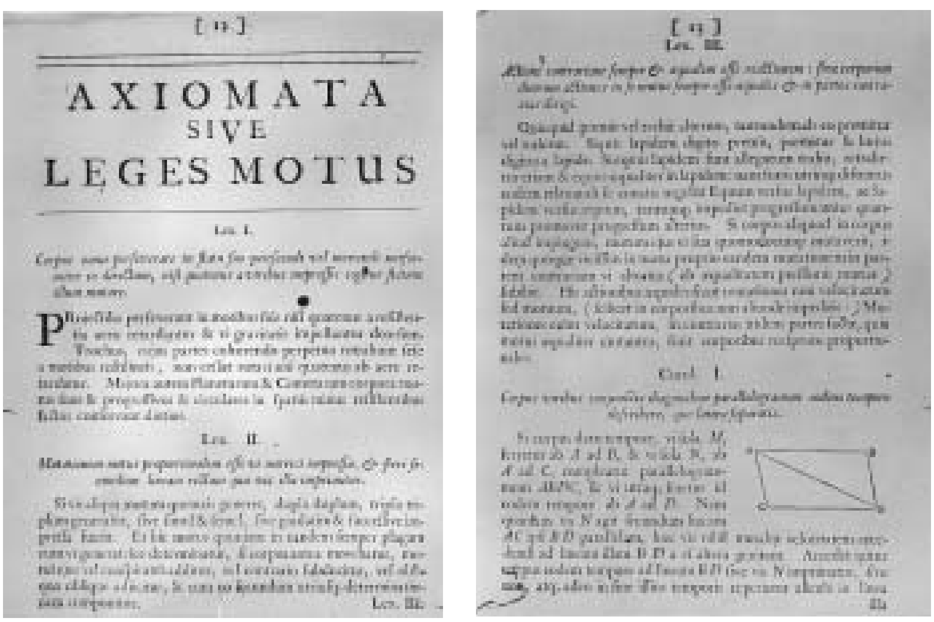
Newton's first law of motion is also called the law of inertia. Expressed in modern terms, it states:

> 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.

Notice that Newton is not saying that there are no forces acting on an object at rest or moving with uniform velocity. Rather, he is staying that if there are any forces they must all cancel out if the object is to be in a state of rest or uniform velocity.

For Aristotle, an object rolling horizontally on a tabletop was thought to have a constant force acting on it to keep it moving; otherwise it would stop as soon as the force is removed. Newton's first law of motion makes the situation just the reverse. An object moving with uniform velocity or at rest needs no net force to keep it in that state of motion; instead, any "unbalanced force" (such as friction, air resistance, or a push or pull) will change its state of moving with uniform velocity. Remove all forces and obstacles, and the object will continue on forever. In real life it is very difficult to come close to a situation where all forces are absent or balanced out. But a hockey puck moving on flat ice, after it has been pushed, is a close example of such an object.



AXIOMATA
SIVE
LEGES MOTUS

Lex. I.

Lex. II.

Lex. III.

Corol. I.

FIGURE 3.5 Pages from the original (Latin) edition of Newton's *Philosophiae Naturalis Principia Mathematica (The Mathematical Principles of Natural Philosophy)* presenting the three laws of motion and the parallelogram rule for the addition of forces (See Secs. 3.3 and 3.4).

We must now define exactly what is meant by an "unbalanced force." In fact, what is a force?

3.2 FORCES IN EQUILIBRIUM

The word "force" still has the connotation of violence that Aristotle gave it. In physics, it refers to a push or a pull. You know without having to think about it that forces can make things move. Forces can also hold things still. A cable supporting the main span of the Golden Gate Bridge is under the influence of mighty forces, yet it remains at rest.

This is not surprising. Think of two children quarreling over a toy. If each child pulls with equal determination in the opposite direction, the toy goes nowhere. In this case we say that the forces are "balanced." Or think of a grand chandelier hanging from a ceiling. The pull down by gravity is exactly balanced by the pull upward on the chandelier by the cord and chain on which it hangs. In all such cases we can think of forces in terms of arrows which represent the sizes and directions of the forces in a given situation. As with velocity, forces have both a magnitude (size) and a direction. As discussed in Section 1.5, we call any physical quantity that has both a

FIGURE 3.6 The Golden Gate Bridge in San Francisco—one example of an exquisite arrangement of balanced forces on the structure.

FIGURE 3.7 Children playing tug-of-war. Until one side pulls the other with acceleration, the net force is zero.

magnitude and a direction a "vector," and represent it in a diagram by an arrow. These arrows, representing vectors, can be added up graphically to obtain the resultant, for example, the "net force." (Vectors are discussed further in the next section.) As you can see from Figure 3.8, the two equally strong but opposing forces are represented by arrows equal in size but opposite in direction. The force pulling to the left is "balanced" exactly by the force pulling to the right. So these two forces cancel. The "net force" on the puppet is zero in this case.

Now suppose the child on the left suddenly makes an extra effort and pulls even harder. At that point the forces of course no longer balance each other. There is a net force to the left, and the toy starts to go from rest into motion to the left (Figure 3.8b).

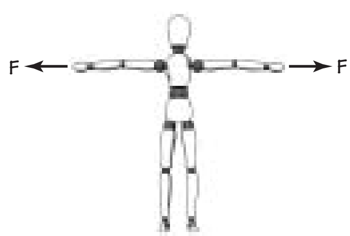


FIGURE 3.8a Diagram of equal forces on a doll.

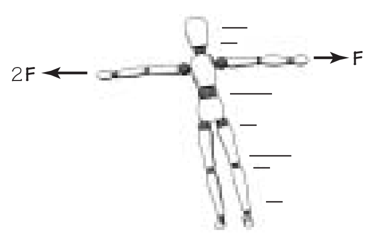


FIGURE 3.8b Diagram of unequal forces on a doll.

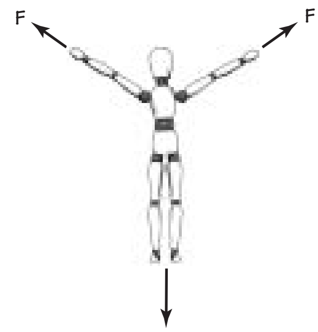


FIGURE 3.8c Diagram of three forces on a doll (non-parallel).

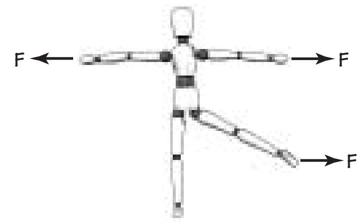


FIGURE 3.8d Diagram of three forces on a doll (parallel).

Suppose now that a third child eyes the toy and tries to grab it from the other two. Perhaps the three children pull in the directions shown in Figure 3.8c. Again there are forces on the toy, but they all balance out, the net force is zero, so the toy stays at rest. Finally, suppose that the original two children decide to "join forces" against the intruder and pull together parallel to each other. As shown in Figure 3.8d, their two forces add together, and the net result of all three forces is in their direction. The result is: they "win" (if the toy is not already torn apart).

The point to keep in mind most of all here is that you can have many forces all acting on an object at once and in different directions; but the net force is zero if the forces are balanced, and in that case the object stays in its original state of motion, either at rest or in uniform velocity. This is the meaning of Newton's first law of motion.

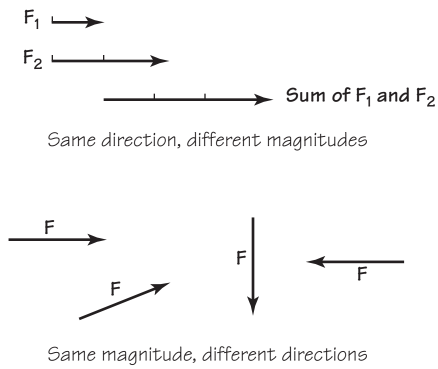
On the other hand, whenever there is an unbalanced or net force on an object, such as a toy, a car, or the space shuttle taking off, a change in its velocity must occur.

This leads to the next step: as you know from Chapter 1, whenever there is a change in uniform velocity there is, by definition, an *acceleration*. So, net forces are related to accelerations. "How" they are related is the subject of one of the mightiest laws of physics, Newton's second law of motion. But first, let's look a little closer at vectors.

3.3 MORE ABOUT VECTORS

As just discussed, forces belong in a class of concepts called *vector quantities*, or just *vectors* for short. Some characteristics of vectors are easy to represent by arrows. It is not obvious that forces should behave like arrows. But arrows drawn on paper happen to be useful for calculating how forces

FIGURE 3.9 Vector sums.



add. (If arrows weren't useful, we simply would look for other symbols that did work.) In particular, vector quantities have *magnitude*, which can be represented by the length of an arrow drawn to scale. They also have *direction*, which can be shown by the direction of an arrow. By experiment, we find that vectors can be *added* in such a way that the total effect of two or more vectors can be represented by the addition of the corresponding arrows placed tail to head. The total effect is represented by a new arrow, from the tail of the first to the head of the last, and is called the *vector resultant*, or the vector sum.

One example of a vector sum involves the distance traveled in a round trip over several days. Each leg of the trip undertaken each day may be represented by a displacement vector, each of which has both a scalar distance traveled and a direction. Since each leg of the trip begins at the point where the previous day left off, the displacement during the course of the trip may be represented by a series of arrows arranged tail to head. The length of each arrow represents the net distance traveled each day, the direction of the arrow represents the direction of the finishing point from the starting point. The net vector displacement from the start at the end of each day can be represented by a vector from the start to the head of the last vector. This is how vectors are added together to form the vector resultant.

One surprising result of this definition is that by the end of the round trip the vector resultant is zero! In other words, while the scalar distance traveled may have been many kilometers, the net displacement was zero. In terms of vectors, the traveler has gone nowhere.

Similar results occur in the example of the tug-of-war between two tots over a toy, where we determined the total effect of equal but opposing vec-

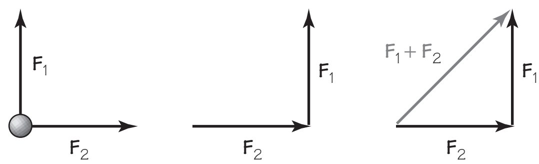


FIGURE 3.10 Adding vectors $\mathbf{F_1}$ and $\mathbf{F_2}$ head to tail to achieve the resultant $\mathbf{F_1} + \mathbf{F_2}$.

tor forces. If two forces act in the *same* direction, the resultant force is found in much the same way as two displacement vectors.

If two forces act at some angle to each other, the same type of sketch is still useful. For example, suppose two forces of equal magnitude are applied to an object at rest but free to move. One force is directed due east and the other due west. The resultant is found by moving each of the vectors parallel to each other and placing them tail to head. The resultant is the vector drawn from the tail of the first vector to the head of the last vector. In this case, this results in a vector of zero length. The object remains in equilibrium, without any acceleration, even though it is under the stress of enormous forces.

