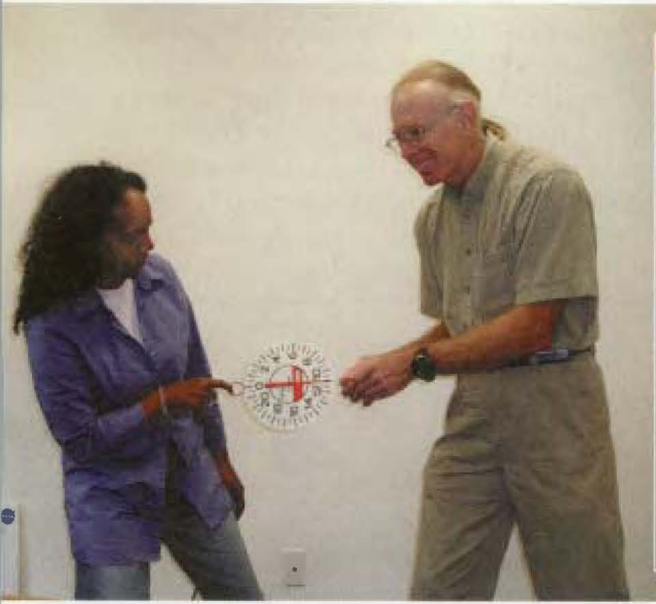
5 Newton's Third Law of Motion



1 Darlene Librero pulls with one finger; Paul Doherty pulls with both hands. Who exerts more force on the scale? **2** Does the racquet hit the ball or does the ball hit the racquet? Answer: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet—that's the law! **3** Wife Lil and I demonstrate Newton's third law— that you cannot touch without being touched.

When Isaac Newton was 26 years old he was appointed the Lucasian Professor of Mathematics at Trinity College in Cambridge. He had personal conflicts with the religious positions of the College, namely questioning the idea of the Trinity as a foundational tenet of Christianity at that time. At the age of 46, his energies turned somewhat from science when he was elected to a 1-year term as a member of Parliament. (At 57, he was elected to a second term.) In his two years in Parliament, he never gave a speech. One day he rose and the House fell silent to hear the great man. Newton's "speech" was very brief; he simply requested that a window be closed because of a draft.

A further turn from his work in science was his appointment as warden, and then as master, of the mint. Newton resigned his professorship and directed his efforts toward greatly improving the workings of the mint, to the dismay of counterfeiters who were then flourishing. He maintained his membership in the Royal Society and at age 60 was elected president, then was reelected each year for the rest of his life.

Although Newton's hair turned gray at age 30, it remained full, long, and wavy all his life, and, unlike others in his time, he did not wear a wig. He was a modest man, overly sensitive to criticism, and he never married. He remained healthy in body and mind into old age. At 80, he still had all his teeth, his eyesight and hearing were sharp, and his mind was alert. In his lifetime he was regarded by his countrymen as the greatest scientist who ever lived. In 1705, he was knighted by Queen Anne. Newton died at the age of 84 and was buried in Westminster Abbey along with England's monarchs and heroes. His laws of motion were all that was needed 242 years later to put humans on the Moon. This chapter presents the third of his three laws of motion.

Forces and Interactions

So far we've treated force in its simplest sense—as a push or pull. Yet no push or pull ever occurs alone. Every force is part of an *interaction* between one thing and another. When you push on a wall with your fingers, more is happening than your push on the wall. You're interacting with the wall, which also pushes back on you. This is evident in your bent fingers, as illustrated in Figure 5.1. There is a pair of forces involved: your push on the wall and the wall pushes back on you. These forces are equal in magnitude (have the same strength) and opposite in direction, and they constitute a single interaction. In fact, you can't push on the wall *unless* the wall pushes back.[1]

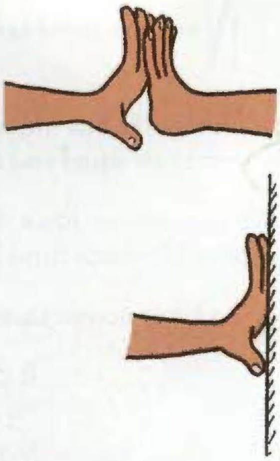


FIGURE 5.1

INTERACTIVE FIGURE

You can feel your fingers being pushed by your friend's fingers. You also feel the same amount of force when you push on a wall and it pushes back on you. As a point of fact, you can't push on the wall *unless* it pushes back on you!

Consider a boxer's fist hitting a massive punching bag. The fist hits the bag (and dents it) while the bag hits back on the fist (and stops its motion). A pair of forces is involved in hitting the bag. The force pair can be quite large. But what of hitting a piece of tissue paper, as discussed earlier? The boxer's fist can only exert as much force on the tissue paper as the tissue paper can exert on the fist. Furthermore, the fist can't exert any force at all unless what is being hit exerts the same amount of force back. An interaction requires a *pair* of forces acting on *two* separate objects.

FIGURE 5.2

When you lean against a wall, you exert a force on the wall. The wall simultaneously exerts an equal and opposite force on you. Hence you don't topple over.

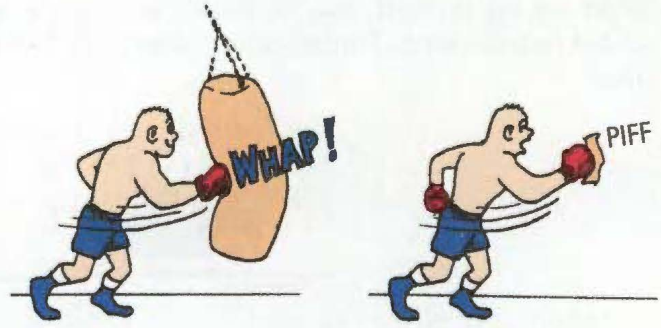


FIGURE 5.3

He can hit the massive bag with considerable force. But with the same punch he can exert only a tiny force on the tissue paper in midair.

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Forces and Interaction

Other examples: You pull on a rope attached to a cart, acceleration occurs. When doing so, the cart pulls back on you, as evidenced perhaps by the tightening of the rope wrapped around your hand. A hammer hits a stake and drives it into the ground. In doing so, the stake exerts an equal amount of force on the hammer, which brings the hammer to an abrupt halt. One thing interacts with another—you with the cart, or the hammer with the stake.

Which exerts the force and which receives the force? Isaac Newton's response was that neither force has to be identified as "exerter" or "receiver"; he concluded that both objects must be treated equally. For example, when you pull the cart, the cart pulls on you. This pair of forces, your pull on the cart and the cart's pull on you, makes up the single interaction between you and the cart. In the interaction between the hammer and the stake, the hammer exerts a force against the stake but is itself brought to a halt in the process. Such observations led Newton to his third law of motion.

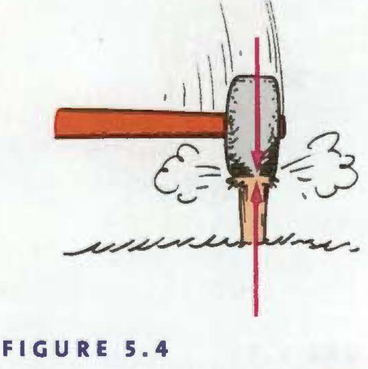

FIGURE 5.4

In the interaction between the hammer and the stake, each exerts the same amount of force on the other.

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[1] We tend to think that only living things are capable of pushing and pulling. But inanimate things can do the same. So please don't be troubled about the idea of the inanimate wall pushing on you. It does, just as another person leaning against you would.

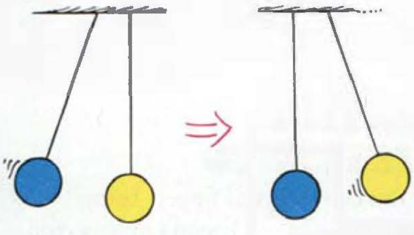

FIGURE 5.5
The impact forces between the blue ball and the yellow ball move the yellow ball and stop the blue ball.

Newton's Third Law of Motion

Newton's third law states:

> **Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.**

We can call one force the *action force* and the other the *reaction force.* Then we can express Newton's third law in the form:

> **To every action there is always an opposed equal reaction.**

FIGURE 5.6
In the interaction between the car and the truck, is the force of impact the same on each? Is the damage the same?

