MINDS • ON PHYSICS

READER CHAPTER 2 DESCRIBING INTERACTIONS

Introduction. *Dynamics* is the study of how objects affect the motion of other objects through *interactions*. The way in which one object influences the motion of another object involves the idea of a *force,* and the response of the object is often characterized by a change in velocity (that is, an acceleration). This is why we have spent so much time thus far helping you to develop your ideas about acceleration. Now we will learn about what causes something to accelerate. We will also explain how interactions can be present even when something is not accelerating.

2.1 INTERACTIONS AND FORCES

Interactions. When two objects influence each other, we say that they are *interacting.* Depending on the circumstances, the effect of the interaction might be:

- the motion of one or both objects is changed in some way (speeding up, slowing down, changing direction, etc.)
- the shape of one or both objects changes, such as when a spring is compressed.

Sometimes neither effect is visible, such as when a glass is sitting at rest on a table top. However, we can say that the motion is different from what we would expect if the table were not there. In other words, without the table, the glass would fall; therefore the motion of the glass is certainly affected by the table. In fact, though we cannot see it for ourselves, the positions of the atoms on the surface of the table are certainly affected by the glass sitting on it. So, the shape of the table changes, though microscopically. Therefore, we can say that the glass and the table are interacting. An *inter*action is always two-way—always between "object *A*" and "object *B*". (You should be able to identify the two objects.)

Forces. Whenever two objects interact, we say that each exerts a *force* on the other. A force consists of two parts: (1) how strongly each object influences the other, and (2) the direction of the influence. (Force is a vector quantity, so it has both a magnitude and a direction.)

We have many different ways of saying that two objects influence each other, all of which are equivalent. For example:

- *There is an interaction between this object and that object.*
- *These two objects are interacting with each other.*
- *These two objects act on each other.*
- *Each of these two objects exerts a force on the other.*
- *Object A exerts a force on object B, and object B exerts a force on object A.*

All of these statements are just different ways of saying the same thing. For example, when you throw a ball, *there is an interaction between* the ball *and* your hand. The hand *exerts a force on* the ball, setting the ball in motion, and the ball *exerts a force on* the hand, which you can feel, either because your skin is compressed or because your fingers are bent backwards.

When something interacts with you, you might feel pushed or pulled by it. The force tells you how strong the push or pull feels at any particular instant of time. (The force also tells you the direction.) The force can be different at different instants. Imagine giving something a push in slow motion. You might be aware of pushing less hard at the beginning of the push, pushing hardest in the middle of the push, and then pushing less hard again at the end. Or imagine swinging a ball on a string in a large circle. As you are swinging the ball, the direction of the force on it is constantly changing. The total effect of a push (or pull, or combination of both) is called an *impulse*, which we will introduce later in the course.

Measuring forces. Because interactions affect the shape of many objects, we have a way of measuring forces. Springs are easily stretched or compressed, so we often use a spring scale to measure the magnitude of a force being exerted on an object. Platform scales (such as a typical bathroom scale) use springs that are compressed rather than stretched. In general, before using a spring scale, we need to make sure we know what it is we are measuring with it. For example, if someone pushes down on your shoulders while you are standing on a bathroom scale, the scale will not read your weight, but a value slightly larger. Scales are usually calibrated so that the distance the spring stretches or compresses is proportional to the magnitude of the force exerted on it.

Units of force. The unit of force most commonly used in the United States is the *pound* (lb). In the metric (SI) system, the proper unit of force is the *newton* (N). One pound is just less than $4\frac{1}{2}$ newtons; one newton is a little less than $\frac{1}{4}$ pound. (More precisely, 1lb = 4.45N, so 1N = 0.225lb.) Convert your own weight (in lbs) to newtons. Remembering your weight in both pounds and newtons will give you a stronger sense of how *small* a newton is. (For instance, go tell a classmate that he or she weighs over 500 newtons, and see what he or she thinks about that!)

Identifying forces. A force is one side of an interaction between two objects. To identify a force, you must:

Identify both interacting objects. You can usually identify the interaction pair by answering questions such as "What is exerting the force?" and "What is the force being exerted on?"