If one force on the object is directed due east and the other is directed due north, the object will accelerate in the northeast direction, the direction of the resultant force (see Figure 3.10.) The magnitude and direction of the resultant force vector are represented by the length and direction of the arrow representing the resultant.

The same addition procedure applies to forces of any magnitude and acting at any angle to each other. Suppose one force is directed due east and a somewhat larger force is directed northeast. The resultant vector sum can be found as shown in Figure 3.11.

To summarize, a vector quantity has both direction and magnitude. Vectors can be added by constructing a head-to-tail arrangement of vector arrows (graphical method). An equivalent technique, known as the parallel-

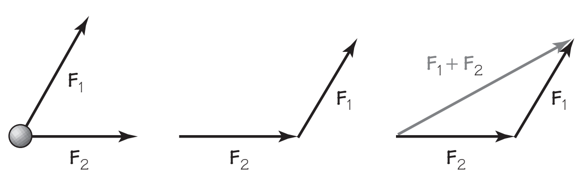
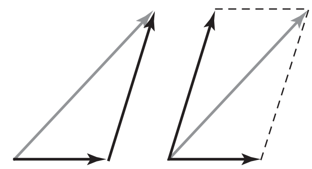


FIGURE 3.11 Adding non-perpendicular vectors ("head-to-tail" method).

FIGURE 3.12 You can use equally well a graphical construction called the "parallelogram method." It looks different from the "head-to-tail" method, but it is actually equivalent. In the parallelogram construction, the vectors to be added are represented by arrows joined tail-to-tail instead of head-to-tail, and the resultant is obtained by completing the diagonal of the parallelogram.



ogram method, is briefly explained in Figure 3.12. Vectors also have other properties which you will study if you take further physics courses.

3.4 NEWTON'S SECOND LAW OF MOTION

You saw in Chapter 1 that Galileo made tremendous progress in describing motion, speed, acceleration, and free fall, but that he refrained from attempting to uncover the causes of these motions, leaving that to "the attention of other minds." One of the foremost "other minds" was Isaac Newton, who lived from 1642 to 1727. His second law of motion goes far beyond Galileo in attributing the cause of all changes of motion to the action of forces. Once again, it is important to know that Newton's laws of motion are *universal* laws of nature. This means that they apply not just to falling balls and inclined planes and toys pulled by tots, but to all matter everywhere and always—on Earth, in the solar system, and throughout the Universe. (However, at very high speeds, close to the speed of light, relativity theory introduces a modification of the kinematic quantities that enter into these laws.)

As noted earlier, the description of motion, without looking at its causes, is called *kinematics*. The study of motion that involves the causes of changes of motion is called *dynamics*. Together, kinematics and dynamics form the science of *mechanics*, and at the center of this new science are Newton's three laws of motion.

Newton's second law of motion has to do with force and acceleration. We know what acceleration is (see Chapter 1) and we know that force has to do with pushes and pulls generated either by people or by objects, such as magnets or springs.

Newton's second law provides an answer to the question: *What happens when an unbalanced force acts on an object?* Since we think of the force as *causing* the resulting motion, this law is the fundamental law of dynamics.

In qualitative terms, the second law of motion says little more than this: *The reason for a deviation from "natural" motion (i.e., motion with a constant* *or zero velocity) is that a nonzero net force acts on the object*. However, the law tells us much more: it provides a simple *quantitative* relationship between the change in the state of motion—the acceleration—and the net force. As usual in science, the best way to discern quantitative relationships between two concepts is to head for the laboratory. We will first consider a situation in which different forces act on the same object; then we will consider a situation in which the same force acts on different objects; finally, we will combine the two results into a general relationship. You might do these experiments yourself. We will describe only briefly the procedures and the results here.

Different Forces Acting on the Same Object

In our first experiment we accelerated an object with a steady force so that it accelerated continuously. The object was a cart on wheels but it could be a dry-ice disk or any other nearly frictionless object on a flat table. The force was produced by the horizontal pull provided by a string attached over a pulley to a descending weight. We determined the acceleration (**a**) by measuring the distance between the dots made every 0.1 s on a tape pulled by the cart.

Repetitions of this experiment with different amounts of force (**F**) on the same cart produced by different amounts of weight yielded the following results, in words and symbols:

The force **F** caused an acceleration of **a**.

The force 2**F** caused an acceleration of 2**a**.

The force ½**F** caused an acceleration of ½ **a**.

The force 5.2**F** caused an acceleration of 5.2**a**.

As you can see, as the force increased or decreased, the acceleration increased or decreased by the exact same amounts. What can you conclude from these results about the general relationship between the force and the acceleration? Here is our conclusion:

> The acceleration of an object is directly proportional to, and in the same direction as, the net force acting on the object.

If **a** stands for the acceleration of the object and $\mathbf{F}_{net}$ stands for the net force on it, this statement may be expressed in symbols as follows:

$$\mathbf{F}_{net} \propto \mathbf{a}.$$

Notice that the force and the acceleration are both *vector* quantities. In our experiment, the force provided by the horizontal pull of the string and the acceleration of the cart to which the string is attached were both in the same direction. It is understood that when *vectors* are proportional, they must point in the same direction as well as have proportional magnitudes. We used the net force in this conclusion because there was still some friction opposing the force with which we pulled the cart.

To say that two quantities are proportional means that if one quantity is doubled (or multiplied by any number), the other quantity is also doubled (or multiplied by the same number). Thus, as our data indicated, if a certain force produces a certain acceleration, twice the force (on the same object) will produce twice as great an acceleration in the same direction.

The Same Force Acting on Different Objects

Once again we tried an experiment, this time to see what happens when the same force acts on different objects. We can select different objects in different ways, such as by size, shape, density, or weight. In terms of force and motion, one of the most important differences among objects is the amount of matter, or mass, they contain. We can see this when we attempt to apply the same force to a child's wagon and to a parked car in neutral. Each contains a different amount of matter, which is called mass. (Mass is further discussed below.)

In this experiment the different objects are the same cart on wheels but loaded with objects of different masses. In each case we applied the same horizontal force to the cart, by using the same system of a string, a pulley, and a suspended weight. (You can perhaps try this with other setups.) Again we determined the acceleration (**a**) by measuring the distance between the dots made every 0.1 s on a tape pulled by the cart.

Repetitions of this experiment with different total masses m for the cart and its load yielded the following results, in words:

The mass m experienced an acceleration of $\mathbf{a}$.

The mass $2m$ experienced an acceleration of $\frac{1}{2}\mathbf{a}$.

The mass $\frac{1}{3}m$ experienced an acceleration of $3\mathbf{a}$.

The mass $5.2m$ experienced an acceleration of $(1/5.2)\mathbf{a}$.

This time you can see that, as the mass changed, the acceleration changed by exactly the inverse amount. We can conclude from this:

> The acceleration of an object is inversely proportional to the mass of the object. The larger the mass of an object, the smaller will be its acceleration if a given net force is applied to it.

This relationship between acceleration and mass may also be written in symbols. Let a stand for the acceleration (the *magnitude* of the acceleration vector **a**) and m stand for mass. Then,

$$a \propto 1/m$$

as long as the same net force is acting. Notice that an object with twice (or three times, or whatever) the mass of another object will experience one-half (or one-third, or one-whatever) the acceleration if subjected to the same net force.

Notice also that it is the mass of an object that determines how large a force is required to change its motion. In other words, the mass of an object is a measure of its inertia. It is sometimes called *inertial mass*, to emphasize that it measures inertia. Mass is a *scalar* quantity (it has no direction), and it does not affect the direction of the acceleration.

The General Relationship Between Force, Mass, and Acceleration

We concluded from our two experiments that the acceleration of an object is proportional to:

(1) the net force (for constant m); and
(2) to $1/m$, the reciprocal of the mass (for constant $\mathbf{F}_{\text{net}}$).

It follows from these two proportions that the acceleration is proportional to the product of the net force and the reciprocal of the mass:

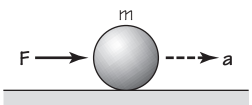
$$\mathbf{a} \propto \mathbf{F}_{\text{net}} \cdot \frac{1}{m}.$$

Are there any other quantities (other than net force and mass) on which the acceleration depends? Newton proposed that the answer is no. Only the *net force on the object* and the *mass of the object* being accelerated affect the acceleration. All experience since then indicates that he was right.

Since there are no other factors to be considered, we can make the proportionality into an equality; that is, we can write

$$\mathbf{a} = \frac{\mathbf{F}_{\text{net}}}{m}.$$

FIGURE 3.13 Ball accelerated by an applied force.



This relationship can also be written as the famous equation

$$\mathbf{F}_{net} = m\mathbf{a}.$$

In both these equations we have again written $\mathbf{F}_{net}$ to emphasize that it is the *net* force that determines the acceleration.

This relationship is probably the most basic equation in mechanics and, therefore, in physics. Without symbols we can state it as follows:

> Newton's second law of motion: 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: $\mathbf{F} = m\mathbf{a}$.

It does not matter whether the forces that act are magnetic, gravitational, simple pushes and pulls, or any combination of these; whether the masses are those of electrons, atoms, stars, or cars; whether the acceleration is large or small, in this direction or that. The law applies universally. And if you think about this and other "universal" laws of science, it is remarkable that there are only two disciplines—physics and mathematics—that have found laws or statements that apply everywhere in the Universe!

3.5 MEASURING MASS AND FORCE

How should we define the units of mass and force that are used in the Newton's laws of motion? The answer depends on the meaning of these two concepts. As you just saw, the *mass* of an object is its inertia, its resistance to changes in its motion. A net force, on the other hand, is what pushes or pulls against the mass to produce an acceleration. If you apply a force to a small mass, you would produce a larger acceleration than if you applied the same force to a larger mass. For instance, pushing a new shopping cart over a smooth surface would produce a larger acceleration than pushing a truck in neutral over the same surface with the same force.

Measuring mass (or inertia) and defining its units are quite different from measuring force and defining its units. When you think of measuring the mass of an object, you might first think of weighing it on a scale—and some laboratory scales are calibrated to convert the weight of the object into a measure of its mass. *But mass and weight are two different concepts*. In the most basic terms: *mass* is the inertia of an object; *weight* is the gravitational force exerted on the object.

The stretch of a spring can be used as a measure of force, since the amount of stretch is proportional to the force exerted. (You may have observed this in the laboratory, as suggested in the *Student Guide*.) If you take apart a typical household scale—a bathroom scale, for instance—you will find that it usually just consists of a spring that compresses as you stand on it. This indicates that it measures your weight, not your inertia or mass, when you stand on it, since the contraction of the spring inside the scale exerts on you an upward force that balances the gravitational force you experience downward. The amount of contraction is also proportional to the force exerted and the scale gives a reading of the corresponding amount of force, which is your weight at your location on the Earth. However, if you stand on your bathroom scale on the Moon, it will show a much smaller *weight*, since the gravitational pull on you downward is less on the Moon than on the Earth. Nevertheless, you will have just the same mass, or inertia.