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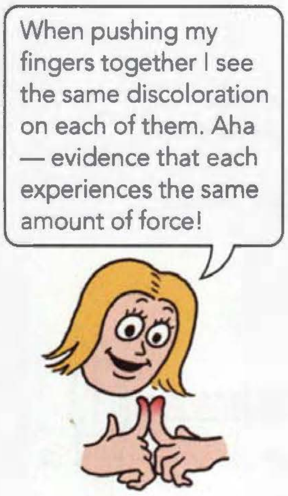
Tutorial
Newton's Third Law

It doesn't matter which force we call *action* and which we call *reaction.* The important thing is that they are co-parts of a single interaction and that neither force exists without the other.

When you walk, you interact with the floor. You push against the floor, and the floor pushes against you. The pair of forces occurs at the same time (they are *simultaneous*). Likewise, the tires of a car push against the road while the road pushes back on the tires—the tires and road simultaneously push against each other. In swimming, you interact with the water, pushing the water backward, while the water simultaneously pushes you forward—you and the water push against each other. The reaction forces are what account for our motion in these examples. These forces depend on friction; a person or car on ice, for example, may be unable to exert the action force to produce the needed reaction force. Forces occur in *force pairs.* Neither force exists without the other.



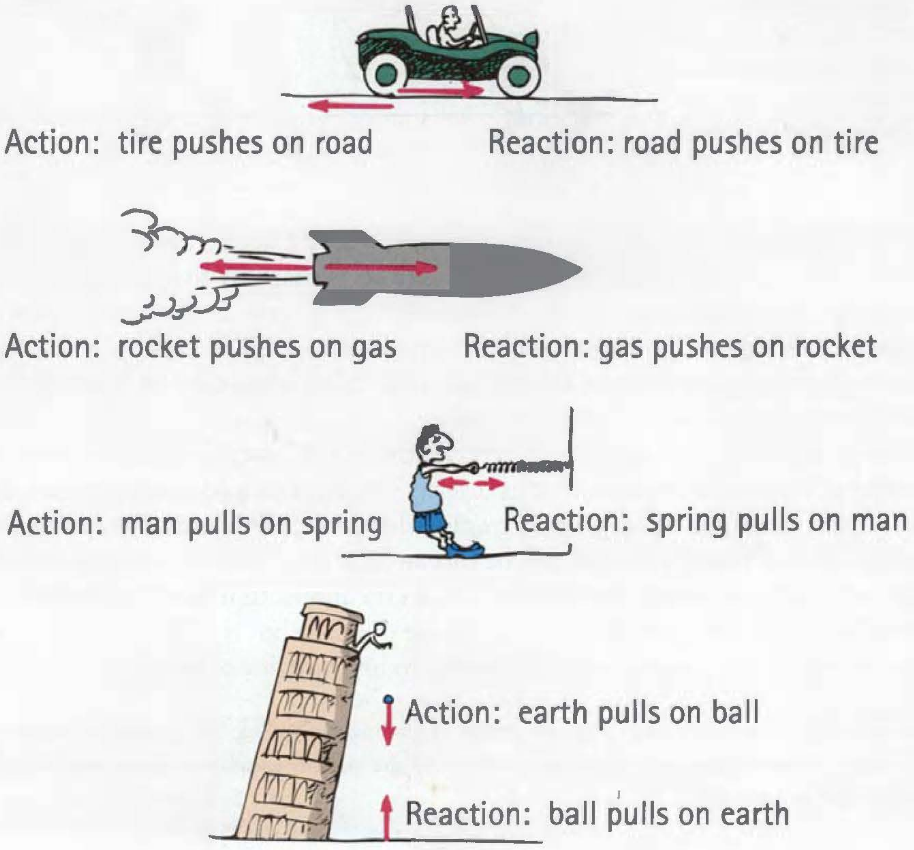


FIGURE 5.7
Action and reaction forces. Note that when action is "*A* exerts force on *B*," the reaction is then simply "*B* exerts force on *A*."

CHECK POINT

Does a speeding missile possess force?

Check Your Answer

No, a force is not something an object *has,* like mass, but is part of an interaction between one object and another. A speeding missile may possess the capability of exerting a force on another object when interaction occurs, but it does not possess force as a thing in itself. As we will see in the following chapters, a speeding missile possesses momentum and kinetic energy.

DEFINING YOUR SYSTEM

An interesting question often arises: Since action and reaction forces are equal and opposite, why don't they cancel to zero? To answer this question, we must consider the *system* involved. Consider, for example, a system consisting of a single orange, Figure 5.8. The dashed line surrounding the orange encloses and defines the system. The vector that pokes outside the dashed line represents an external force on the system. The system accelerates in accord with Newton's second law. In Figure 5.9, we see that this force is provided by an apple, which doesn't change our analysis. The apple is outside the system. The fact that the orange simultaneously exerts a force on the apple, which is external to the system, may affect the apple (another system), but not the orange. You can't cancel a force on the orange with a force on the apple. So, in this case, the action and reaction forces don't cancel.

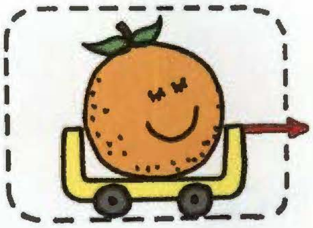


FIGURE 5.8

INTERACTIVE FIGURE

A force acts on the orange, and the orange accelerates to the right.

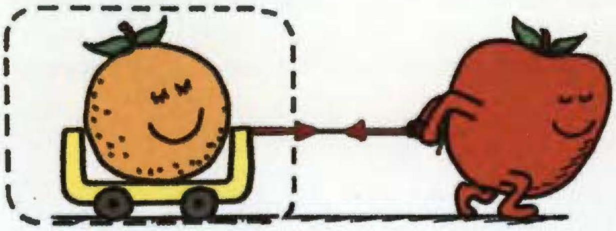


FIGURE 5.9

INTERACTIVE FIGURE

The force on the orange, provided by the apple, is not cancelled by the reaction force on the apple. The orange still accelerates.

A system may be as tiny as an atom or as large as the universe.

Now let's consider a larger system, enclosing *both* the orange and the apple. We see the system bounded by the dashed line in Figure 5.10. Notice that the force pair is *internal* to the orange–apple system. Then these forces *do* cancel each other. They play no role in accelerating the system. A force external to the system is needed for acceleration. That's where friction with the floor plays a role (Figure 5.11). When

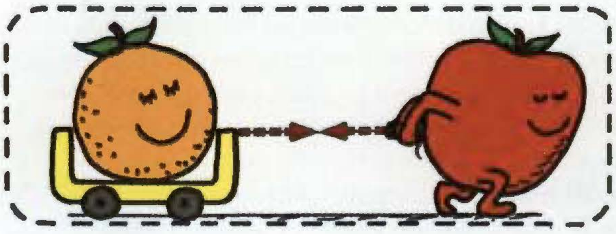


FIGURE 5.10

INTERACTIVE FIGURE

In the larger system of orange + apple, action and reaction forces are internal and cancel. If these are the only horizontal forces, with no external force, no acceleration of the system occurs.

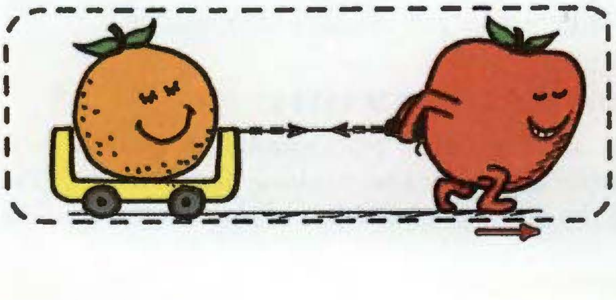


FIGURE 5.11

INTERACTIVE FIGURE

An external horizontal force occurs when the floor pushes on the apple (reaction to the apple's push on the floor). The orange–apple system accelerates.

the apple pushes against the floor, the floor simultaneously pushes on the apple—an external force on the system. The system accelerates to the right.