Identify the kind of force or interaction. There are two main categories for forces: (1) Contact forces are those that require two objects to be touching. Examples are the spring force and the friction force. (2) Action-at-a-distance forces are those that do not require contact (touching each other), such as the electric force, the magnetic force, and the gravitational force.

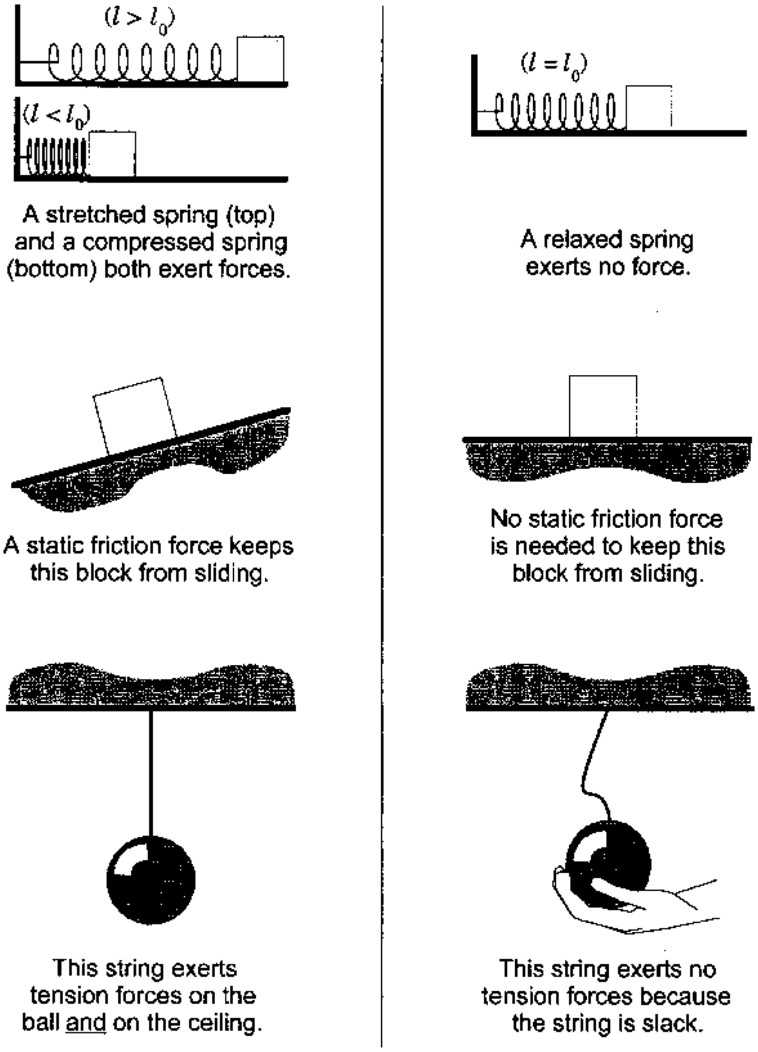
Within these two categories, there are many different types of forces. Most of the everyday forces are listed in the Table of Common Forces found in the Appendix (starting after page R60). In this table you will find:

- a description of each force, telling you what factors affect the magnitude and direction of the force, and what kinds of objects usually cause it to be present;
- guidelines for determining when each force is present and when each can be neglected or ignored; and
- (if possible) a force law or relationship that allows you to calculate the value of each force when you know certain information about the situation.

It is important for you to familiarize yourself with a variety of example situations to help you understand when a particular kind of force is present and when it is not. Most forces require contact: In most cases, two objects must be touching each other in order for them to exert forces on each other. No contact; no force. For example, the force that your hand exerts on a ball is no longer there as soon as the ball leaves your hand. The only exceptions (that will be considered this year) are the gravitational, magnetic, and electrostatic forces.

Contact alone is not enough to guarantee that a force will be exerted. For example, when a spring is attached to something, but remains unstretched and uncompressed, it exerts no force on the object it is touching. When a book is sitting on a table, there is no friction force exerted on it. When a string is attached to something, it must be *taut* in order for a tension force to be exerted. A *slack* string exerts no force.