Since the mass of an object is the same for that object *everywhere*, while the weight depends on the location, the wise thing to do is to choose the unit of mass first, and let the unit of force follow later. The simplest way to define a unit of mass is to choose some convenient object as the *universal standard of mass*, and then compare the masses of all other objects with that one. What is selected to serve as the standard object is arbitrary. In Renaissance England the standard used was a grain of barley ("from the middle of the ear"). The original metric commission, established in France in 1799 in the wake of the French Revolution, proposed the mass of a cubic centimeter of water as the standard mass. Today, for scientific purposes, the standard mass is, by international agreement, a cylinder of platinum–

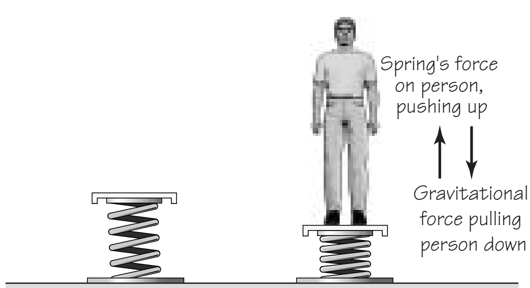


FIGURE 3.14 Person on spring scale.

iridium alloy kept at the International Bureau of Weights and Measures near Paris. The mass of this cylinder is *defined* to be 1 kilogram (kg), or 1000 grams (g). Accurately made copies of this cylinder are used in various standards laboratories throughout the world to calibrate precision equipment. Further copies are made from these for distribution. (The mass of 1 cm^3 of water is still exactly 1 g, but only under very specific conditions of temperature and pressure. The mass of 1 liter (l) of water under standard conditions is 1000 g, or 1 kg.)

The international agreements that have established the kilogram as the unit of mass also established units of length and time. The meter (m) was originally defined in terms of the circumference of the Earth, but modern measurement techniques make it more precise to define the meter in terms of the wavelength of light, generated in a specific way. The second of time (s) was also originally defined with respect to the Earth (as a certain fraction of the year), but it, too, is now more precisely defined in terms of light waves emitted by a specific group of atoms. The meter and second together determine the units of speed (m/s) and acceleration (m/s^2). The crash of a Mars probe due to a mix-up over the use of the metric or American system of units in guiding the probe is a good example of why it is so important to define and use only one set of units for all measurements.

With the metric units defined so far, we can now go back and calibrate the spring balances used for measuring force. While in the American system of units, the unit of force is the pound or ounce, in the metric system

FIGURE 3.15 The standard kilogram, kept at the Bureau des Poids et Mesures.

the unit of force is called, appropriately the "newton" (N), in honor of Isaac Newton. Again by international agreement, 1 N of force is *defined* to be the amount of net force required to accelerate a mass of 1 kg at the uniform acceleration of one meter per second every second, or, in symbols, 1 m/s/s, which may be written 1 m/s^2. Because of Newton's second law ($\mathbf{F}_{net} = m\mathbf{a}$), we have

$$\mathbf{F}_{net} = m\mathbf{a}$$

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

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

If we are working with the smaller metric units of centimeter (cm) and grams (g), then the unit of force is no longer a newton, since the definition of the newton involves meters, kilograms, and seconds. For centimeters, grams, and seconds another unit of force has been defined. It is called the "dyne" with the symbol D. In this case,

$$1 \text{ D} = 1 \text{ g cm/s}^2.$$

The kilogram (kg), meter (m), and second (s) are the fundamental units of the "mks" system of measurement. The gram (g), centimeter (cm), and second (s) are the fundamental units of the "cgs" system of measurement. Together with units for light and electricity, the mks and cgs units form the International System of units, known as SI (SI stands for *Système Internationale*). Other systems of units are possible. But since the ratios between related units are more convenient to use in a decimal (metric) system, all scientific and technical work, and most industrial work, is now done with SI units in most countries, including the United States.

Example. A 900-kg car accelerates from rest to 50 km/hr in 10 s (50 km/hr is equal to 13.9 m/s). What is the net force on the car?

We need to find the acceleration first

$$a = \frac{\Delta v}{t} = \frac{13.9 \text{ m/s}}{10 \text{ s}} = 1.39 \text{ m/s}^2.$$

We can now find the force

$$F = ma = (900 \text{ kg})(1.39 \text{ m/s}) = 1251 \text{ kg m/s}^2 = 1251 \text{ N}.$$

Example. A 5-g ping-pong ball at rest is hit by a paddle, propelling it to 50 cm/s in 0.1 s. What is the force on the ball?

Again we need to find the acceleration first

$$a = \frac{\Delta v}{t} = \frac{50 \text{ cm/s}}{0.1 \text{ s}} = 500 \text{ cm/s}^2,$$

$$F = ma = (5 \text{ g})(500 \text{ cm/s}^2) = 2500 \text{ g cm/s}^2 = 2500 \text{ D}.$$

3.6 MORE ABOUT WEIGHT, AND WEIGHTLESSNESS

Whenever you observe an object in acceleration, you know there is a force acting on the object. Forces need not be exerted by contact only (often called "mechanical forces"). They can also result from gravitational, electric, magnetic, or other actions originating from objects that are not touching the object that is being accelerated. Newton's laws of motion hold for all of these forces.

The force of gravity acts between objects, attracting them to each other, even if they are not in direct contact. As you know, the gravitational force exerted by the Earth on an object is called the *weight* of the object. Your weight is the downward force that the Earth exerts on your mass, whether you stand or sit, fly or fall, or merely stand on a scale to "weigh" yourself.

The symbol $\mathbf{F}_g$ is often used for gravitational force. The size, or magnitude, of the gravitational pull $\mathbf{F}_g$ on a given mass is roughly the same everywhere on the surface of the Earth. This is because, for objects on the surface, the magnitude of the force of gravity depends on only the mass of the object and the distance from the center of the Earth. Since the Earth is nearly a sphere, the magnitudes of the gravitational force on a given mass at different places on the Earth's surface are nearly the same. Since the gravitational force is a vector, it also has a direction. It is always to the center of the Earth, which means that it is perpendicular to the level ground at every point on the Earth's surface. Scientists since Newton's time have known that an object having a mass of 1.0 kg experiences a gravitational force of about 9.8 N everywhere on the surface of the Earth. An object of mass 2 kg would experience a force twice that of a 1-kg object, or about 19.6 N; a 10-kg object would have a force of 98 N, and so on.

However, these weights are not exactly the same everywhere on the surface of the Earth, since the Earth is not a perfect sphere, nor is it homogeneous. For instance, an object having a mass of 1 kg will experience a gravitational force of 9.812 N in London, but only 9.796 N in Denver, Colorado. Geologists make use of minute variations in locating oil and mineral deposits.

You can sense the magnitude of the gravitational force on an object, for example, the weight of a 1-kg ball, by holding it stationary in your hand. Why doesn't the ball accelerate if there is a gravitational force on it? . . . Remember what Newton's first law of motion tells us. If you hold the ball stationary in your hand, your hand is exerting an upward force that exactly balances the force of gravity downward. It is the upward force that you provide which equals (numerically) the weight of the ball. Since all forces on the ball are balanced, it remains stationary in your hand.

Now release the ball. What happens? The gravitational force is no longer balanced. Rather, it acts as a net force on the 1-kg ball of 9.8 N downward, so the ball begins to accelerate. What is the rate of acceleration? We can obtain this from Newton's second law:

$$\mathbf{F}_g = m\mathbf{a},$$

so

$$\mathbf{a} = \frac{\mathbf{F}_g}{m} = \frac{9.8\ \text{N}}{1.0\ \text{kg}} = 9.8\ \text{N/kg} = 9.8\ \text{m/s}^2 \quad \text{downward.}$$

Now try this with a 2.0-kg ball. As given above, there is a larger force of gravity of 19.6 N downward. What is the acceleration in this case?

$$\mathbf{a} = \frac{\mathbf{F}_g}{m} = \frac{19.6\ \text{N}}{2.0\ \text{kg}} = 9.8\ \text{N/kg} = 9.8\ \text{m/s}^2 \quad \text{downward.}$$

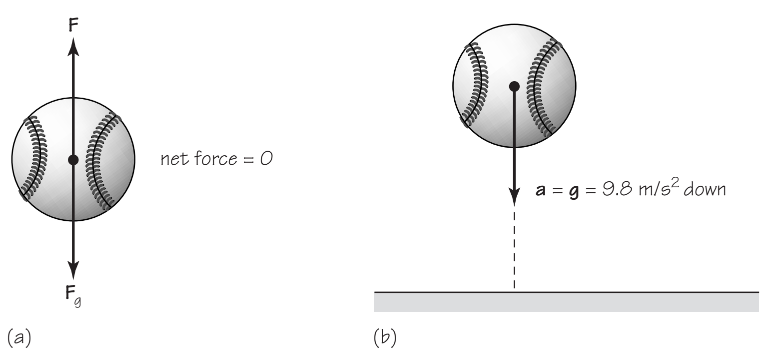


FIGURE 3.16 (a) net force on ball being held in gravitational field is zero; (b) the ball falls with acceleration g if it is not held in the gravitational field.

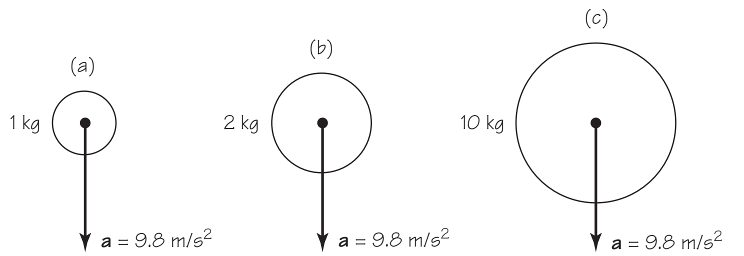


FIGURE 3.17 Acceleration is constant for freely falling balls of different mass.

Finally, the 10-kg ball:

$$\mathbf{a} = \frac{\mathbf{F}_g}{m} = \frac{98\ \text{N}}{10\ \text{kg}} = 9.8\ \text{m/s}^2 \quad \text{downward.}$$

You see the pattern that is emerging. In each case the mass was different and the force of gravity was different, *but the acceleration was the same*.