Inside a football are trillions and trillions of interatomic forces at play. They hold the ball together, but they play no role in accelerating the ball. Although every one of the interatomic forces is part of an action–reaction pair within the ball, they combine to zero, no matter how many of them there are. A force external to the football, like a kick, is needed to accelerate it. In Figure 5.12, we note a single interaction between the foot and the football.

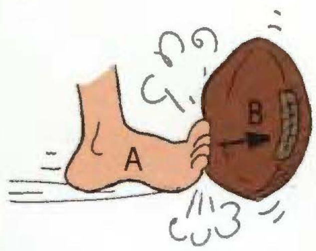


FIGURE 5.12
A acts on B, and B accelerates.

The football in Figure 5.13, however, does not accelerate. In this case, there are two interactions occurring—two forces acting on the football. If they are simultaneous, equal, and opposite, then the net force is zero. Do the two opposing kicks make up an action–reaction pair? No, for they act on the same object, not on different objects. They may be equal and opposite, but, unless they act on different objects, they are not an action–reaction pair. Get it?

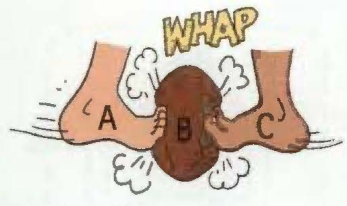


FIGURE 5.13
Both A and C act on B. They can cancel each other, so B does not accelerate.

If this is confusing, it may be well to note that Newton had difficulties with the third law himself. (See insightful examples of Newton's third law on pages 21 and 22 in the *Concept Development Practice Book.*)

CHECK POINT

1. On a cold, rainy day, you find yourself in a car with a dead battery. You must push the car to move it and get it started. Why can't you move the car by remaining comfortably inside and pushing against the dashboard?
2. Why does a book sitting on a table never accelerate "spontaneously" in response to the trillions of interatomic forces acting within it?
3. We know that Earth pulls on the Moon. Does it follow that the Moon also pulls on Earth?
4. Can you identify the action and reaction forces in the case of an object falling in a vacuum?

Check Your Answers

1. In this case, the system to be accelerated is the car. If you remain inside and push on the dashboard, the force pair you produce acts and reacts within the system. These forces cancel out as far as any motion of the car is concerned. To accelerate the car, there must be an interaction between the car and something external—for example, you on the outside pushing against the road and on the car.
2. Every one of these interatomic forces is part of an action–reaction pair within the book. These forces add up to zero, no matter how many of them there are. This is what makes Newton's *first* law apply to the book. The book has zero acceleration unless an *external* force acts on it.
3. Yes, both pulls make up an action–reaction pair of forces associated with the gravitational interaction between Earth and Moon. We can say that (1) Earth pulls on Moon and (2) Moon likewise pulls on Earth; but it is more insightful to think of this as a single interaction—both Earth and Moon simultaneously pulling on each other, each with the *same* amount of force. You can't push or pull on something unless that something simultaneously pushes or pulls on you. That's the law!
4. To identify a pair of action–reaction forces in any situation, first identify the pair of interacting objects involved—Body A and Body B. Body A, the falling object, is interacting (gravitationally) with Body B, the whole Earth. So Earth pulls downward on the object (call it action), while the object pulls upward on Earth (reaction).

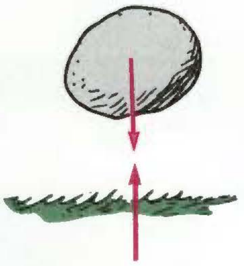


FIGURE 5.14
Earth is pulled up by the boulder with just as much force as the boulder is pulled downward by Earth.

ACTION AND REACTION ON DIFFERENT MASSES

As strange as it may first seem, a falling object pulls upward on Earth with as much force as Earth pulls downward on it. The resulting acceleration of the falling object is evident, while the upward acceleration of Earth is too small to detect. So strictly speaking, when you step off a curb, the street rises ever so slightly to meet you.

We can see that Earth accelerates slightly in response to a falling object by considering the exaggerated examples of two planetary bodies, parts (a) through (e) in Figure 5.15. The forces between bodies A and B are equal in magnitude and oppositely directed in *each* case. If acceleration of planet A is unnoticeable in (a), then it is more noticeable in (b), where the difference between the masses is less extreme. In (c), where both bodies have equal mass, acceleration of object A is as evident as it is for B. Continuing, we see that the acceleration of A becomes even more evident in (d) and even more so in (e).

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Action and Reaction on Different Masses
Action and Reaction on Rifle and Bullet

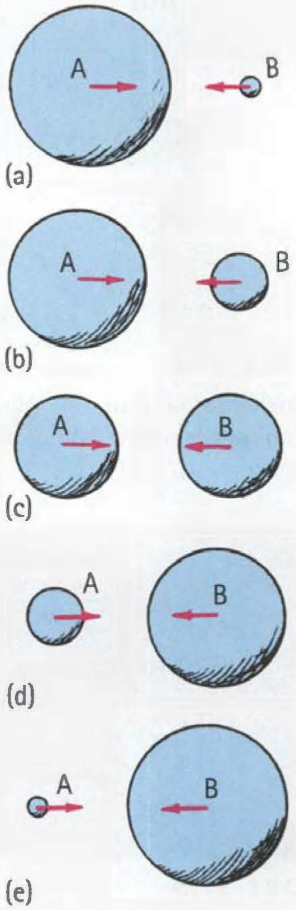


FIGURE 5.15
Which falls toward the other, A or B? Although the forces between each pair are the same, do accelerations differ?

The role of different masses is evident in a fired cannon. When a cannon is fired, there is an interaction between the cannon and the cannonball (Figure 5.16). A pair of forces acts on both cannon and cannonball. The force exerted on the cannonball is as great as the reaction force exerted on the cannon; hence, the cannon recoils. Since the forces are equal in magnitude, why doesn't the cannon recoil with the same speed as the cannonball? In analyzing changes in motion, Newton's second law reminds us that we must also consider the masses involved. Suppose we let F represent both the action and reaction force, m the mass of the cannonball, and ${\Large m}$ the mass of the much more massive cannon. The accelerations of the cannonball and the cannon are then found by comparing the ratio of force to mass. The accelerations are:

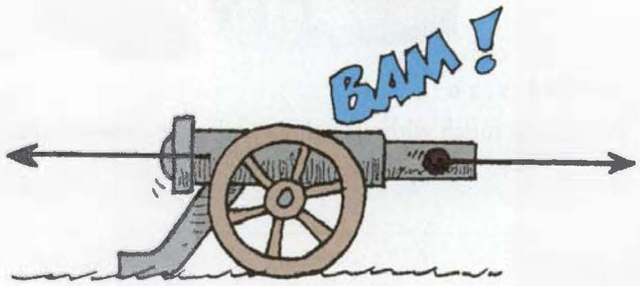
$$\text{Cannonball: } \frac{F}{m} = {\Huge a}$$

$$\text{Cannon: } \frac{F}{{\Huge m}} = a$$

This shows why the change in velocity of the cannonball is so large compared with the change in velocity of the cannon. A given force exerted on a small mass produces a large acceleration, while the same force exerted on a large mass produces a small acceleration.

Going back to the example of the falling object, if we used similarly exaggerated symbols to represent the acceleration of Earth reacting to a falling object, the symbol m for the Earth's mass would be astronomical in size. The force F, the weight of the falling object, divided by this large mass would result in a microscopic a to represent the acceleration of Earth toward the falling object.

FIGURE 5.16
INTERACTIVE FIGURE
The force exerted against the recoiling cannon is just as great as the force that drives the cannonball inside the barrel. Why, then, does the cannonball accelerate more than the cannon?



We can extend the idea of a cannon recoiling from the ball it fires to understanding rocket propulsion. Consider an inflated balloon recoiling when air is expelled (Figure 5.17). If the air is expelled downward, the balloon accelerates upward. The same principle applies to a rocket, which continually "recoils" from the ejected exhaust gas. Each molecule of exhaust gas is like a tiny cannonball shot from the rocket (Figure 5.18).

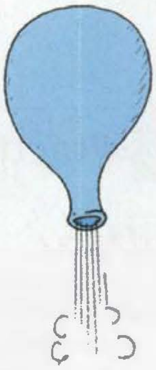


FIGURE 5.17
The balloon recoils from the escaping air, and it moves upward.