The following examples show situations in which some of the common forces are exerted and similar situations in which they are not.



A stretched spring (top) and a compressed spring (bottom) both exert forces.

A relaxed spring exerts no force.

A static friction force keeps this block from sliding.

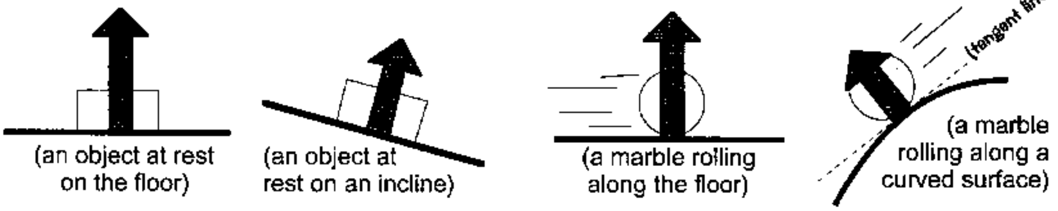
No static friction force is needed to keep this block from sliding.

This string exerts tension forces on the ball <u>and</u> on the ceiling.

This string exerts no tension forces because the string is slack.

situations in which particular forces are exerted (left) and are not exerted (right)

It is important also to know how to find the <u>direction</u> of any particular force. For example, the normal force always points directly away from the surface exerting the force, as shown below.



(an object at rest on the floor)

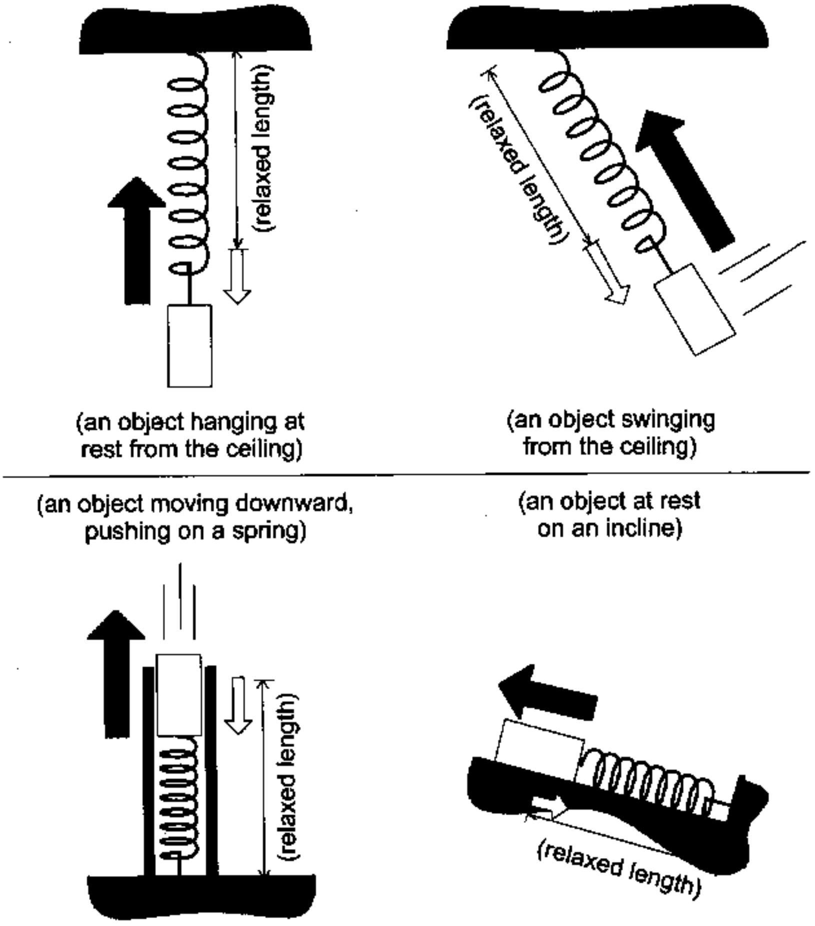
(an object at rest on an incline)

(a marble rolling along the floor)

(a marble rolling along a curved surface)

four situations showing the direction of the normal force

The direction of a spring force is always opposite to the displacement of the end of the spring from its relaxed position. In the examples below, the displacement of the end of the spring is represented by a small white arrow, and the direction of the spring force is represented by a large gray arrow. The direction of the spring force has nothing to do with the motion of the object. Rather, its direction is always along the axis of the spring.