Now we can understand more clearly the results of Galileo's experiments on falling objects. You may recall (or see Chapter 1) that he found that, in the absence of friction, all objects fall at the same location with the same uniform acceleration. Different masses have different weights, but because they are about the same distance from the center of the Earth, the ratio of weight (force of gravity) to mass always gives the same result at the same location on the surface of the Earth, a uniform acceleration of about 9.8 m/s^2 (give or take a fraction of a percent at different locations around the Earth). This acceleration is called the *acceleration of gravity*. It is often given the symbol **g**. It is a vector quantity with a magnitude 9.8 m/s^2 (or 980 cm/s^2 or 32 ft/s^2) and a direction downward toward the center of the Earth at each place on the surface of the Earth. Free fall is an example of uniform acceleration. All objects fall with the same acceleration, $\mathbf{g} = 9.8$ m/s^2 downward, at the same location on the surface of the Earth. The weight, mass, and acceleration of all objects are related to each other by Newton's second law: $\mathbf{F} = m\mathbf{a}$.

What about weightlessness, such as experienced by astronauts orbiting in the space shuttle? How does that arise? Gravity constantly pulls us and every material object down toward the center of the Earth, but our body hardly "feels" the gravitational force itself. What you can experience directly is the *acceleration* due to gravity as, for instance, when you fall through the air when you dive into a pool. If you stand on a scale to weigh yourself, the spring in it compresses, as noted earlier, until it exerts an upward force on you strong enough to balance the downward force of gravity. The compression of the spring registers on the scale, which indicates your weight in pounds or in newtons. So, what you actually experience as "weight" when you stand on a scale, sit in a chair, or walk on a sidewalk is not the force of gravity but the opposing force of the scale or chair or ground.

Other bodies in the solar system exert the same kind of gravitational forces on objects on their surfaces. For instance, the Moon exerts a gravitational force on objects on or near it, but that force is much smaller than the pull of the Earth at its surface. The astronauts who landed on the surface of the Moon felt the effects of the pull of the Moon, which they experienced as weight, but, since that force was much smaller than on the surface of the Earth, they felt much "lighter" than on Earth and had a grand time bouncing around on the surface.

From the discussion so far you can see that true weightlessness can occur only when there is no net gravitational force pulling on an object—for example, in space, far from any sun or planet. In that case there would be no opposing force that you would experience as your weight. In such a spaceship, when you stand on a scale, it would register zero. But astronauts orbiting the Earth *seem* to be weightless, floating in their spaceship. Does this mean that they are beyond the Earth's pull of gravity and are therefore really weightless? The answer is NO. They are still being pulled by gravity, so they do have weight. But they cannot experience this weight because, while they orbit the Earth or the Moon, they are in free fall! (We will come to explain this curious phenomenon in Section 3.11.)

FIGURE 3.18 Astronauts in "weightless" environment.

In order to get a start on what happens with the apparent weightlessness during orbiting, try taking a bathroom scale into an elevator. While standing on it, notice what happens as the elevator briefly accelerates upward and downward. If you do so, you will notice that the scale registers more than your normal weight when accelerating upward, and less when accelerating downward.

Now imagine for a moment a ridiculous but instructive thought experiment. Suppose you are weighing yourself on a scale in an elevator or room on Earth. As you stand on the scale, the floor suddenly gives way. Like Alice in Wonderland, you and the scale drop into a deep well in free fall. At every instant, your increasing speed of fall and the scale's increasing speed of fall are equal, since all objects fall on Earth with the same acceleration. In fact, any objects that fell into the well with you will fall with you at the same increasing speed as you are experiencing. But to you they appear to float with or around you. Your feet now touch the scale only barely (if at all). Before you awake from this nightmare, you look down at the dial on the scale and see that the scale registers zero because the spring inside is not being compressed. This does not mean that you have lost your weight (the force of gravity on you). Gravity still acts on you as before. In fact, it is the dominant force on you, accelerating you downward. But since the scale is accelerating with you, you are no longer pushing down on it, nor is it pushing up on you. You *feel* weightless, but you still have weight; you just cannot experience it while you are falling. What you do experience is an apparent, but not real, weightlessness.

3.7 NEWTON'S THIRD LAW OF MOTION

In his first law, Newton described the behavior of objects when there are no forces acting on them or when the forces all balance, yielding a net force of zero. His second law explained how the motion of objects changes when the net force is not zero. Newton's third law added an original, new, and surprising insight into forces.

Consider this problem: In a 100-m dash, an athlete goes from rest to nearly top speed in less than 3 s. We could measure the runner's mass before the dash, and we could use high-speed photography to obtain the acceleration. With the mass and acceleration known, we could find the net force acting on the sprinter during the initial acceleration. But where does this force come from? Obviously it must have something to do with the runner himself. But is it possible for him to exert a force on himself as a whole?

Newton's *third law of motion*, also called the *law of action and reaction*, helps to explain just such puzzling situations. In modern language it states:

> 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.

The startling idea in this statement is that forces always act in pairs, one force acting on one object, the other acting on another object. A single force acting alone, without another force acting back on something else, does not exist in nature. For example, consider the sprinter. When the gun goes off to start the dash, his act of pushing with his feet *back* against the starting blocks (call it the "action") involves simultaneously a push by the starting blocks of an equal amount acting on him in the *forward* direction (call it the "reaction"). It is the reaction by the blocks that propels him forward. The action does not "cause" the reaction; the two forces simply coexist. If somehow the starting blocks came loose from the ground so that they cannot push back on his feet, they would just slide away when he tried to give them a big push, rather than providing the reacting force and the acceleration he needs to get started on the sprint.

A common mistake is to think that these action and reaction forces can balance each other to zero, and give equilibrium, as in the first law of motion. But in fact the two forces do not act on the same object; *each acts on a different object*, so they can't balance out. It is like debt and credit. One is impossible without the other; they are equally large but of opposite sign, and they happen to two different accounts.

Every day you see many examples of Newton's third law of motion at work. A car is set in motion by the push of the ground on the tires forward

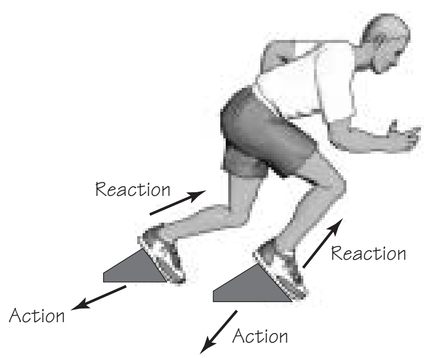


FIGURE 3.19 Force diagram on feet of sprinter and on blocks.

■ NOW YOU TRY IT

Michael Johnson, the American sprinter, set a new world record in 1999 of 43.18 s for 400 m, breaking the previous record by 0.11 s.

(a) What was his average speed for the entire run?
(b) Assuming that he was able to accelerate to the average speed in 2.5 s, what was his average acceleration at the start?
(c) Assuming that his mass is about 75 kg, how large was the force on his legs while he accelerated? (Ignore air resistance.)
(d) Explain why the force produced by his legs on the starting block was *not* the force that accelerated him during the first 2.5 s.

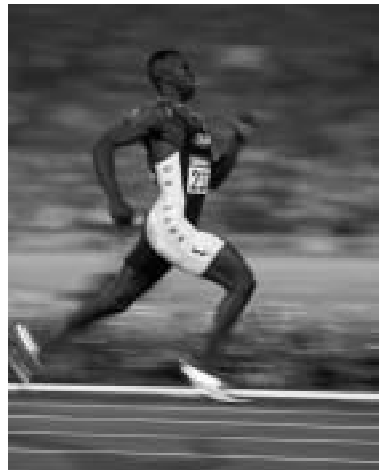
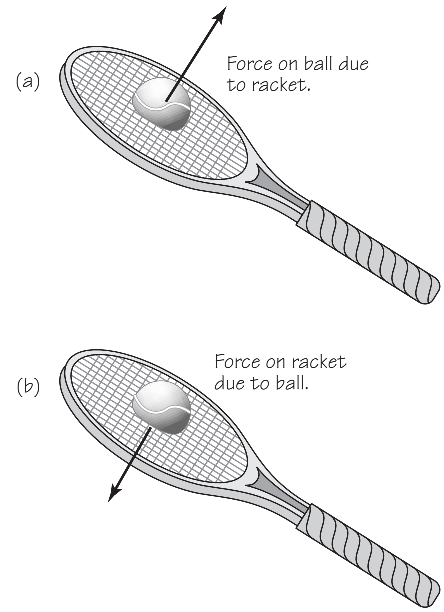


FIGURE 3.20 Michael Johnson just off the blocks.

in reaction to the push of the tires on the ground backward. When friction is not sufficient, as when trying to start the car moving on ice, the car just spins its wheels in place because there is no reacting forward push of the ground on the tires. A tennis racket hits a tennis ball, accelerating the ball forward, even while the tennis ball exerts a force backward on the racket, causing tennis elbow in some cases, or even broken arm bones. The Earth exerts a force on an apple and the apple exerts an equally large force on the Earth. When the apple falls, pulled down by the gravitational pull of the Earth (the weight of the apple), the Earth, in turn, is pulled upward by the equal but opposite attraction of the Earth to the apple. Hence, during the apple's fall the Earth accelerates upward—though by only an infinitesimal amount. Of course, we don't notice this motion of the Earth because of the difference in mass between the Earth and the apple, but the effect is there and in all similar situations. Similarly, after the sprinter has left the starting block behind and runs forward (owing to the force the ground exerts *on* his feet), the Earth moves a little in the opposite direction because of the force applied to it *by* his feet. On a small enough planet, this might become noticeable!

The universal nature of Newton's third law of motion makes it, like the other two laws of motion, an extremely valuable and useful law in physics.

FIGURE 3.21 Tennis racquet: (a) Force on ball and (b) reaction force on racquet.



B. THE THREE LAWS IN ACTION

3.8 PROJECTILE MOTION

You have already seen various types of motion, and you have seen that forces account for changes in motion. Now let's look at some common motions that have major significance for physics, and for our understanding of events around us. The first type is projectile motion: the flight of an arrow shot from a bow, a baseball batted into the outfield, a golf ball hit horizontally from a platform, or an elementary particle shot out into an evacuated tube of an "accelerator." Once again, Galileo was the first person to comprehend fully what is happening here, and to use the results in making some very important conclusions about the heliocentric theory of the solar system.

Returning once again to Galileo's inclined plane (and again neglecting friction and air resistance), you may recall that he obtained two very important results. First, by extrapolation to a 90° angle for the incline, he showed that free fall near the Earth's surface is an example of uniform acceleration, with the acceleration of gravity for all freely falling objects. Second, at the other extreme, for zero-angle inclination for a second inclined plane, he concluded that once in motion a ball will maintain its uniform velocity forever, until something gets in the way or alters its course. Now he considered what happens when something *does* alter a ball's course—namely, what happens when the ball rolls so far in the laboratory that it eventually falls off the table? Galileo realized that a ball rolling with uniform velocity on a flat tabletop will maintain its uniform velocity (constant speed and direction) in the horizontal direction even after it leaves the edge of the table, since there is no net force in the horizontal direction to change its horizontal motion. However, once the ball leaves the tabletop the unbalanced force of gravity also sets it into free fall in the vertical direction. Therefore the ball has two motions simultaneously after it leaves the tabletop:

(1) uniform velocity in the horizontal direction;
(2) uniform acceleration downward, in the vertical direction.

