



Lava spews from a volcanic eruption. Notice the parabolic paths of embers projected into the air. All projectiles follow a parabolic path in the absence of air resistance. (© Arndt/Premium Stock/PictureQuest)

- 4.1 The Position, Velocity, and Acceleration Vectors
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4 Motion in Two Dimensions

In this chapter, we explore the kinematics of a particle moving in two dimensions. Knowing the basics of two-dimensional motion will allow us—in future chapters—to examine a variety of motions ranging from the motion of satellites in orbit to the motion of electrons in a uniform electric field. We begin by studying in greater detail the vector nature of position, velocity, and acceleration. We then treat projectile motion and uniform circular motion as special cases of motion in two dimensions. We also discuss the concept of relative motion, which shows why observers in different frames of reference may measure different positions and velocities for a given particle.

4.1 The Position, Velocity, and Acceleration Vectors

In Chapter 2, we found that the motion of a particle along a straight line is completely known if its position is known as a function of time. Let us now extend this idea to two-dimensional motion of a particle in the xy plane. We begin by describing the position of the particle by its **position vector** \vec{r} , drawn from the origin of some coordinate system to the location of the particle in the xy plane, as in Figure 4.1 (page 72). At time t_p , the particle is at point \textcircled{A} , described by position vector \vec{r}_p . At some later time t_f , it is at point \textcircled{B} , described by position vector \vec{r}_f . The path from

Ⓐ to Ⓑ is not necessarily a straight line. As the particle moves from Ⓐ to Ⓑ in the time interval $\Delta t = t_f - t_i$, its position vector changes from \vec{r}_i to \vec{r}_f . As we learned in Chapter 2, displacement is a vector, and the displacement of the particle is the difference between its final position and its initial position. We now define the **displacement vector** $\Delta\vec{r}$ for a particle such as the one in Figure 4.1 as being the difference between its final position vector and its initial position vector:

Displacement vector ►

$$\Delta\vec{r} \equiv \vec{r}_f - \vec{r}_i \quad (4.1)$$

The direction of $\Delta\vec{r}$ is indicated in Figure 4.1. As we see from the figure, the magnitude of $\Delta\vec{r}$ is *less* than the distance traveled along the curved path followed by the particle.

As we saw in Chapter 2, it is often useful to quantify motion by looking at the ratio of a displacement divided by the time interval during which that displacement occurs, which gives the rate of change of position. Two-dimensional (or three-dimensional) kinematics is similar to one-dimensional kinematics, but we must now use full vector notation rather than positive and negative signs to indicate the direction of motion.

We define the **average velocity** \vec{v}_{avg} of a particle during the time interval Δt as the displacement of the particle divided by the time interval:

Average velocity ►

$$\vec{v}_{\text{avg}} \equiv \frac{\Delta\vec{r}}{\Delta t} \quad (4.2)$$

Multiplying or dividing a vector quantity by a positive scalar quantity such as Δt changes only the magnitude of the vector, not its direction. Because displacement is a vector quantity and the time interval is a positive scalar quantity, we conclude that the average velocity is a vector quantity directed along $\Delta\vec{r}$.

The average velocity between points is *independent of the path* taken. That is because average velocity is proportional to displacement, which depends only on the initial and final position vectors and not on the path taken. As with one-dimensional motion, we conclude that if a particle starts its motion at some point and returns to this point via any path, its average velocity is zero for this trip because its displacement is zero. Consider again our basketball players on the court in Figure 2.2 (page 21). We previously considered only their one-dimensional motion back and forth between the baskets. In reality, however, they move over a two-dimensional surface, running back and forth between the baskets as well as left and right across the width of the court. Starting from one basket, a given player may follow a very complicated two-dimensional path. Upon returning to the original basket, however, a player's average velocity is zero because the player's displacement for the whole trip is zero.