A common misconception is that a rocket is propelled by the impact of exhaust gases against the atmosphere. In fact, before the advent of rockets, it was generally thought that sending a rocket to the Moon was impossible. Why? Because there is no air above Earth's atmosphere for the rocket to push against. But this is like saying

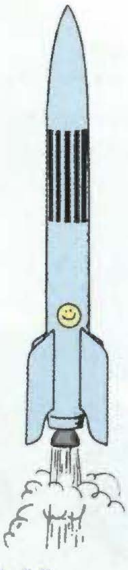


FIGURE 5.18

The rocket recoils from the "molecular cannonballs" it fires, and it moves upward.

FIGURE 5.19

Geese fly in a V formation because air pushed downward at the tips of their wings swirls upward, creating an updraft that is strongest off to the side of the bird. A trailing bird gets added lift by positioning itself in this updraft, pushes air downward, and creates another updraft for the next bird, and so on. The result is a flock flying in a V formation.

a cannon wouldn't recoil unless the cannonball had air to push against. Not true! Both the rocket and recoiling cannon accelerate because of the reaction forces exerted by the material they fire—not because of any pushes on the air. In fact, a rocket operates better above the atmosphere where there is no air resistance.

Using Newton's third law, we can understand how a helicopter gets its lifting force. The whirling blades are shaped to force air particles down (action), and the air forces the blades up (reaction). This upward reaction force is called *lift.* When lift equals the weight of the aircraft, the helicopter hovers in midair. When lift is greater, the helicopter climbs upward.

This is true for birds and airplanes. Birds fly by pushing air downward. The air in turn pushes the bird upward. When the bird is soaring, the wings must be shaped so that moving air particles are deflected downward. Slightly tilted wings that deflect oncoming air downward produce lift on an airplane. Air that is pushed downward continuously maintains lift. This supply of air is obtained by the forward motion of the aircraft, which results from propellers or jets that push air backward. The air, in turn, pushes the propellers or jets forward. We will learn in Chapter 14 that the curved surface of a wing is an airfoil, which enhances the lifting force.

We see Newton's third law at work everywhere. A fish pushes the water backward with its fins, and the water pushes the fish forward. When the wind pushes against the branches of a tree and the branches push back on the wind, we have whistling sounds. Forces are interactions between different things. Every contact requires at least a twoness; there is no way that an object can exert a force on nothing. Forces, whether large shoves or slight nudges, always occur in pairs, each of which is opposite to the other. Thus, we cannot touch without being touched.

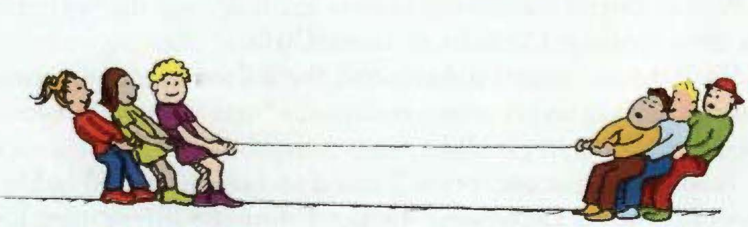
FIGURE 5.20

You cannot touch without being touched—Newton's third law.

Practicing Physics

Tug of War

Perform a tug-of-war between guys and gals. Do it on a polished floor that's somewhat slippery, with guys wearing socks and gals wearing rubber-soled shoes. Who will surely win, and why? (*Hint:* Who wins a tug-of-war, those who pull harder on the rope or those who push harder against the floor?)



CHECK POINT

1. A car accelerates along a road. Identify the force that moves the car.
2. A high-speed bus and an innocent bug have a head-on collision. The force of impact splatters the poor bug over the windshield. Is the corresponding force that the bug exerts against the windshield greater, less, or the same? Is the resulting deceleration of the bus greater than, less than, or the same as that of the bug?

Check Your Answers

1. It is the road that pushes the car along. Really! Only the road provides the horizontal force to move the car forward. How does it do this? The rotating tires of the car push back on the road (action). The road simultaneously pushes forward on the tires (reaction). How about that!
2. The magnitudes of both forces are the same, for they constitute an action–reaction force pair that makes up the interaction between the bus and the bug. The accelerations, however, are very different because the masses are different. The bug undergoes an enormous and lethal deceleration, while the bus undergoes a very tiny deceleration—so tiny that the very slight slowing of the bus is unnoticed by its passengers. But if the bug were more massive—as massive as another bus, for example—the slowing down would unfortunately be very apparent. (Can you see the wonder of physics here? Although so much is *different* for the bug and the bus, the amount of force each encounters is the *same*. Amazing!)

Jellyfish have been using rocket or jet propulsion for eons.

Summary of Newton's Three Laws

Newton's first law, the law of inertia: An object at rest tends to remain at rest; an object in motion tends to remain in motion at constant speed along a straight-line path. This property of objects to resist change in motion is called *inertia.* Mass is a measure of inertia. Objects will undergo changes in motion only in the presence of a net force.

Newton's second law, the law of acceleration: When a net force acts on an object, the object will accelerate. The acceleration is directly proportional to the net force and inversely proportional to the mass. Symbolically, $a = F/m$. Acceleration is always in the direction of the net force. When objects fall in a vacuum, the net force is simply the weight—the pull of gravity—and the acceleration is g (the symbol g denotes that acceleration is due to gravity alone). When objects fall in air, the net force is equal to the weight minus the force of air resistance, and the acceleration is less than g. If and when the force of air resistance equals the weight of a falling object, acceleration terminates, and the object falls at constant speed (called *terminal speed*).

Newton's third law, the law of action–reaction: Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first. Forces occur in pairs, one action and the other reaction, which together constitute the interaction between one object and the other. Action and reaction always occur simultaneously and act on different objects. Neither force exists without the other.

Isaac Newton's three laws of motion are rules of nature that enable us to see how beautifully so many things connect with one another. We see these rules in operation in our everyday environment.

FIGURE 5.21

This vector, scaled so that 1 cm equals 20 N, represents a force of 60 N to the right.

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Tutorial
Vectors

The valentine vector says, "I was only a scalar until you came along and gave me direction."

Vectors

We have learned that any quantity that requires both magnitude and direction for a complete description is a **vector quantity.** Examples of vector quantities include force, velocity, and acceleration. By contrast, a quantity that can be described by magnitude only, not involving direction, is called a **scalar quantity.** Mass, volume, and speed are scalar quantities.

A vector quantity is nicely represented by an arrow. When the length of the arrow is scaled to represent the quantity's magnitude, and the direction of the arrow shows the direction of the quantity, we refer to the arrow as a **vector.**

Adding vectors that act along parallel directions is simple enough: If they act in the same direction, they add; if they act in opposite directions, they subtract. The sum of two or more vectors is called their **resultant.** To find the resultant of two vectors that don't act in exactly the same or opposite direction, we use the *parallelogram rule.*[2] Construct a parallelogram wherein the two vectors are adjacent sides—the diagonal of the parallelogram shows the resultant. In Figure 5.22, the parallelograms are rectangles.

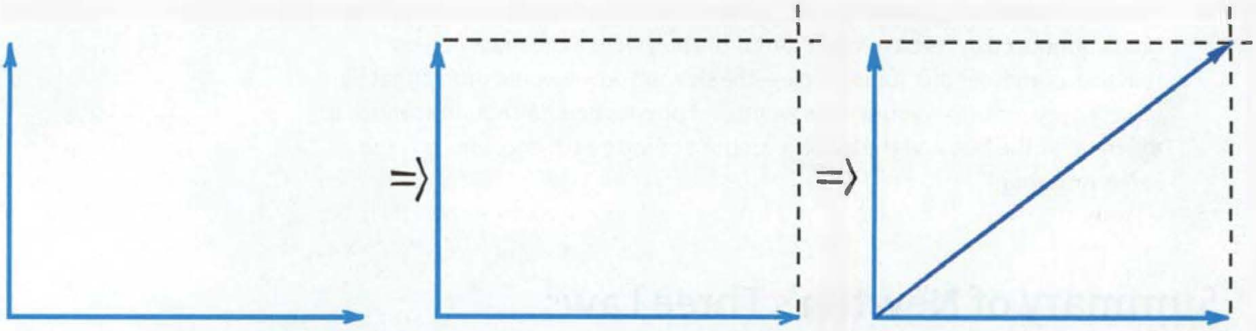

FIGURE 5.22

INTERACTIVE FIGURE

The pair of vectors at right angles to each other make two sides of a rectangle, the diagonal of which is their resultant.