These two motions are completely independent of each other. What happens to one of them has no effect on the other. As the ball flies off the table, the two motions are "compounded" together to form the curved motion of a projectile, or any other object flying through space. The motion of a projectile is the result of two independent motions, put together to form the observed "trajectory" of the object. That is what we now would call our new understanding of "natural" motion.

A real experiment using a stroboscopic camera will help clarify this idea better. In the famous photograph in Figure 3.22, a ball is fired horizontally. At the same moment a second ball is allowed to fall freely down to the same floor. Although the motion of the objects may be too rapid to follow with the eye, if you tried it your ears will tell you that they do in fact

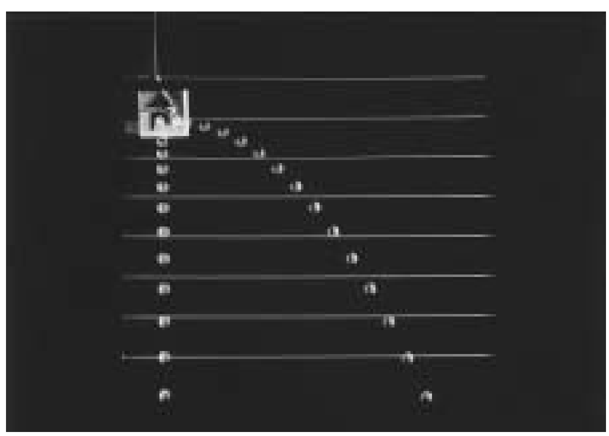


FIGURE 3.22 The two balls in this stroboscopic photograph were released simultaneously. The one on the left was simply dropped from a rest position; the one on the right was given an initial velocity in the horizontal direction.

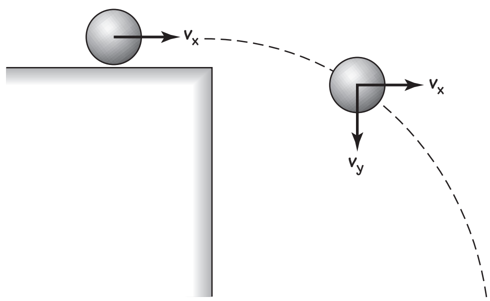


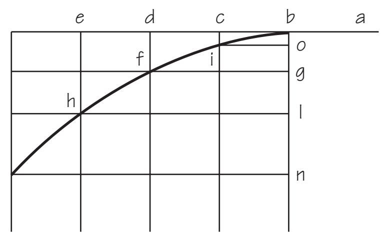
FIGURE 3.23 Schematic of ball on parabolic path.

impact the floor at the same time. This could happen only if they both fell with the exact same vertical motion, even though they had different horizontal motions. To see if this is indeed the case, with equally spaced horizontal lines were introduced into Figure 3.22 to aid the examination of the two motions. Look first at the ball on the left, the one that was released without any horizontal motion. You can see that it accelerates downward because it moves a greater distance downward between successive flashes of the strobe's light in equal time intervals. Now compare the vertical positions of the other ball, the one that was fired horizontally, with the vertical positions of the first ball falling freely. The horizontal lines show that the distances of fall are almost exactly the same for corresponding time intervals (air resistance has a tiny effect). Neglecting the effect of air resistance, the two balls are undergoing the same acceleration in the vertical direction. This experiment supports the idea that the vertical motion is the same whether or not the ball has a horizontal motion. *The horizontal motion does not affect the vertical motion*—something we recall that the Aristotelians did not believe possible.

But does the vertical motion affect the horizontal motion? To answer this question, measure the horizontal distance of the projected ball between each image. You will find that the horizontal distances are practically equal. Since the time intervals between producing each image are equal, you can conclude that the horizontal velocity is constant during the curved descent. *Therefore*, *the vertical motion does not affect the horizontal motion*. Together, the vertical and horizontal motions make up the path of the projectile that we see. What is this path? Obviously, it's some kind of a curve, as shown in the photograph. On examination it turns out that the actual path, or trajectory, is what is known as a parabola. (See the *Student Guide* for a derivation showing that it is indeed a parabola.)

You can see that the trajectory of a projectile is a parabola more clearly for a ball thrown into the air. Here you can see both halves of the parabola. The second half, the downward side, is equivalent to the motion of the ball

FIGURE 3.24 Drawing of a parabolic trajectory from Galileo's *Two New Sciences.*



projected straight out horizontally. On the upward side of the trajectory, the ball has uniform velocity in the horizontal direction and uniform acceleration downward due to gravity, as before, but it also has a vertical velocity, straight up. Gravity works against the vertical velocity, slowing it down until the vertical velocity finally reaches zero at the top of the arc. (*Note:* The vertical *velocity* reaches zero, but *not* the gravitational acceleration, which stays constant throughout.) At the top of the arc, the ball still has the same horizontal velocity as at the start, since gravity cannot affect motion in the horizontal direction. So the ball continues after reaching the top and begins the downward side of the arc. The vertical velocity now starts accelerating at the acceleration of gravity; the projectile reaches greater and greater speeds until it reaches the initial level with about the same vertical speed and horizontal velocity with which it started (assuming air resistance plays only a minor role).

3.9 THE EARTH CAN MOVE!

As the previous section indicates, understanding the motion of a projectile is not easy to grasp by simple observation. After much thought and study, Galileo concluded that projectile motion is a single motion compounded of two independent motions: uniform velocity in the horizontal direction and changing velocity in the vertical direction owing to the effect of the uniform acceleration of gravity. Once he understood this, Galileo was able to answer at last one of the major objections against the moving-Earth hypothesis, raised at that time and given at the beginning of this chapter. If the Earth really is rotating on its axis once a day, then the surface of the Earth must be moving very rapidly (about 1000 mi/hr at the equator). If that's the case, some argued, then a stone dropped from a high tower would

FIGURE 3.25 Stroboscopic photograph of a ball thrown into the air.

not land directly at the tower's base. During the time the stone is falling, the tower would move forward many meters. The stone would be left behind while it is falling and so would land far away from the base of the tower. But this is *not* what happens. Except for very slight variations, the stone always lands directly below the point of release. Therefore, many of Galileo's critics argued that the tower and the Earth could not possibly be in motion.

Galileo answered this objection showing that the tower experiment can be understood as an example of projectile motion. While the stone lies or is held at the top of the tower, it has the same horizontal velocity as the tower. During the time the stone falls after it is released, Galileo said, the stone continues to have the same horizontal velocity, and it gains vertical

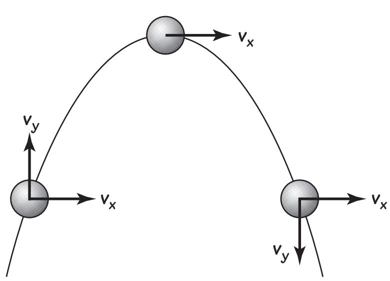
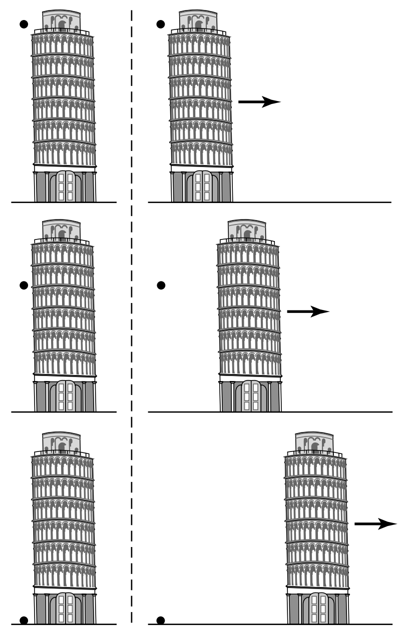


FIGURE 3.26 Components of velocity of a ball in flight.

FIGURE 3.27 Galileo's critics' view of how a ball would drop to Earth.



speed as it falls freely under the force of gravity. But during the brief time of the stone's fall, the stone and the tower and the ground under them all continue to move forward with the same uniform horizontal velocity as before; the falling stone behaves like any other projectile. The horizontal and vertical components of its motion are independent of each other. Since the tower and the stone continue to have the same horizontal velocity throughout, the stone will not be left behind as it falls. Therefore, no matter what the speed of the Earth, the stone will always land at the base of the tower. So the fact that falling stones are not left behind can *not* be used to argue that the Earth is standing still. The Earth can be in motion.

Similarly, Galileo said, a stone dropped from the crow's nest at the top of a ship's mast lands at the foot of the mast, whether the ship is standing still or moving with constant velocity in calm water. This was actually tested by experiment in 1642, and many observations today support this view. For example, if you drop or toss a book in a car or bus or train that is moving with constant velocity (no bumps in the road!), you see the book move just as it would if the vehicle were standing still. Similarly, a person walking at constant speed and tossing a ball into the air and catching it, will see the ball move straight up and straight down, as if he were standing still. Try it!

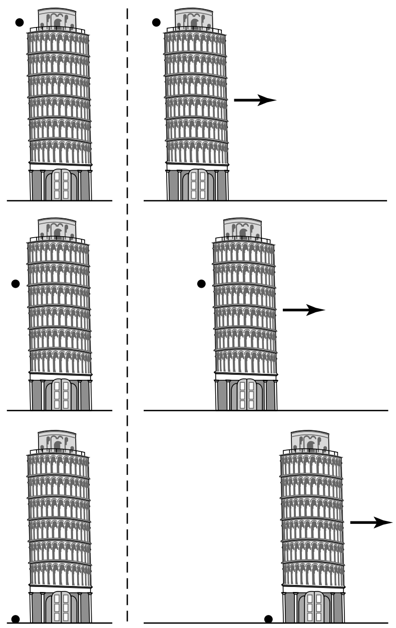


FIGURE 3.28 Galileo argued that while falling, the ball would continue its initial horizontal motion so that it would fall to the base of the tower. Therefore, an observer on Earth could not tell whether the Earth moved by watching the path of the ball.

3.10 GALILEAN RELATIVITY

The observations in the previous section all indicated that objects in a system, such as the Earth, or a ship, or a car, that is moving at constant velocity, will move within that system exactly in the same way as if they were in a system that is at rest. Here is how Galileo himself expressed it in a beautiful thought experiment recounted in 1632 in his *Dialogue on Two Chief World Systems*:

> Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the dis-

> tances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether you were moving or standing still.