Consider again the motion of a particle between two points in the xy plane as shown in Figure 4.2. As the time interval over which we observe the motion

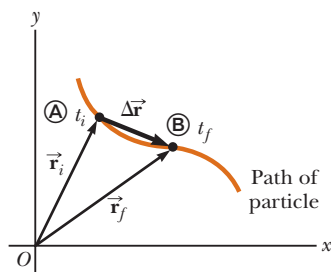


Figure 4.1 A particle moving in the xy plane is located with the position vector \vec{r} drawn from the origin to the particle. The displacement of the particle as it moves from Ⓐ to Ⓑ in the time interval $\Delta t = t_f - t_i$ is equal to the vector $\Delta\vec{r} = \vec{r}_f - \vec{r}_i$.

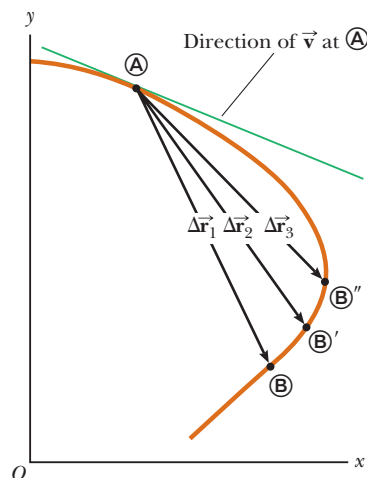


Figure 4.2 As a particle moves between two points, its average velocity is in the direction of the displacement vector $\Delta\vec{r}$. As the end point of the path is moved from Ⓑ to Ⓑ' to Ⓑ'', the respective displacements and corresponding time intervals become smaller and smaller. In the limit that the end point approaches Ⓐ, Δt approaches zero and the direction of $\Delta\vec{r}$ approaches that of the line tangent to the curve at Ⓐ. By definition, the instantaneous velocity at Ⓐ is directed along this tangent line.

becomes smaller and smaller—that is, as \textcircled{B} is moved to \textcircled{B}' and then to \textcircled{B}'' , and so on—the direction of the displacement approaches that of the line tangent to the path at \textcircled{A} . The **instantaneous velocity** \vec{v} is defined as the limit of the average velocity $\Delta\vec{r}/\Delta t$ as Δt approaches zero:

$$\vec{v} \equiv \lim_{\Delta t \rightarrow 0} \frac{\Delta\vec{r}}{\Delta t} = \frac{d\vec{r}}{dt} \quad (4.3) \quad \leftarrow \text{Instantaneous velocity}$$

That is, the instantaneous velocity equals the derivative of the position vector with respect to time. The direction of the instantaneous velocity vector at any point in a particle's path is along a line tangent to the path at that point and in the direction of motion.

The magnitude of the instantaneous velocity vector $v = |\vec{v}|$ of a particle is called the *speed* of the particle, which is a scalar quantity.

As a particle moves from one point to another along some path, its instantaneous velocity vector changes from \vec{v}_i at time t_i to \vec{v}_f at time t_f . Knowing the velocity at these points allows us to determine the average acceleration of the particle. The **average acceleration** \vec{a}_{avg} of a particle is defined as the change in its instantaneous velocity vector $\Delta\vec{v}$ divided by the time interval Δt during which that change occurs:

$$\vec{a}_{\text{avg}} \equiv \frac{\vec{v}_f - \vec{v}_i}{t_f - t_i} = \frac{\Delta\vec{v}}{\Delta t} \quad (4.4) \quad \leftarrow \text{Average acceleration}$$

Because \vec{a}_{avg} is the ratio of a vector quantity $\Delta\vec{v}$ and a positive scalar quantity Δt , we conclude that average acceleration is a vector quantity directed along $\Delta\vec{v}$. As indicated in Figure 4.3, the direction of $\Delta\vec{v}$ is found by adding the vector $-\vec{v}_i$ (the negative of \vec{v}_i) to the vector \vec{v}_f because, by definition, $\Delta\vec{v} = \vec{v}_f - \vec{v}_i$.

When the average acceleration of a particle changes during different time intervals, it is useful to define its instantaneous acceleration. The **instantaneous acceleration** \vec{a} is defined as the limiting value of the ratio $\Delta\vec{v}/\Delta t$ as Δt approaches zero:

$$\vec{a} \equiv \lim_{\Delta t \rightarrow 0} \frac{\Delta\vec{v}}{\Delta t} = \frac{d\vec{v}}{dt} \quad (4.5) \quad \leftarrow \text{Instantaneous acceleration}$$

In other words, the instantaneous acceleration equals the derivative of the velocity vector with respect to time.