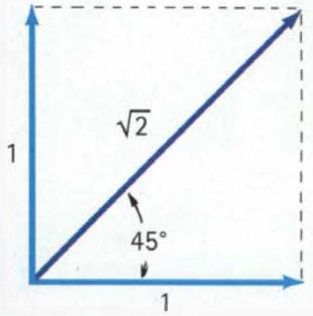

FIGURE 5.23

When a pair of equal-length vectors at right angles to each other are added, they form a square. The diagonal of the square is the resultant, $\sqrt{2}$ times the length of either side.

In the special case of two vectors that are equal in magnitude and perpendicular to each other, the parallelogram is a square (Figure 5.23). Since for any square the length of a diagonal is $\sqrt{2}$, or 1.41, times one of the sides, the resultant is $\sqrt{2}$ times one of the vectors. For example, the resultant of two equal vectors of magnitude 100 acting at a right angle to each other is 141.

FORCE VECTORS

Figure 5.24 shows a pair of forces acting on a box. One is 30 newtons and the other is 40 newtons. Simple measurement shows the resultant of this pair of forces is 50 newtons.

Figure 5.25 shows Nellie Newton hanging at rest from a clothesline. Note that the clothesline acts like a pair of ropes that make different angles with the vertical. Which side has the greater tension? Investigation will show there are three forces acting on Nellie: her weight, a tension in the left-hand side of the rope, and a tension in the right-hand side of the rope. Because of the different angles, different rope tensions will occur in each side. Figure 5.25 shows a step-by-step solution. Because Nellie hangs in equilibrium, her weight must be supported by two rope

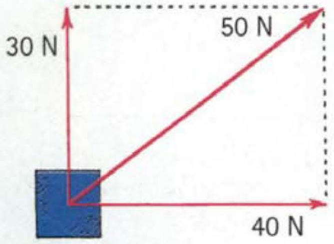

FIGURE 5.24

The resultant of the 30-N and 40-N forces is 50 N.

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[2] A parallelogram is a four-sided figure with opposite sides parallel to each other. Usually, you determine the length of the diagonal by measurement; but, in the special case in which the two vectors **X** and **Y** are perpendicular (a square or a rectangle), you can apply the Pythagorean Theorem, $\mathbf{R}^2 = \mathbf{X}^2 + \mathbf{Y}^2$, to find the resultant: $\mathbf{R} = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2}$.

tensions, which must add vectorially to be equal and opposite to her weight. The parallelogram rule shows that the tension in the right-hand rope is greater than the tension in the left-hand rope. If you measure the vectors, you'll see that tension in the right rope is about twice the tension in the left rope. Both rope tensions combine to support her weight.

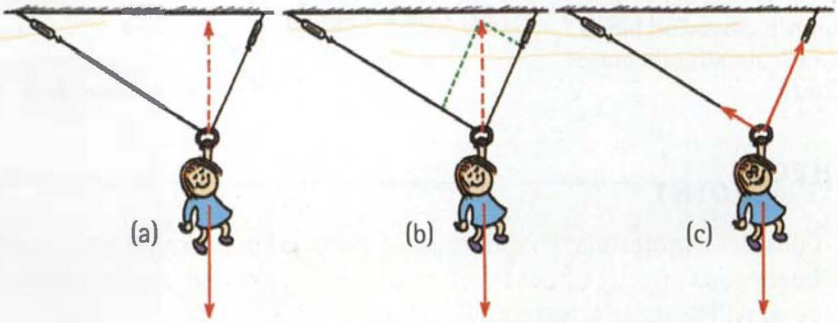

FIGURE 5.25

INTERACTIVE FIGURE

(a) Nellie's weight is shown by the downward vertical vector. An equal and opposite vector is needed for equilibrium, shown by the dashed vector. (b) This dashed vector is the diagonal of a parallelogram defined by the green lines. (c) Both rope tensions are shown by the constructed vectors. Tension is greater in the right rope, the one more likely to break.

More about force vectors can be found in Appendix D at the end of this book and in the *Practicing Physics* book.

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Videos

Vector Representations: How to Add and Subtract Vectors

Geometric Addition of Vectors

VELOCITY VECTORS

Recall, from Chapter 3, the difference between speed and velocity—speed is a measure of "how fast"; velocity is a measure of both how fast and "in which direction." If the speedometer in a car reads 100 kilometers per hour (km/h), you know your speed. If there is also a compass on the dashboard, indicating that the car is moving due north, for example, you know your velocity—100 km/h north. To know your velocity is to know your speed and your direction.

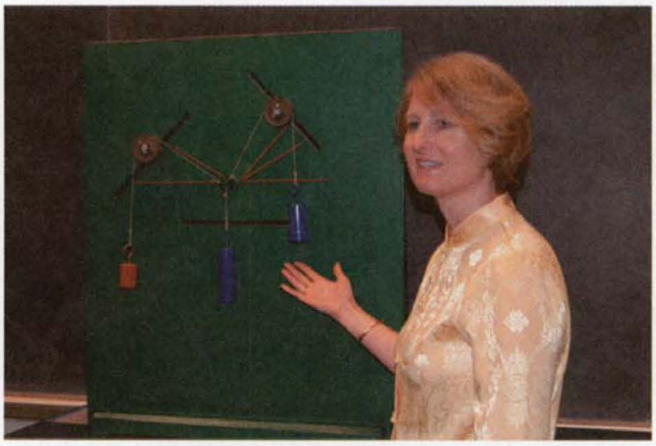


FIGURE 5.26

Diana Lininger Markham illustrates the vector arrangement of Figure 5.25.

Consider an airplane flying due north at 80 km/h relative to the surrounding air. Suppose that the plane is caught in a 60-km/h crosswind (wind blowing at right angles to the direction of the airplane) that blows it off its intended course. This example is represented with vectors in Figure 5.27 with velocity vectors scaled so that 1 centimeter (cm) represents 20 km/h. Thus, the 80-km/h velocity of the airplane is shown by the 4-cm vector, and the 60-km/h crosswind is shown by the 3-cm vector. The diagonal of the constructed parallelogram (a rectangle, in this case) measures 5 cm, which represents 100 km/h. So the airplane moves at 100 km/h relative to the ground, in a direction between north and northeast.

The pair of 6-unit and 8-unit vectors at right angles to each other say, "We may be a six and an eight, but together we're a perfect ten."

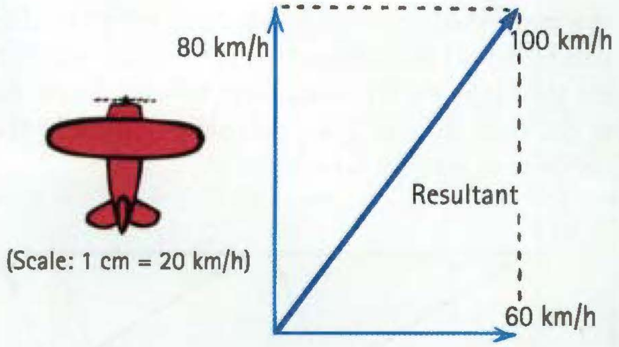


FIGURE 5.27
The 60-km/h crosswind blows the 80-km/h aircraft off course at 100 km/h.

CHECK POINT

Consider a motorboat that normally travels 10 km/h in still water. If the boat heads directly across the river, which also flows at a rate of 10 km/h, what will be its velocity relative to the shore?

Check Your Answer

When the boat heads cross-stream (at right angles to the river flow), its velocity is 14.1 km/h, 45 degrees downstream (in accord with the diagram in Figure 5.23).

COMPONENTS OF VECTORS

Just as two vectors at right angles can be combined into one resultant vector, any vector can be resolved into two *component* vectors perpendicular to each other. These two vectors are known as the **components** of the given vector they replace (Figure 5.28). The process of determining the components of a vector is called *resolution*. Any vector drawn on a piece of paper can be resolved into a vertical and a horizontal component.