(an object hanging at rest from the ceiling)

(an object swinging from the ceiling)

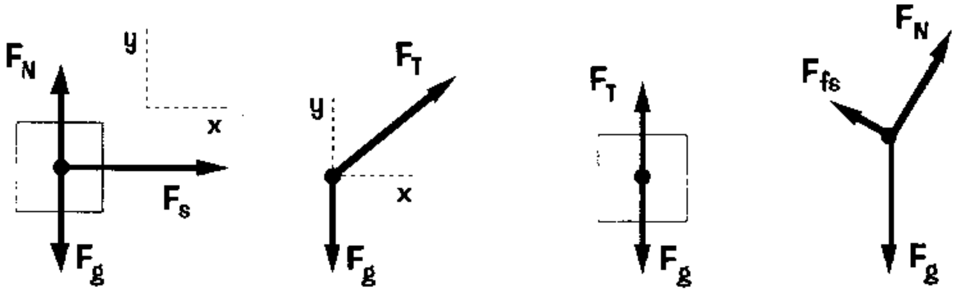
(an object moving downward, pushing on a spring)

(an object at rest on an incline)

four situations showing the direction of the spring force

Free-body diagrams: A way to help us inventory forces. To begin to understand how an object's motion is affected by the forces exerted on it, we must identify all the forces that contribute to the combined effect. A *free-body diagram* is an excellent way of presenting a "total picture" of an object's force situation. A free-body diagram shows all the forces exerted on a single, isolated object (called the "free body"). The idea is that we remove everything interacting with our object, and replace their effect with the forces they exert. This is because the motion of our object is completely determined by the forces exerted on it. So the motion of the free body (with the particular set of forces exerted on it) is the same as the motion of the "real" object.

Some valid free-body diagrams are shown below.



some valid free-body diagrams

By convention, in order to reduce confusion and the possibility for error, we follow these rules for drawing valid free-body diagrams:

- Only forces (not velocities, accelerations, or the net force) should be put onto a free-body diagram.
- All the forces exerted on the object are put onto the diagram, but
- None of the objects exerting those forces are put onto the diagram.
- We usually use a point to represent the "free" body. (We can use a point to represent the body whenever we can consider it a *point object*, in other words, whenever it does not matter where on the object a force is exerted. For example, if we only care about the overall falling motion of a diver going off a high board, and we are not interested in the different paths followed by her head and her feet as she rotates in the air, then we can represent her as a point object.) All forces start from this point, and this point is placed away from all other diagrams and illustrations.
- Each force is represented by a *directed line segment* (an arrow; a straight line with an arrowhead on one end). The tail end of the arrow is placed at the point representing the object. The direction of the arrow is the same as the direction of the force. Whenever possible, the length of each arrow should be roughly proportional to the magnitude of the force it represents.

- Each force is clearly labeled and distinguishable from all the other forces exerted in the physical situation.

And there are also two optional features:

- A sketch of the object might appear in the free-body diagram. The orientation of the object is always preserved.
- A coordinate system might appear as well.

Before you can determine which forces belong in a particular free-body diagram, you should familiarize yourself with the contents of the Table of Common Forces in the Appendix. However, there are some simple guidelines to help you draw free-body diagrams, as listed below.

Normal force and friction force: For each surface touching the object there is a normal force and (possibly) a friction force. If the surface is described as being *frictionless*, then the friction force is zero. (**Note:** Sometimes the term *smooth* is used to mean that the surface is frictionless.)

Spring force: For each spring attached to the object, there is (possibly) a spring force. If the spring is neither stretched nor compressed, the spring force is zero.