Various changes can occur when a particle accelerates. First, the magnitude of the velocity vector (the speed) may change with time as in straight-line (one-dimensional) motion. Second, the direction of the velocity vector may change with time even if its magnitude (speed) remains constant as in two-dimensional motion along a curved path. Finally, both the magnitude and the direction of the velocity vector may change simultaneously.

PITFALL PREVENTION 4.1 Vector Addition

Although the vector addition discussed in Chapter 3 involves *displacement* vectors, vector addition can be applied to *any* type of vector quantity. Figure 4.3, for example, shows the addition of *velocity* vectors using the graphical approach.

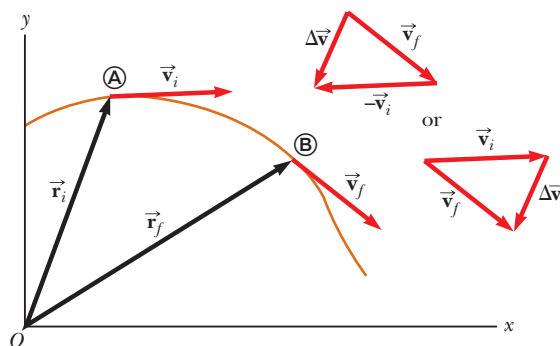


Figure 4.3 A particle moves from position \textcircled{A} to position \textcircled{B} . Its velocity vector changes from \vec{v}_i to \vec{v}_f . The vector diagrams at the upper right show two ways of determining the vector $\Delta\vec{v}$ from the initial and final velocities.

Quick Quiz 4.1 Consider the following controls in an automobile: gas pedal, brake, steering wheel. What are the controls in this list that cause an acceleration of the car? (a) all three controls (b) the gas pedal and the brake (c) only the brake (d) only the gas pedal

4.2 Two-Dimensional Motion with Constant Acceleration

In Section 2.5, we investigated one-dimensional motion of a particle under constant acceleration. Let us now consider two-dimensional motion during which the acceleration of a particle remains constant in both magnitude and direction. As we shall see, this approach is useful for analyzing some common types of motion.

Before embarking on this investigation, we need to emphasize an important point regarding two-dimensional motion. Imagine an air hockey puck moving in a straight line along a perfectly level, friction-free surface of an air hockey table. Figure 4.4a shows a motion diagram from an overhead point of view of this puck. Recall that in Section 2.4 we related the acceleration of an object to a force on the object. Because there are no forces on the puck in the horizontal plane, it moves with constant velocity in the x direction. Now suppose you blow a puff of air on the puck as it passes your position, with the force from your puff of air *exactly* in the y direction. Because the force from this puff of air has no component in the x direction, it causes no acceleration in the x direction. It only causes a momentary acceleration in the y direction, causing the puck to have a constant y component of velocity once the force from the puff of air is removed. After your puff of air on the puck, its velocity component in the x direction is unchanged, as shown in Figure 4.4b. The generalization of this simple experiment is that **motion in two dimensions can be modeled as two independent motions in each of the two perpendicular directions associated with the x and y axes. That is, any influence in the y direction does not affect the motion in the x direction and vice versa.**

The position vector for a particle moving in the xy plane can be written

$$\vec{r} = x\hat{i} + y\hat{j} \quad (4.6)$$

where x , y , and \vec{r} change with time as the particle moves while the unit vectors \hat{i} and \hat{j} remain constant. If the position vector is known, the velocity of the particle can be obtained from Equations 4.3 and 4.6, which give

$$\vec{v} = \frac{d\vec{r}}{dt} = \frac{dx}{dt}\hat{i} + \frac{dy}{dt}\hat{j} = v_x\hat{i} + v_y\hat{j} \quad (4.7)$$