We can perform the same experiment today with butterflies or baseballs in a boat, or in a car or train or plane. Today, such a "system" is usually called a *reference frame*, since it is the frame of reference for our observations. The fact that the motions of baseballs and butterflies stay the same, regardless of whether or not the reference frame is moving at constant velocity, indicates that Newton's laws of motion are the same—in fact, that all mechanics (science of motion) is the same—for all reference frames at rest or moving with uniform velocity relative to each other. This conclusion has been called the *Galilean relativity principle*. It can be stated as follows:

> The laws of mechanics are exactly the same for every observer in every reference frame that is at rest or is moving with uniform velocity.

Since objects move in a reference frame that is at rest or in uniform velocity—such as a boat, or the Earth's surface for reasonably short periods—as they were in a frame at rest, there is no way to find out the speed of one's *own* reference frame from any mechanical experiment done *within* that frame. Nor can one pick out any one reference frame as the "true" frame, the one that is, say, absolutely at rest. Thus, there can be no such thing as the "absolute" velocity of an object. All measured velocities are *relative*.

Three centuries later, Albert Einstein expanded upon the Galilean relativity principle in formulating his theory of relativity, as you will see in Chapter 9.

3.11 ORBITING SATELLITES

To recapitulate: After obtaining his new concept of "natural motion" Galileo investigated what happens when a rolling ball moving with uniform velocity reaches the end of the plane on which it is rolling. He observed that it flies off the table and goes into projectile motion. He discovered that this motion is really a compound of independent motions: uniform velocity in

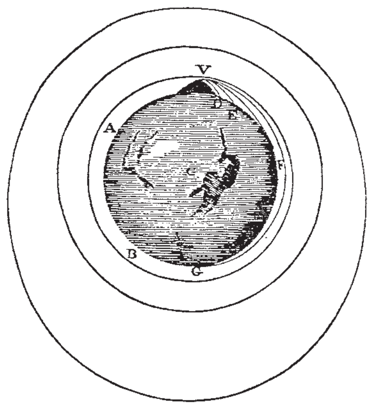


FIGURE 3.29 ". . . the greater the velocity . . . with which [a stone] is projected, the farther it goes before it falls to the Earth. We may therefore suppose the velocity to be so increased that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the Earth, till at last, exceeding the limits of the Earth, it should pass into space without touching it."—Newton, *Principia*.

the horizontal direction and free fall (with uniform acceleration of gravity) in the vertical direction.

Newton took Galileo's ideas one step further. He considered what happens when a projectile is launched horizontally from a high tower or a mountain on the Earth. Three factors determine where the object strikes the Earth. These are the height of the mountain, the acceleration due to the force of gravity, and the horizontal speed of the projectile. Keeping the first two constant (by starting from the top of the same high mountain), as the horizontal launch speed of the projectile is increased, it will strike the Earth at points farther and farther from the base of the mountain. This is shown in the diagram, taken directly from Newton's *Principia*. Eventually, if it is fast enough at launch, the projectile goes so far that the curvature of the Earth comes into play. Since gravity always pulls objects toward the center of the Earth, the trajectory of the projectile is no longer a parabola because gravity pulls it from slightly different directions as it moves over the curve of the Earth.

If the launch speed is increased even more, the projectile will strike the Earth at points farther and farther around the Earth. Finally, at a certain speed the projectile would not fall fast enough in order to strike the Earth before it returns to its original launch location. At that point, if it is not slowed by air resistance, the projectile would just keep going around and around the Earth, never actually reaching the Earth even though it "keeps falling" toward the Earth. In other words, it would go into orbit: always falling toward the Earth in free fall but moving too fast in the orbit's direction to hit the curved Earth. The amount of fall of the projectile away from its original horizontal motion is roughly matched by the curvature of the Earth's surface. Therefore, the projectile stays in orbit at roughly a constant distance above the surface. (Actually, as Kepler's first law tells us, the orbits may be ellipses, of which the circle is a special case.)

FIGURE 3.30 Space Shuttle blast-off.

The "projectile" could be a research satellite, launched into orbit by a rocket, instead of a ball projected from a high mountain. Putting Newton's third law of motion to work, the rocket, with the satellite fastened to it, lifts off from the launch pad. During its motion upward it is made to tilt in the horizontal direction, moving faster and faster and further from the Earth, until it reaches orbital velocity at the desired height above the surface of the Earth. At that point the main engines shut down and are jettisoned, and the satellite is in orbit.

A common question about the motion of a satellite in orbit is, "What is holding it up"? The answer is of course that it is not being held up. In fact, the tons of metal and electronics are constantly falling toward the Earth, pulled down by gravity. The only difference from direct fall downward is that the satellite also has such a tremendous orbital speed, as much as 18,000 mi/hr (or 29,000 km/hr). This prevents it from ever reaching the curved Earth as it falls downward because the curvature of the satellite's trajectory is about the same as the Earth's curvature. The satellite will stay in orbit as long as it maintains sufficient speed. This can change of course if, following Newton's second law, there acts on it an unbalanced force, say

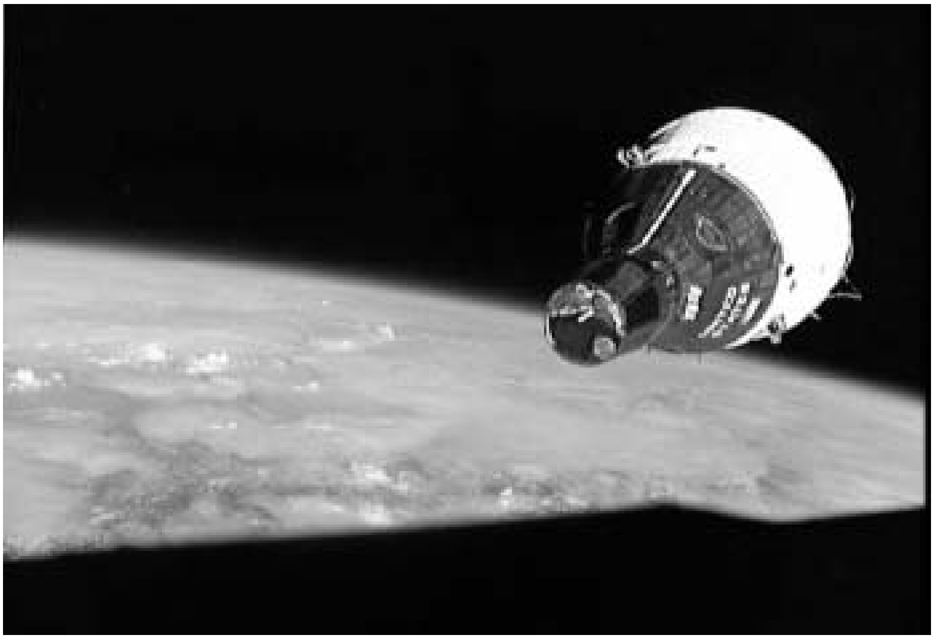


FIGURE 3.31 An early manned space capsule in orbit.

in the horizontal direction. (One already exists in the vertical direction—gravity.) Such a horizontal force can arise from air resistance, or if the pilot in a space shuttle turns on the forward thrusters to slow the shuttle down and begin the long spiral inward for a landing.

Special Satellites

Three special types of satellites are: communications satellites, weather satellites, and global positioning satellites. Communications satellites are placed into orbits for which the horizontal speed exactly matches the rotational speed of the Earth—this is called a "geosynchronous orbit." Hence the satellite stays over the same location on the Earth, appearing to hang stationary in the sky. This is very useful for television transmission and wireless reception because ground-based satellite dishes can then be aimed at a fixed point in the sky to send and receive signals.

Some weather satellites are placed in polar orbits, in which they orbit the Earth in the north–south direction. As the Earth rotates west to east, the entire Earth passes under the orbit of the satellite. The satellite's cameras can then be turned on at the appropriate time to record events on any desired portion of the Earth.

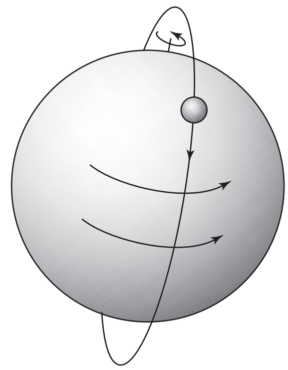


FIGURE 3.32 Path of satellite in polar orbit.

In the Global Positioning System 24 satellites are in orbit around the Earth. A signal is emitted by a satellite and is picked up by a receiver on Earth. From the timing of the sending and receiving of the signal, three of the satellites are used to "triangulate" the location. The fourth satellite corrects for timing errors.

FIGURE 3.33 Space Shuttle with Solar Max satellite (in background) to be launched.

The Space Shuttle

Some might think an orbiting space vehicle stays in orbit because it is far beyond the pull of gravity. After all, they argue, the astronauts and any equipment not fastened down can float around as if "weightless," which "proves" there is no gravity on them and the space shuttle itself. But, as you saw earlier, in orbital motions gravity continues to act. When a space shuttle is about 500 km above the surface of the Earth (whose radius is about 6370 km), the Earth's gravitational force there is still about 90% of its value at the Earth's surface. In fact, if there were no gravity acting on the shuttle, there would be no net force on it, in which case Newton's first law of motion would come into play. According to the first law of motion, the shuttle would fly off into outer space on a straight line at uniform velocity and never go into orbit. As you will see below (Section 3.12), we need a net force owing to gravity to keep any object in orbit; without it there would be no orbit!

So, how can the astronauts feel weightless inside the space shuttle even though the force of gravity is acting on them? The answer is that they are in "free fall," when everything behaves as if it were weightless. For instance, if you

FIGURE 3.34 Astronaut during space walk.

were in free fall and released a bunch of keys taken from your pocket, they would stay with you, falling alongside you, as if gravity had been "turned off."

In order to answer the further objections that people after Copernicus raised against the idea that the Earth is in motion, we have to look a little closer at circular motion.

3.12 CIRCULAR MOTION

The simplest kind of circular motion is *uniform circular motion*. This is motion in a circle at constant speed. If you are in a test car that goes around a perfectly circular track so that at every instant the speedometer reading is, say, 60 mi/hr, you are in uniform circular motion. This is not the case if the track is of any shape other than circular, or if your speed changes at any point.