Gravitational force: Every object in the universe exerts a gravitational force on every other object. However, if the separation of two objects is very large (such as between you and the planet Jupiter), or if both are relatively light (such as you and your neighbor), then we can neglect the effect of gravitation. However large separations can be compensated by large masses, such as the effect that the sun has on the earth. For everyday objects, we usually consider only the nearest celestial object, like the earth, moon, or sun. When objects are called *massless* or *light*, then we ignore the gravitational force on these objects.

Tension force: For each string attached to the object, there is (possibly) a tension force. If the string is described as being *slack*, then the tension force is zero. However, if the string is described as being *taut*, then the tension force is non-zero.

Air resistance force: Whenever an object moves relative to the surrounding air (or other gas), there is an air resistance force. Unless the relative speed between the object and the air is very large, we usually ignore this effect.

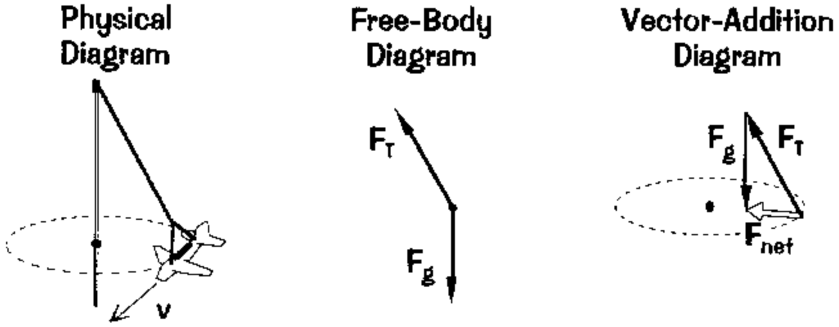
Buoyant force: Whenever an object is in a fluid, and both are in a gravitational field, there is a buoyant force. Often, because the density of the fluid (such as air) is much smaller than the density of the object, we can ignore this effect.

The net force. Force is a vector quantity, which means it has both magnitude and direction. The *net force* or *resultant force* is the vector sum of all the forces exerted on a particular object:

$$\mathbf{F}_{\text{net}} \equiv \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \ldots \qquad \textbf{definition of net force}$$

where $\mathbf{F}_1$, $\mathbf{F}_2$, ... refer to the individual forces exerted on an object. It is the net force that determines the motion of the object. The net force is not exerted by any one thing and is not a separate force that exists outside of the others. Rather, it is the total effect of all the individual forces. Therefore, a free-body diagram, which shows all the individual forces, should never show the net force as an individual or separate force.

An amusement park ride consists of an airplane on the end of a cable whirled in a horizontal circle, as shown on the left below. We can see that a large cable is used to support the airplane and to keep it moving in a circle. This means there are only two (non-negligible) forces on the airplane: (1) the gravitational force exerted by the earth, and (2) the tension force exerted by the cable. (We have assumed that the air resistance force is small enough to ignore.) The free-body diagram for the airplane is shown below in the middle. The net force is directed toward the center of the horizontal circle, as shown in the *vector-addition diagram*. (You will find out exactly why a little later!) Therefore, the tension force has been drawn just the right size so that when we add these two forces, the resultant is horizontal and toward the center, as shown on the right.



three different diagrams for an amusement-park ride

In the next section, we describe the physical laws governing how the forces exerted on an object affect its motion.