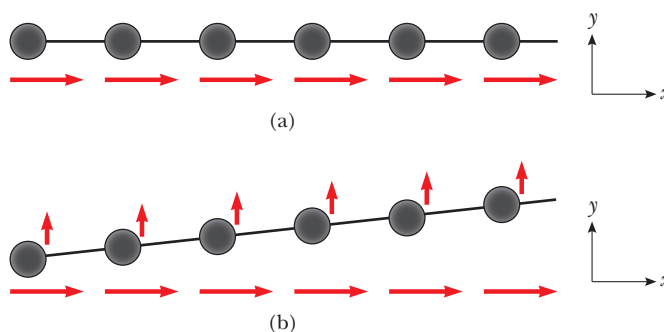


Figure 4.4 (a) A puck moves across a horizontal air hockey table at constant velocity in the x direction. (b) After a puff of air in the y direction is applied to the puck, the puck has gained a y component of velocity, but the x component is unaffected by the force in the perpendicular direction. Notice that the horizontal red vectors, representing the x component of the velocity, are the same length in both parts of the figure, which demonstrates that motion in two dimensions can be modeled as two independent motions in perpendicular directions.

Because the acceleration \vec{a} of the particle is assumed constant in this discussion, its components a_x and a_y also are constants. Therefore, we can model the particle as a particle under constant acceleration independently in each of the two directions and apply the equations of kinematics separately to the x and y components of the velocity vector. Substituting, from Equation 2.13, $v_{xf} = v_{xi} + a_x t$ and $v_{yf} = v_{yi} + a_y t$ into Equation 4.7 to determine the final velocity at any time t , we obtain

$$\begin{aligned}\vec{v}_f &= (v_{xi} + a_x t)\hat{i} + (v_{yi} + a_y t)\hat{j} = (v_{xi}\hat{i} + v_{yi}\hat{j}) + (a_x\hat{i} + a_y\hat{j})t \\ \vec{v}_f &= \vec{v}_i + \vec{a}t\end{aligned}\quad (4.8)$$

◀ Velocity vector as a function of time

This result states that the velocity of a particle at some time t equals the vector sum of its initial velocity \vec{v}_i at time $t = 0$ and the additional velocity $\vec{a}t$ acquired at time t as a result of constant acceleration. Equation 4.8 is the vector version of Equation 2.13.

Similarly, from Equation 2.16 we know that the x and y coordinates of a particle moving with constant acceleration are

$$x_f = x_i + v_{xi}t + \frac{1}{2}a_x t^2 \quad y_f = y_i + v_{yi}t + \frac{1}{2}a_y t^2$$

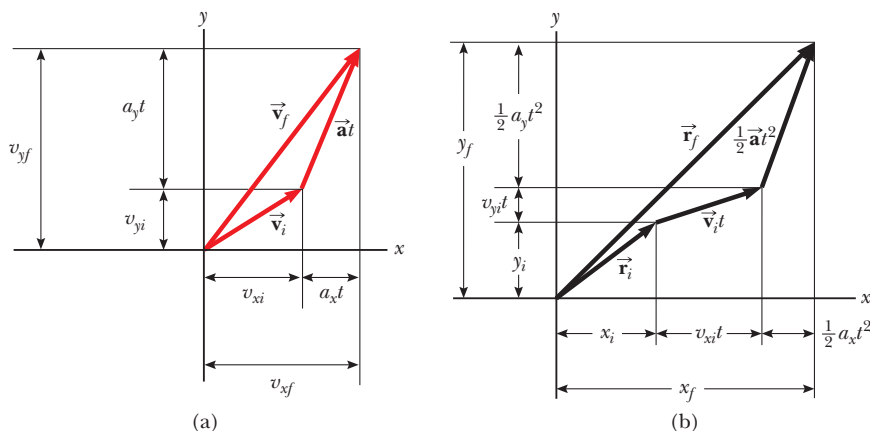
Substituting these expressions into Equation 4.6 (and labeling the final position vector \vec{r}_f) gives

$$\begin{aligned}\vec{r}_f &= (x_i + v_{xi}t + \frac{1}{2}a_x t^2)\hat{i} + (y_i + v_{yi}t + \frac{1}{2}a_y t^2)\hat{j} \\ &= (x_i\hat{i} + y_i\hat{j}) + (v_{xi}\hat{i} + v_{yi}\hat{j})t + \frac{1}{2}(a_x\hat{i} + a_y\hat{j})t^2 \\ \vec{r}_f &= \vec{r}_i + \vec{v}_i t + \frac{1}{2}\vec{a}t^2\end{aligned}\quad (4.9)$$

◀ Position vector as a function of time

which is the vector version of Equation 2.16. Equation 4.9 tells us that the position vector \vec{r}_f of a particle is the vector sum of the original position \vec{r}_i , a displacement $\vec{v}_i t$ arising from the initial velocity of the particle and a displacement $\frac{1}{2}\vec{a}t^2$ resulting from the constant acceleration of the particle.