How can you find out if an object in circular motion is moving at constant speed? You can apply the same test used earlier to decide whether or not an object traveling in a straight line does so with constant average speed: measure the distances traveled along the circumference in given time intervals and determine if the ratios $\Delta d/\Delta t$ are equal. For circular motion, it is often convenient to use one complete circumference of the circle as the distance traveled. If we know the radius r, this distance C is given by the formula: $C = 2\pi r$. Here π is the Greek letter "pi." It represents the value, sufficient for all our calculations, of approximately 3.14. (More precisely, pi represents the value 3.141592653. . . .) The time required for an object to complete one revolution around the circle is the *period* (T) of the mo-

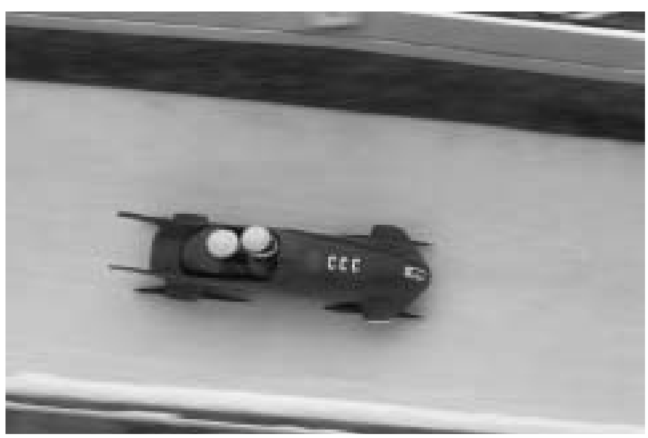


FIGURE 3.35 Bobsled rounding curve.

tion. The number of revolutions completed by an object in a unit of time is called the *frequency* (f) of the motion. If the unit of time is chosen to be one period, then one revolution is completed in one period. So, the frequency of revolution is just 1/period, or $f = 1/T$.

(There is another measure of speed used in circular motion, called *angular speed*. Instead of distance traveled per time interval, which is called *linear speed*, angular speed refers to the angle of the circular segment traversed per time interval. An analogue music record turns at a uniform angular speed, but a modern-day CD turns at a constantly changing rate so that the data, which are arranged along a tight spiral, pass over a laser beam at constant linear speed. In this text we will use only linear speed in uniform circular motion.)

Using the radius of the circle and the frequency of revolution, we can obtain the average linear speed of an object in uniform circular motion as follows:

$$\text{average speed} = \frac{\text{distance traveled on circumference}}{\text{elapsed time}},$$

$$v_{\text{av}} = \frac{2\pi r}{T}$$

or, dropping the "av," if we can assume that there is no change of speed during the elapsed time, we have

$$v = \frac{2\pi r}{T}.$$

This expression is essentially the definition of the speed of an object in uniform circular motion.

What about the *velocity*, which is speed *with direction*? To find out the direction of the velocity of a circulating object, carefully whirl a small object on the end of a string. Being careful not to hit anyone, release the object while it is whirling on the string. In what direction does it move? You will notice that it does not move straight outward from the circle, as one might intuitively believe, nor does it keep spiraling for a while as it moves outward. Instead, upon release it immediately moves in a straight line along a tangent to the circle at the point where you released it. Try this at different points on the circle. You will notice that the object always flies away on a tangent at that point. *We conclude from this that the velocity vector is tangent to the circle at every point on the circle.*

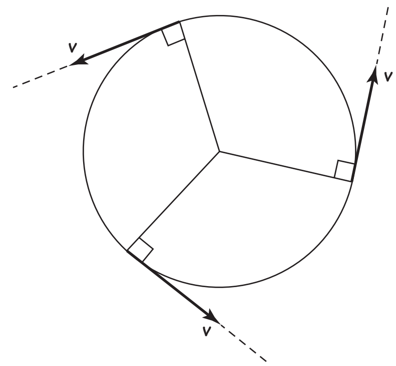


FIGURE 3.36 Velocity vectors for uniform circular motion at three points.

This is a very important conclusion. Since the tangent to a circle is different for every point on the circle, this conclusion means: *the direction of the velocity is different at each point on the circle, even though the speed is the same over the entire circle*. Since the velocity is constantly changing in direction—even though not in magnitude (speed)—there is a uniform acceleration. But it is different from the accelerations we have encountered so far. It is an acceleration that changes only the direction but not the speed of the moving object.

Where there is an acceleration there is a net force. *What is the direction of the vector representing the net force?* Remember that a vector can be represented by an arrow in the direction of the vector. The magnitude of the vector is represented by its length. Since the magnitude of the velocity vector, or the speed, is not changing in uniform circular motion, the lengths of the arrows in the above diagram are all equal. But their directions are all different. Since the force does not help or hinder the speed, it must be perpendicular to the velocity vectors. Since a tangent to a circle is always perpendicular to the radius at that point, the force must lie along the radius, either straight in or straight out.

Now let's look at what happens when arrow **A,** representing the veloc-

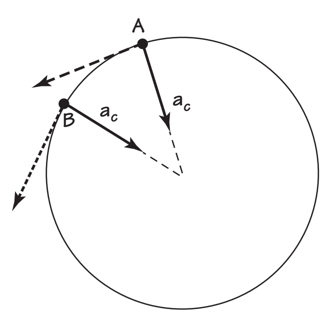


FIGURE 3.37 Force and acceleration vectors on a uniformly circulating object, at two points on its path.

ity vector of a ball in uniform circular motion at point A, turns into arrow **B** at point B. If there is no net force, Newton's first law tells us that the ball will fly off on a straight line in the direction of arrow **A**. But there is a net force, which pulls the ball off the straight-line course, changing the velocity at A, represented by arrow **A**, into a velocity at B in a new direction, represented by the direction of arrow **B**. To force the ball off course and around the curve, you can almost feel how you must pull it inward, not outward. This force must be an inward force along the radius and pointing toward the center. Since it is a pull toward the center, it is often called the *centripetal force*, literally "moving, or directed, toward the center."

The centripetal force acting on a mass causes an acceleration toward the center, the *centripetal acceleration*. These are both vectors and they both point inward toward the center of the circle along the radius at each point on the circle. The magnitude of each is related to the speed of the object and the radius of the circle. You can almost feel that the faster a ball whirls on a string, the harder you must pull on it to keep it in circular motion. As shown in the *Student Guide*, the magnitude of the centripetal acceleration, symbol a_c, is given by

$$a_c = \frac{v^2}{r}.$$

The magnitude of the centripetal force F is given by $F_c = ma_c$, or

$$F_c = \frac{mv^2}{r}.$$

From this you can see that the force and acceleration increase rapidly as you increase speed, while they go down more slowly as you increase the radius of the circle.

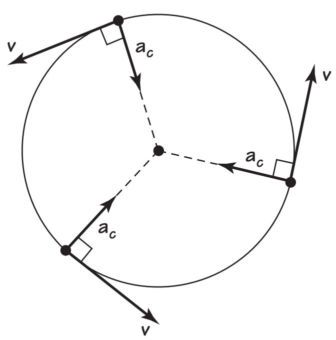


FIGURE 3.38 Velocity and acceleration vectors at three points on the path of a uniformly circulating object.

Some Examples

We have learned now that without a centripetal force there cannot be a circular motion. Unless acted upon by a net, unbalanced force, all objects move in a straight line at constant speed. To make objects change their direction and move in a circle at uniform speed, something must provide a force toward the center of the circle. A stone whirling on a string requires a pull inward on the string. As soon as the inward pull ceases or the string breaks, the ball ceases to be in circular motion.

Another example involves cars traveling at high speed on a curved highway. Why are these highways usually banked on the curves? The reason is to use part of the weight of the car itself to help provide the centripetal force. The faster the expected speeds of the cars, the steeper the bank (according to the square of the speeds). Even with a bank, there must be enough friction between the tires and the road to provide additional centripetal force to enable the cars to perform the circular turn. If the friction is lost on a rainy or icy day, the road might not supply enough centripetal friction force to enable the cars to make the turn. The cars will skid off on a straight line, with possibly disastrous results. This is why speed limits are (or should be) reduced in inclement weather.

An example of nearly uniform circular motion around the Earth was the flight of the space shuttle *Endeavor* in January 1996. Let's find out how fast it was going and what its centripetal acceleration was. To calculate these using the formulas above, we need to know the radius and period of its orbit. According to information supplied by NASA's site on the World Wide Web (http://spacelink.nasa.gov), the average altitude of the *Endeavor* shuttle above the Earth's surface was 288 mi. This is equivalent to 463.4 km. But this is not the radius of its orbit! The orbit is centered on the center of the Earth, which we can assume to be a sphere of radius 6370 km. So the radius of the orbit was

$$R = 6370 \text{ km} + 463 \text{ km} = 6833 \text{ km}.$$

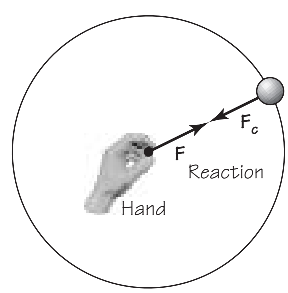


FIGURE 3.39 The centripetal force F_c on the object is equal in magnitude and opposite in direction to the reaction force felt by the hand.

FIGURE 3.40 Space Shuttle in orbit around the Earth.

NASA's Web site also reports that *Endeavor* made 142 orbits of the Earth in approximately 8 days and 22 hr, or 214 hr total. So the period for one orbit is

$$T = \frac{214 \text{ hr}}{142 \text{ orbits}}$$

$$= 1.51 \text{ hr} \times 3600 \text{ s/hr}$$

$$= 5425 \text{ s}.$$

We are now ready to obtain the speed of the shuttle in its orbit

$$v = \frac{2\pi R}{T} = 2\pi \times \frac{6833 \text{ km}}{5425 \text{ s}} = 7.91 \text{ km/s}.$$

This is equivalent to a horizontal speed of 17,798 mi/hr. Some projectile! However, at any speed slower than this, the shuttle would not be able to stay in this orbit, but would spiral down to a lower orbit. If it still decreased in speed, it could not stay in orbit at all and would have to land—which is exactly what it does intentionally when it returns to Earth.

With the speed and the radius of the shuttle in its orbit, we are now ready to obtain the centripetal acceleration

$$a_c = \frac{v^2}{R} = \frac{(7.91 \text{ km/s})^2}{6833 \text{ km}}$$

$$= 0.0092 \text{ km/s}^2 = 9.2 \text{ m/s}^2.$$

What is the origin of the force that gives rise to this acceleration? You already know that it must be due to the Earth's gravitational attraction. Evidently the centripetal acceleration on the shuttle *Endeavor* was just the acceleration of gravity at that height, 9.2 m/s^2. This is in fact the uniform acceleration at that height of a freely falling object. However, it is about 13.6% less than the gravitational acceleration at the surface of the Earth, which is 9.8 m/s^2. It appears, then, that the gravitational force does extend into outer space and that it accounts for the centripetal force acting on orbiting objects, but it appears to decrease with distance.

Is it possible that the same situation occurs for other orbiting objects, such as the Moon around the Earth, the moons of Jupiter observed by Galileo orbiting Jupiter, and perhaps even for the Earth and other planets orbiting the Sun? Is there a centripetal force holding the Earth and the other planets in orbits around the Sun, or is the Earth really physically different from all the other planets, as people believed for centuries? If the former case, what is the exact nature of this centripetal force? For answers to these and other fundamental questions we turn, in the next chapter, to the work of Isaac Newton.