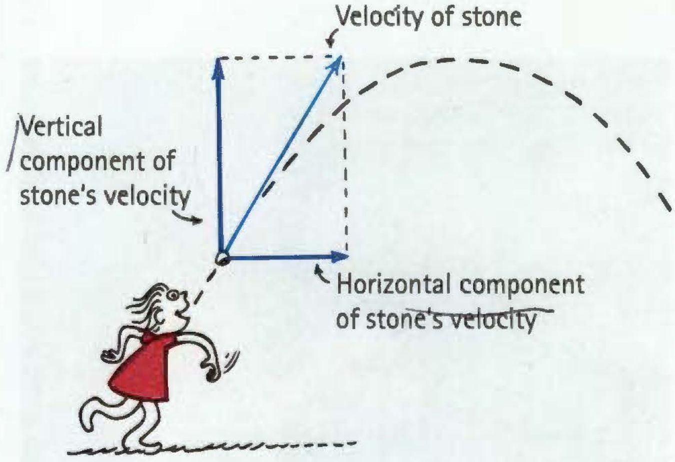


FIGURE 5.28
The horizontal and vertical components of a stone's velocity.

Vector resolution is illustrated in Figure 5.29. A vector **V** is drawn in the proper direction to represent a vector quantity. Then vertical and horizontal lines *(axes)* are

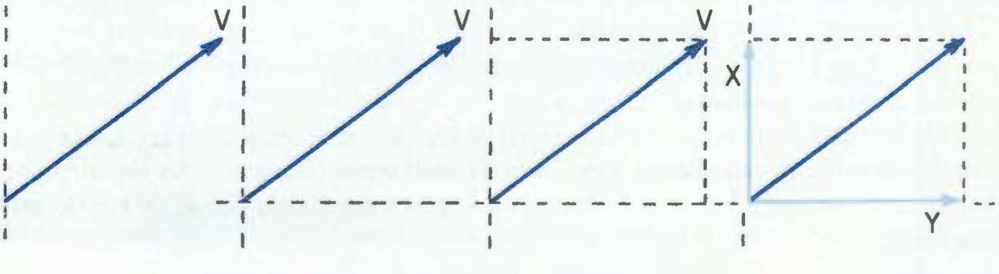


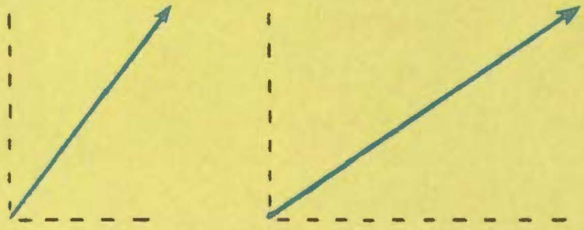
FIGURE 5.29
Construction of the vertical and horizontal components of a vector.

drawn at the tail of the vector. Next, a rectangle is drawn that has **V** as its diagonal. The sides of this rectangle are the desired components, vectors **X** and **Y**. In reverse, note that the vector sum of vectors **X** and **Y** is **V**.

We'll return to vector components when we treat projectile motion in Chapter 10.

CHECK POINT

With a ruler, draw the horizontal and vertical components of the two vectors shown. Measure the components and compare your findings with the answers given at the bottom of the page.



Answers

Left vector: The horizontal component is 2 cm; the vertical component is 2.6 cm.
Right vector: The horizontal component is 3.8 cm; the vertical component is 2.6 cm.

SUMMARY OF TERMS

Newton's third law Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.

Vector quantity A quantity that has both magnitude and direction. Examples are force, velocity, and acceleration.

Scalar quantity A quantity that has magnitude but not direction. Examples are mass, volume, and speed.

Vector An arrow drawn to scale used to represent a vector quantity.

Resultant The net result of a combination of two or more vectors.

Components Mutually perpendicular vectors, usually horizontal and vertical, whose vector sum is a given vector.

REVIEW QUESTIONS

Forces and Interactions

1. When you push against a wall with your fingers, they bend because they experience a force. Identify this force.
2. A boxer can hit a heavy bag with great force. Why can't he hit a piece of tissue paper in midair with the same amount of force?
3. How many forces are required for an interaction?

Newton's Third Law of Motion

4. State Newton's third law of motion.
5. Consider hitting a baseball with a bat. If we call the force on the bat against the ball the *action* force, identify the *reaction* force.
6. Consider the apple and the orange (Figure 5.9). If the system is considered to be only the orange, is there a net force on the system when the apple pulls?
7. If the system is considered to be the apple and the orange together (Figure 5.10), is there a net force on the system when the apple pulls (ignoring friction with the floor)?
8. To produce a net force on a system, must there be an externally applied net force?
9. Consider the system of a single football. If you kick it, is there a net force to accelerate the system? If a friend kicks it at the same time with an equal and opposite force, is there a net force to accelerate the system?

Action and Reaction on Different Masses

10. Earth pulls down on you with a gravitational force that you call your weight. Do you pull up on Earth with the same amount of force?
11. If the forces that act on a cannonball and the recoiling cannon from which it is fired are equal in magnitude,

why do the cannonball and cannon have very different accelerations?

12. Identify the force that propels a rocket.
13. How does a helicopter get its lifting force?
14. Can you physically touch a person without that person touching you with the same amount of force?

Summary of Newton's Three Laws

15. Fill in the blanks: Newton's first law is often called the law of ________; Newton's second law is the law of ________; and Newton's third law is the law of ________ and ________.
16. Which of the three laws deals with interactions?

Vectors

17. Cite three examples of a vector quantity and three examples of a scalar quantity.
18. Why is speed considered a scalar and velocity a vector?
19. According to the parallelogram rule, what quantity is represented by the diagonal of a constructed parallelogram?
20. Consider Nellie hanging at rest in Figure 5.25. If the ropes were vertical, with no angle involved, what would be the tension in each rope?
21. When Nellie's ropes make an angle, what quantity must be equal and opposite to her weight?
22. When a pair of vectors are at right angles, is the resultant always greater in magnitude than either of the vectors separately?

PROJECT

Hold your hand like a flat wing outside the window of a moving automobile. Then slightly tilt the front edge upward and notice the lifting effect. Can you see Newton's laws at work here?

PLUG AND CHUG

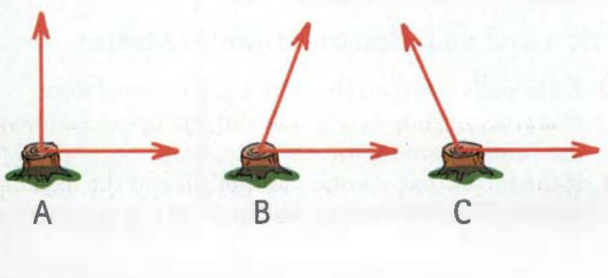
1. Calculate the resultant of the pair of velocities 100 km/h north and 75 km/h south. Calculate the resultant if both of the velocities are directed north.

Resultant of two vectors at right angles to each other:
$\mathbf{R} = \sqrt{\mathbf{X}^2 + \mathbf{Y}^2}$

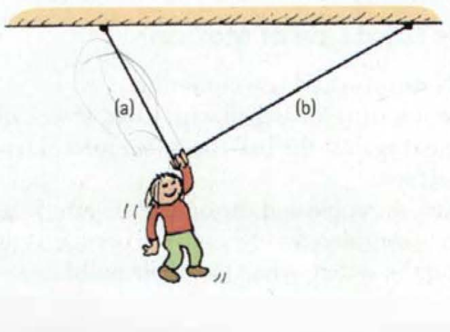
2. Calculate the magnitude of the resultant of a pair of 100-km/h velocity vectors that are at right angles to each other.
3. Calculate the resultant of a horizontal vector with a magnitude of 4 units and a vertical vector with a magnitude of 3 units.
4. Calculate the resultant velocity of an airplane that normally flies at 200 km/h if it encounters a 50-km/h wind from the side (at a right angle to the airplane).

RANKING

1. As seen from above, a stubborn stump is pulled by a pair of ropes, each with a force of 200 N, but at different angles as shown. From greatest to least, rank the net force on the stump.