Graphical representations of Equations 4.8 and 4.9 are shown in Active Figure 4.5. The components of the position and velocity vectors are also illustrated in the figure. Notice from Active Figure 4.5a that \vec{v}_f is generally not along the direction of either \vec{v}_i or \vec{a} because the relationship between these quantities is a vector expression. For the same reason, from Active Figure 4.5b we see that \vec{r}_f is generally not along the direction of \vec{v}_i or \vec{a} . Finally, notice that \vec{v}_f and \vec{r}_f are generally not in the same direction.



ACTIVE FIGURE 4.5

Vector representations and components of (a) the velocity and (b) the position of a particle moving with a constant acceleration \vec{a} .

Sign in at www.thomsonedu.com and go to ThomsonNOW to investigate the effect of different initial positions and velocities on the final position and velocity (for constant acceleration).

EXAMPLE 4.1 Motion in a Plane

A particle starts from the origin at $t = 0$ with an initial velocity having an x component of 20 m/s and a y component of -15 m/s. The particle moves in the xy plane with an x component of acceleration only, given by $a_x = 4.0$ m/s².

(A) Determine the total velocity vector at any time.

SOLUTION

Conceptualize The components of the initial velocity tell us that the particle starts by moving toward the right and downward. The x component of velocity starts at 20 m/s and increases by 4.0 m/s every second. The y component of velocity never changes from its initial value of -15 m/s. We sketch a motion diagram of the situation in Figure 4.6. Because the particle is accelerating in the $+x$ direction, its velocity component in this direction increases and the path curves as shown in the diagram. Notice that the spacing between successive images increases as time goes on because the speed is increasing. The placement of the acceleration and velocity vectors in Figure 4.6 helps us further conceptualize the situation.

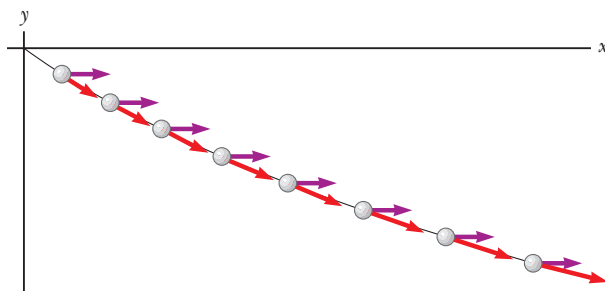


Figure 4.6 (Example 4.1) Motion diagram for the particle.

Categorize Because the initial velocity has components in both the x and y directions, we categorize this problem as one involving a particle moving in two dimensions. Because the particle only has an x component of acceleration, we model it as a particle under constant acceleration in the x direction and a particle under constant velocity in the y direction.

Analyze To begin the mathematical analysis, we set $v_{xi} = 20$ m/s, $v_{yi} = -15$ m/s, $a_x = 4.0$ m/s², and $a_y = 0$.

Use Equation 4.8 for the velocity vector:

$$\vec{v}_f = \vec{v}_i + \vec{a}t = (v_{xi} + a_x t)\hat{i} + (v_{yi} + a_y t)\hat{j}$$

Substitute numerical values:

$$\vec{v}_f = [20 \text{ m/s} + (4.0 \text{ m/s}^2)t]\hat{i} + [-15 \text{ m/s} + (0)t]\hat{j}$$

$$(1) \vec{v}_f = [(20 + 4.0t)\hat{i} - 15\hat{j}] \text{ m/s}$$

Finalize Notice that the x component of velocity increases in time while the y component remains constant; this result is consistent with what we predicted.

(B) Calculate the velocity and speed of the particle at $t = 5.0$ s.