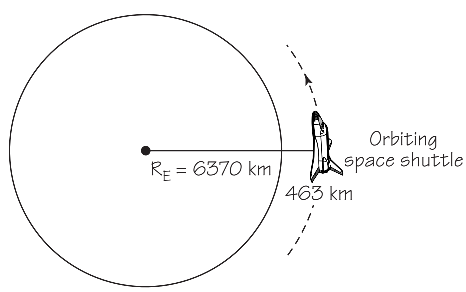


FIGURE 3.41 Diagram of Space Shuttle in orbit.

SUMMARY

Newton's Three Laws of Motion

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.
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: $\mathbf{F} = m\mathbf{a}$.
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.

SOME NEW IDEAS AND CONCEPTS

centrifugal force
centripetal force
force
force, unbalanced
Galilean relativity principle
inertia
mass
natural motion
net force
projectile motion
reference frame
uniform circular motion
violent motion
weight
weightlessnes

FURTHER READING

G. Holton and S.G. Brush, *Physics, The Human Adventure* (Piscataway, NJ: Rutgers University Press, 2001), Chapters 8–10.

R.S. Westfall, *The Construction of Modern Science: Mechanisms and Mechanics* (New York: Cambridge University Press, 1978).

T.S. Kuhn, *The Copernican Revolution: Planetary Astronomy in the Development of Western Thought* (Cambridge, MA: Harvard University Press, 1982).

STUDY GUIDE QUESTIONS

1. Look at every equation, graph, table, law, and definition in this chapter and be sure that you understand their meaning to the extent that you are able to explain each of them in your own words to another person.
2. List all the different types of motion discussed in this chapter. Then attempt to see how Newton's laws of motion apply to each one.

A. THE THREE LAWS OF MOTION

3.1 Natural Motion and Newton's First Law

1. What were the so-called natural motion and violent motion? Why did they seem reasonable?
2. How is the old idea of natural motion contradicted by the observation that two objects of different mass fall at the same rate when dropped from the same height?
3. What did Galileo discover about a ball moving on a tabletop without friction?
4. Express the law of inertia in your own words.
5. A roller-blader coasts for a distance along a flat stretch of a street. How would Aristotle and Galileo each account for his motion?

3.2 Forces in Equilibrium

1. What are balanced forces?
2. Give some examples of unbalanced forces.
3. Sketch the examples in Question 2 and represent the forces by vectors.
4. What are two possible states of motion for objects on which balanced forces act?

3.3 More about Vectors

1. Draw arrows to represent two or more forces acting on an object. Then describe how you would find the net vector force acting on the object.
2. A swimmer tries to swim across a fast-moving stream flowing west to east at 4 mi/hr. The swimmer sets out to cross the stream by swimming 3 mi/hr due north. What is his resultant velocity?

3.4 Newton's Second Law of Motion

1. What is a universal law?
2. How do we know that Newton's laws of motion are universal laws?
3. Describe an experiment that explored the relationship between force and acceleration. What was the conclusion?
4. Describe an experiment that explored the relationship between mass and acceleration. What was the conclusion?

5. State Newton's second law of motion in your own words.
6. A net force of 10 N gives an object a constant acceleration of 4 m/s^2. What is the mass of the object?
7. Does Newton's second law hold only when frictional forces are absent? Explain.
8. An unbalanced force can cause acceleration, yet you can push hard on a broken shopping cart on a rough pavement and it still moves only at constant velocity. Explain.
9. What does it mean to say that mass is a scalar quantity?

3.5 Measuring Mass and Force

1. What is weight, and how is it different from mass?
2. How are the kilogram, meter, and second defined?
3. What exactly is inertial mass?
4. What is a "newton"?
5. What are the cgs and mks systems of units? Are they both metric systems?

3.6 More about Weight, and Weightlessness

1. You are standing on a platform on Earth that is part of a "weighing scale."
   (a) Using the metric conversion (to kilograms), how much do you weigh?
   (b) What is your mass?
   (c) In a sketch, draw the forces on you and on the scale.
   (d) If the net force on you is zero, why does the scale register your "weight"?
   (e) The ground suddenly gives way and you fall freely into a deep well. Before you panic, you look down at the scale. What is it reading as your weight?
   (f) What is your mass as you fall in free fall?
2. An astronaut walking on the Moon, which has one-sixth the gravitational pull of the Earth, has a certain amount of weight and mass. Are they the same or different from his weight and mass on the Earth, and if different, by how much?
3. If an object is accelerating, what can we say about the forces acting on it?
4. Name some common types of forces.
5. Different masses on Earth have different weights, yet they have the same acceleration in free fall. How can this be?
6. How do Newton's second law and the force of gravity account for the fact that two objects of different mass hit the ground together when dropped from the same height? (Neglect air resistance.)
7. Why does a skydiver in free fall feel weightless? Is he/she really weightless? Explain.
8. An astronaut is orbiting on the International Space Station, where he feels weightless. At that altitude, the acceleration due to gravity is 13% less than its value on the surface of the Earth. Which of the following is/are true?
   (a) The astronaut's weight is zero.
   (b) The astronaut's mass is zero.

(c) The astronaut's weight is 13% less than its value on Earth.
(d) The astronaut's mass is 13% less than its value on Earth.

3.7 Newton's Third Law of Motion

1. State Newton's third law of motion in your own words.
2. Give some examples of the third law in operation.
3. Why don't action and reaction "cancel out"?

B. THE THREE LAWS IN ACTION

3.8 Projectile Motion

1. A golfer tees off on a fairway, hitting the green some distance away.
   (a) What is the shape of the trajectory of the ball?
   (b) How would Galileo account for the motion of the ball? Would Aristotle agree?
2. What are the two motions, acting at the same time, that make up projectile motion?
3. Does the vertical motion affect the horizontal motion, and vice versa? How do you know?

3.9 The Earth Can Move!

1. What was the main argument against the moving Earth in this section of the text?
2. How did Galileo use the concept of projectile motion to demolish that argument?

3.10 Galilean Relativity

1. What conclusion can be drawn from Galileo's examples of moving objects in systems at rest or in uniform motion?
2. State the Galilean relativity principle in your own words.
3. How does the principle support the argument that the Earth can be in motion?

3.11 Orbiting Satellites

1. Explain how a projectile can become an orbiting satellite.
2. The Space Shuttle weighs hundreds of tons, yet it can orbit the Earth without falling down. How does it stay in orbit if nothing is "holding it up"?
3. Jumbo jets also weigh many tons. What can you say about the forces on them as they are flying at cruising altitude at a constant velocity? What "keeps them up"?
4. Name two types of specialty satellites and describe their orbits.

5. Why do astronauts in the orbiting Space Shuttle feel weightless? Are they really weightless?

3.12 Circular Motion

1. An object is moving around a circle with constant speed. Is the object accelerating, even though the speed is constant? Explain.
2. If an object moving in uniform circular motion is accelerating, then there must be a force on it. Describe the nature of this force, and draw arrows to represent the force vector at different points around a circle depicting the object's motion.
3. What is centripetal acceleration?
4. In which of these cases is an object accelerating?
   (a) Moving with constant speed in a straight line.
   (b) Moving with constant speed in a circle.
   (c) Moving on the trajectory of a projectile.
5. Classify each of the following as either vectors or scalars:
   (a) 4 s;
   (b) 3 m/s eastward;
   (c) 600 g;
   (d) centripetal acceleration;
   (e) 5 N to the right;
   (f) 5 N.

DISCOVERY QUESTIONS

1. During the course of 1 day, observe some of the different motions that you see around you and make a list of them. Examples might be a car accelerating, a bus turning a corner, a rotating fan, falling rain, a basketball arcing toward a basket, even the Sun rising and setting. Now attempt to answer the following:
   (a) What type of motion is each of the motions that you observed?
   (b) If some of these involve combinations of two or more motions, can you break them down into simpler motions?
   (c) Using Newton's laws of motion, try to account for each of these motions.
2. Why do you think that Galileo and Newton found the study of motion to be so difficult? Do you find it difficult?
3. List some examples of action–reaction forces.
4. List some examples of uniform circular motion and describe the centripetal force involved in each case.
5. How would you use a "balance scale" and a set of known masses to measure the mass of an unknown object? How does this make use of Newton's laws of motion?

6. If you know the period and speed of a satellite, you can easily find the acceleration of gravity at the height of the satellite. How would you do this?
7. A person is sitting in a car at rest. In an unfortunate accident, the car is hit from behind. Which way is the person inside thrown, backward or forward? Explain.
8. Have someone drive you for a short distance in a car that includes a number of stops, starts, turning corners and curves, and bumps. Carefully observe and write down all the forces you feel. Then try to explain each one from the material in this chapter. Which of these forces are fictitious forces and which are real forces?
9. While you are sitting in the back of a car on the right side, the car makes a sudden turn to the left. You feel a push on you from the right side of the car. Why?
10. Try the experiment described in Section 3.6. Take a bathroom scale into an elevator and record the reading on the scale as the elevator accelerates upward and downward. Compare the result with the reading when the elevator is at rest. What would the scale read if the acceleration downward increased to the acceleration of gravity, g? What would the scale read if the acceleration upward increased by the same amount?

Quantitative Questions

1. Consider a system consisting of a 1-kg ball and the Earth. The ball is dropped from a short distance above the Earth and falls freely to the Earth (whose mass is 6.0×10^{24} kg).
   (a) Make a vector diagram illustrating the important forces acting on each member of the system during the ball's descent.
   (b) Calculate the acceleration upward of the Earth while the ball accelerates downward.
   (c) Make a vector diagram as in (a), but showing the situation when the ball has come to rest after hitting the ground.
2. A projectile is launched horizontally with a speed of 8 m/s from the edge of a precipice.
   (a) How much time will the projectile take to hit the ground 80 m below?
   (b) How does this time change if the horizontal speed is doubled?
   (c) What is the vertical speed of the projectile when it hits the ground?
   (d) What is the horizontal speed of the projectile when it hits the ground?
3. What is the period of the minute hand of an ordinary clock? If the hand is 3.0 cm long, what is the speed of the tip of the minute hand?
4. Go to the NASA site on the World Wide Web (http://spacelink.nasa.gov) and find data on the orbit of a satellite or space shuttle. From the data given, obtain the speed, period, velocity, and centripetal acceleration of the orbiting object.
5. Do the same as in Question 4 for the International Space Station.
6. What are the velocity and centripetal acceleration of a person standing on the equator of the Earth, owing to the rotation of the Earth?

7. What are the velocity and the centripetal acceleration of the Earth as it orbits the Sun each year? What is the centripetal force on the Earth (mass 6.0×10^{24} kg)?
8. A satellite with a mass of 500 kg completes a circle around the Earth every 380 min in an orbit 18,000 km from the center of the Earth. What are the magnitude and direction of the force vector holding the satellite in orbit? What produces this force?
9. How fast would you have to throw a baseball in order to put it into orbit at the surface of the Earth, assuming that there are no mountains and buildings in the way?