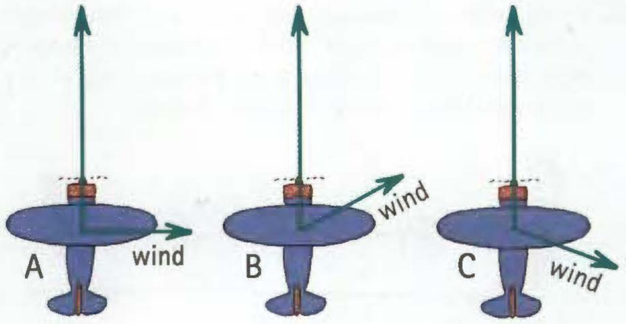


2. Nellie Newton hangs motionless by one hand from a clothesline. Which side of the line, a or b, has the greater



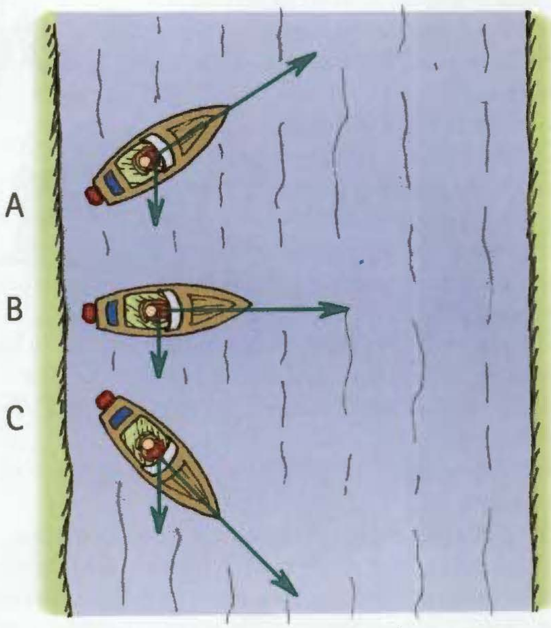
a. horizontal component of tension?
b. vertical component of tension?
c. tension?

3. Here we see a top view of an airplane being blown off course by wind in three different directions. Use a pencil and the parallelogram rule and sketch the vectors that show the resulting velocities for each case. Rank the speeds of the airplane across the ground from fastest to slowest.



4. Here we see top views of three motorboats crossing a river. All have the same speed relative to the water, and all experience the same river flow. Construct resultant vectors showing the speed and direction of the boats. Rank them from most to least for

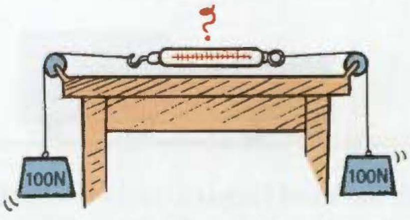
a. the time for the boats to reach the opposite shore.
b. the fastest ride.



EXERCISES

1. A rocket becomes progressively easier to accelerate as it travels through space. Why is this so? (*Hint:* About 90% of the mass of a newly launched rocket is fuel.)
2. The photo shows Steve Hewitt and daughter Gretchen. Is Gretchen touching her dad, or is dad touching her? Explain.

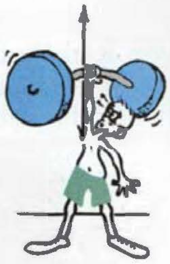
3. When you rub your hands together, can you push harder on one hand than the other?
4. For each of the following interactions, identify action and reaction forces. (a) A hammer hits a nail. (b) Earth gravity pulls down on a book. (c) A helicopter blade pushes air downward.
5. You hold an apple over your head. (a) Identify all the forces acting on the apple and their reaction forces. (b) When you drop the apple, identify all the forces acting on it as it falls and the corresponding reaction forces. Neglect air drag.
6. Identify the action–reaction pairs of forces for the following situations: (a) You step off a curb. (b) You pat your tutor on the back. (c) A wave hits a rocky shore.
7. Consider a baseball player batting a ball. (a) Identify the action–reaction pairs when the ball is being hit and (b) while the ball is in flight.
8. What physics is involved for a passenger feeling pushed backward into the seat of an airplane when it accelerates along the runway during takeoff?
9. If you drop a rubber ball on the floor, it bounces back up. What force acts on the ball to provide the bounce?
10. When you kick a football, what action and reaction forces are involved? Which force, if any, is greater?
11. Is it true that when you drop from a branch to the ground below, you pull upward on Earth? If so, then why is the acceleration of Earth not noticed?
12. Within a book on a table, there are billions of forces pushing and pulling on all the molecules. Why is it that these forces never by chance add up to a net force in one direction, causing the book to accelerate "spontaneously" across the table?
13. Two 100-N weights are attached to a spring scale as shown. Does the scale read 0, 100, or 200 N, or does it give some other reading? (*Hint:* Would it read any differently if one of the ropes were tied to the wall instead of to the hanging 100-N weight?)



14. If you exert a horizontal force of 200 N to slide a crate across a factory floor at constant velocity, how much friction is exerted by the floor on the crate? Is the force of friction equal and oppositely directed to your 200-N

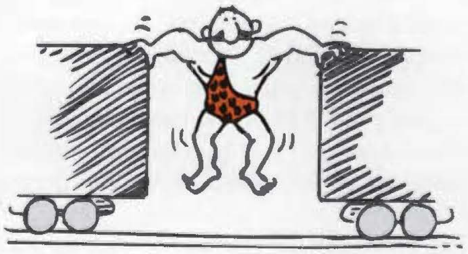
push? If the force of friction isn't the reaction force to your push, what is?

15. When the athlete holds the barbell overhead, the reaction force is the weight of the barbell on his hand. How does this force vary for the case in which the barbell is accelerated upward? Downward?

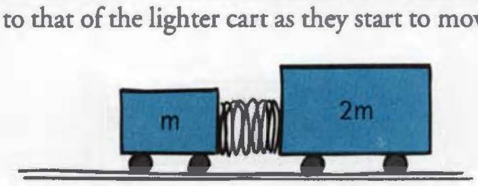


16. Consider the two forces acting on the person who stands still—namely, the downward pull of gravity and the upward support of the floor. Are these forces equal and opposite? Do they form an action–reaction pair? Why or why not?

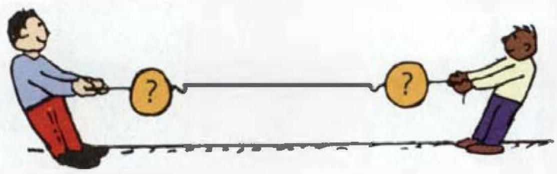
17. Why can you exert greater force on the pedals of a bicycle if you pull up on the handlebars?
18. Does a baseball bat slow down when it hits a ball? Defend your answer.
19. Why does a rope climber pull downward on the rope to move upward?
20. A farmer urges his horse to pull a wagon. The horse refuses, saying that to try would be futile, for it would flout Newton's third law. The horse concludes that she can't exert a greater force on the wagon than the wagon exerts on her and, therefore, that she won't be able to accelerate the wagon. What is your explanation to convince the horse to pull?
21. You push a heavy car by hand. The car, in turn, pushes back with an opposite but equal force on you. Doesn't this mean that the forces cancel one another, making acceleration impossible? Why or why not?
22. The strong man will push the two initially stationary freight cars of equal mass apart before he himself drops straight to the ground. Is it possible for him to give either of the cars a greater speed than the other? Why or why not?



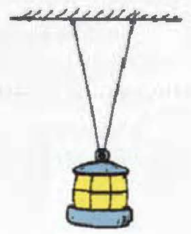
23. Suppose that two carts, one twice as massive as the other, fly apart when the compressed spring that joins them is released. What is the acceleration of the heavier cart relative to that of the lighter cart as they start to move apart?