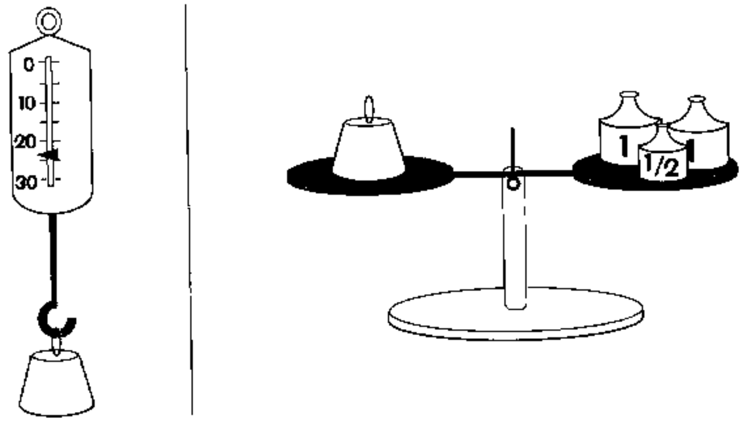
2.2 NEWTON'S LAWS OF MOTION

In 1686, Sir Isaac Newton (1642–1727) published his three laws of motion, which relate the motion of objects (their kinematical behavior or response) to the causes of that motion (the individual forces exerted on the objects). These three laws remain the basis of how scientists view the macroscopic (large-scale) world. We sometimes refer to this view as *Classical Mechanics*.

Mass versus weight. In order to fully understand Newton's laws, we must first make a distinction between the ideas of *mass* and *weight*. Weight is the magnitude of the gravitational force exerted on one object by everything else! Usually this is simply due to the closest celestial object, like the earth or the moon. For most objects a spring scale can be used to measure the object's weight.

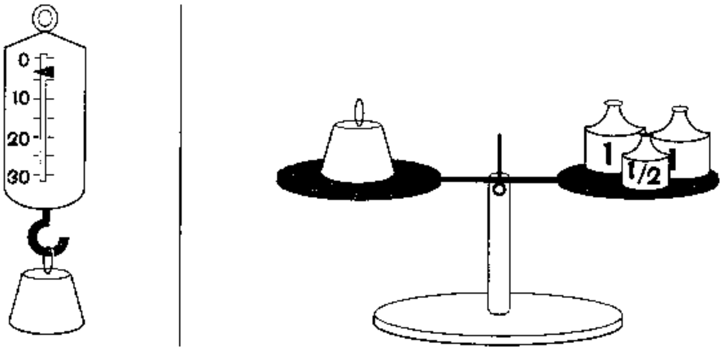
Loosely speaking, mass is the "amount of stuff" we have, which does not change when we change locations. It cannot be measured using a spring scale, because then its value would be different at different locations in the universe. Instead, we use an *equal-arm balance* to measure an object's mass.

Consider an object that weighs (about) 5½lb on the earth, or (about) 24N. On a spring scale, let's say the spring stretches by 12cm (that is, it stretches 1cm for every 2N of weight it measures). On an equal-arm balance, it requires 2½ standard "units" of mass to balance our object, so we say that the object has a mass of 2½ kilograms (or kg). (That is, the standard unit of mass is the kilogram.)



the weight of an object versus its mass as measured on the surface of the earth

On the surface of the moon, we would find some changes. Using the same spring scale we discover that the moon's gravitational pull is weaker, because the spring only stretches by 2cm (instead of 12cm). Therefore, the weight of our object is only 4N on the moon. However, using the same equal-arm balance, we find that the same number of standard units of mass is needed to balance our object. This is because the moon pulls less on our standards by the same proportion that it does on our object. This means our measurement of mass is the same everywhere! (As long as there is a gravitational field!!)



the weight of an object versus its mass as measured on the surface of the moon

When the mass is measured using an equal-arm balance, it is sometimes referred to as the *gravitational mass.* In the next section, we will use the *inertial mass* to show how forces affect the motion of objects. For now, we will assume that these two are identical, and we will use them interchangeably. We will use the same symbol m to represent each one.

Newton's three laws of motion. We now present Newton's Laws of Motion, restated in modern English. For each law, we provide an explanation and, if possible, a mathematical description.

NEWTON'S FIRST LAW OF MOTION

> *An object moving at a particular velocity (speed and direction) will remain at that same velocity until an unbalanced force is exerted on it.*

- Remaining at constant velocity means that its motion does not change:
  (1) An object at rest (stationary) would remain at rest.
  (2) An object going at a particular speed in a particular direction would simply keep going at that speed in that direction.
- An unbalanced force is needed to change either the speed or the direction of motion.
- When the forces exerted on an object are unbalanced, we say there is a "net force on the object". The net force is the vector sum of all the individual forces exerted on the object.