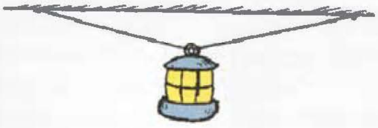
24. If a Mack truck and Honda Civic have a head-on collision, upon which vehicle is the impact force greater? Which vehicle experiences the greater deceleration? Explain your answers.
25. Ken and Joanne are astronauts floating some distance apart in space. They are joined by a safety cord whose ends are tied around their waists. If Ken starts pulling on the cord, will he pull Joanne toward him, or will he pull himself toward Joanne, or will both astronauts move? Explain.
26. Which team wins in a tug-of-war—the team that pulls harder on the rope, or the team that pushes harder against the ground? Explain.
27. In a tug-of-war between Sam and Maddy, each pulls on the rope with a force of 250 N. What is the tension in the rope? If both remain motionless, what horizontal force does each exert against the ground?
28. Your instructor challenges you and your friend to each pull on a pair of scales attached to the ends of a horizontal rope, in tug-of-war fashion, so that the readings on the scales will differ. Can this be done? Explain.



29. Two people of equal mass attempt a tug-of-war with a 12-m rope while standing on frictionless ice. When they pull on the rope, each of them slides toward the other. How do their accelerations compare, and how far does each person slide before they meet?
30. What aspect of physics was not known by the writer of this newspaper editorial that ridiculed early experiments by Robert H. Goddard on rocket propulsion above Earth's atmosphere? "Professor Goddard . . . does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react . . . he seems to lack the knowledge ladled out daily in high schools."
31. Which of the following are scalar quantities, which are vector quantities, and which are neither? (a) velocity; (b) age; (c) speed; (d) acceleration; (e) temperature.
32. What can you correctly say about two vectors that add together to equal zero?
33. Can a pair of vectors with unequal magnitudes ever add to zero? Can three unequal vectors add to zero? Defend your answers.
34. When can a nonzero vector have a zero horizontal component?
35. When, if ever, can a vector quantity be added to a scalar quantity?
36. Which is more likely to break—a hammock stretched tightly between a pair of trees or one that sags more when you sit on it?
37. A heavy bird sits on a clothesline. Will the tension in the clothesline be greater if the line sags a lot or if it sags a little?
38. The rope supports a lantern that weighs 50 N. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.



39. The rope is repositioned as shown and still supports the 50-N lantern. Is the tension in the rope less than, equal to, or more than 50 N? Use the parallelogram rule to defend your answer.

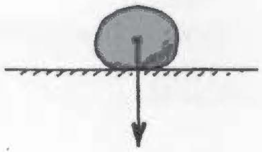


40. Why does vertically falling rain make slanted streaks on the side windows of a moving automobile? If the streaks make an angle of 45°, what does this tell you about the relative speed of the car and the falling rain?

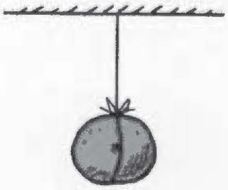
41. A balloon floats motionless in the air. A balloonist begins climbing the supporting cable. In which direction does the balloon move as the balloonist climbs? Defend your answer.

42. Consider a stone at rest on the ground. There are two interactions that involve the stone. One is between the stone and Earth as a whole: Earth pulls down on the stone (its weight) and the stone pulls up on Earth. What is the other interaction?

43. A stone is shown at rest on the ground. (a) The vector shows the weight of the stone. Complete the vector diagram showing another vector that results in zero net force on the stone. (b) What is the conventional name of the vector you have drawn?



44. Here a stone is suspended at rest by a string. (a) Draw force vectors for all the forces that act on the stone. (b) Should your vectors have a zero resultant? (c) Why or why not?

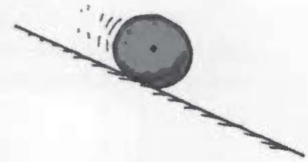


45. Here the same stone is being accelerated vertically upward. (a) Draw force vectors to some suitable scale showing relative forces acting on the stone. (b) Which is the longer vector, and why?

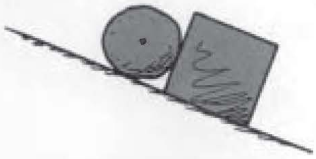
46. Suppose the string in the preceding exercise breaks and the stone slows in its upward motion. Draw a force vector diagram of the stone when it reaches the top of its path.

47. What is the acceleration of the stone of Exercise 46 at the top of its path?

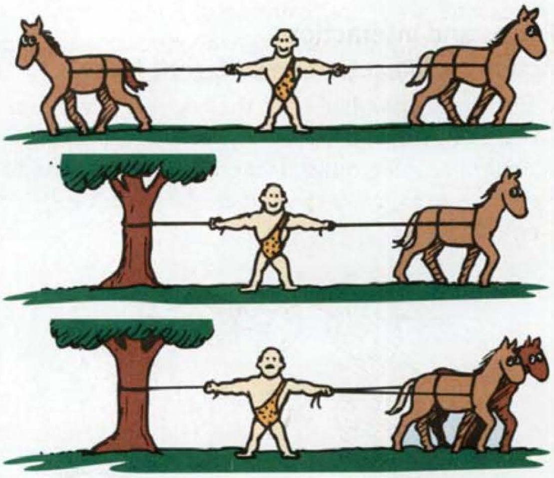
48. Here the stone is sliding down a friction-free incline. (a) Identify the forces that act on it, and draw appropriate force vectors. (b) By the parallelogram rule, construct the resultant force on the stone (carefully showing that it has a direction parallel to the incline—the same direction as the stone's acceleration).



49. Here the stone is at rest, interacting with both the surface of the incline and the block. (a) Identify all the forces that act on the stone, and draw appropriate force vectors. (b) Show that the net force on the stone is zero. (*Hint 1:* There are two normal forces on the stone. *Hint 2:* Be sure the vectors you draw are for forces that act *on* the stone, not *by* the stone on the surfaces.)



50. The strong man can withstand the tension force exerted by the two horses pulling in opposite directions. How would the tension compare if only one horse pulled and the left rope were tied to a tree? How would the tension compare if the two horses pulled in the same direction, with the left rope tied to the tree?



PROBLEMS

1. A boxer punches a sheet of paper in midair and brings it from rest up to a speed of 25 m/s in 0.05 s. (a) What acceleration is imparted to the paper? (b) If the mass of the paper is 0.003 kg, what force does the boxer exert on it? (c) How much force does the paper exert on the boxer?

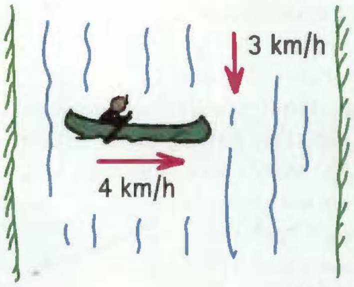
2. If you stand next to a wall on a frictionless skateboard and push the wall with a force of 40 N, how hard does the wall push on you? If your mass is 80 kg, show that your acceleration is 0.5 m/s^2.

3. If raindrops fall vertically at a speed of 3 m/s and you are running at 4 m/s, how fast do they hit your face?

4. Forces of 3.0 N and 4.0 N act at right angles on a block of mass 2.0 kg. Show that the acceleration of the block is 2.5 m/s^2.

5. Consider an airplane that normally has an airspeed of 100 km/h in a 100-km/h crosswind blowing from west to east. Calculate its ground velocity when its nose is pointed north in the crosswind.

6. You are paddling a canoe at a speed of 4 km/h directly across a river that flows at 3 km/h, as shown in the figure. (a) What is your resultant speed relative to the shore? (b) In approximately what direction should you paddle the canoe so that it reaches a destination directly across the river?



• **7.** When two identical air pucks with repelling magnets are held together on an air table and released, they end up moving in opposite directions at the same speed, *v*. Assume the mass of one of the pucks is doubled and the procedure is repeated.

a. From Newton's third law, derive an equation that shows how the final speed of the double-mass puck compares with the speed of the single puck.
b. Calculate the speed of the double-mass puck if the single puck moves away at 0.4 m/s.

CHAPTER 5 ONLINE RESOURCES

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Interactive Figures

- 5.1, 5.8, 5.9, 5.10, 5.11, 5.16, 5.22, 5.25

Tutorials

- Newton's Third Law
- Vectors

Videos

- Forces and Interaction
- Action and Reaction on Different Masses
- Action and Reaction on Rifle and Bullet
- Vector Representation: How to Add and Subtract Vectors
- Geometrical Addition of Vectors

Quizzes

Flashcards

Links