SOLUTION**Analyze**

Evaluate the result from Equation (1) at $t = 5.0$ s:

$$\vec{v}_f = [(20 + 4.0(5.0))\hat{i} - 15\hat{j}] \text{ m/s} = (40\hat{i} - 15\hat{j}) \text{ m/s}$$

Determine the angle θ that \vec{v}_f makes with the x axis at $t = 5.0$ s:

$$\theta = \tan^{-1}\left(\frac{v_{yf}}{v_{xf}}\right) = \tan^{-1}\left(\frac{-15 \text{ m/s}}{40 \text{ m/s}}\right) = -21^\circ$$

Evaluate the speed of the particle as the magnitude of \vec{v}_f :

$$v_f = |\vec{v}_f| = \sqrt{v_{xf}^2 + v_{yf}^2} = \sqrt{(40)^2 + (-15)^2} \text{ m/s} = 43 \text{ m/s}$$

Finalize The negative sign for the angle θ indicates that the velocity vector is directed at an angle of 21° below the positive x axis. Notice that if we calculate v_i from the x and y components of \vec{v}_i , we find that $v_f > v_i$. Is that consistent with our prediction?

(C) Determine the x and y coordinates of the particle at any time t and its position vector at this time.

SOLUTION**Analyze**

Use the components of Equation 4.9 with $x_i = y_i = 0$ at $t = 0$:

$$x_f = v_{xi}t + \frac{1}{2}a_x t^2 = (20t + 2.0t^2) \text{ m}$$

$$y_f = v_{yi}t = (-15t) \text{ m}$$

Express the position vector of the particle at any time t :

$$\vec{r}_f = x_f \hat{i} + y_f \hat{j} = [(20t + 2.0t^2) \hat{i} - 15t \hat{j}] \text{ m}$$

Finalize Let us now consider a limiting case for very large values of t .

What If? What if we wait a very long time and then observe the motion of the particle? How would we describe the motion of the particle for large values of the time?

Answer Looking at Figure 4.6, we see the path of the particle curving toward the x axis. There is no reason to assume that this tendency will change, which suggests that the path will become more and more parallel to the

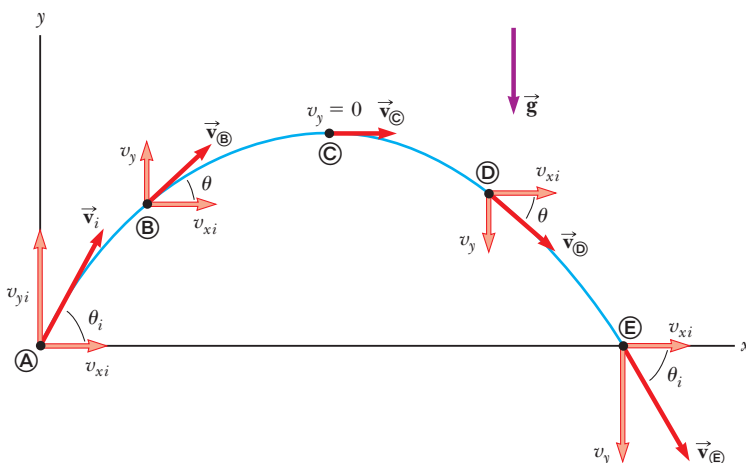
x axis as time grows large. Mathematically, Equation (1) shows that the y component of the velocity remains constant while the x component grows linearly with t . Therefore, when t is very large, the x component of the velocity will be much larger than the y component, suggesting that the velocity vector becomes more and more parallel to the x axis. Both x_f and y_f continue to grow with time, although x_f grows much faster.

4.3 Projectile Motion

Anyone who has observed a baseball in motion has observed projectile motion. The ball moves in a curved path and returns to the ground. **Projectile motion** of an object is simple to analyze if we make two assumptions: (1) the free-fall acceleration is constant over the range of motion and is directed downward,¹ and (2) the effect of air resistance is negligible.² With these assumptions, we find that the path of a projectile, which we call its *trajectory*, is *always* a parabola as shown in Active Figure 4.7. **We use these assumptions throughout this chapter.**

The expression for the position vector of the projectile as a function of time follows directly from Equation 4.9, with $\vec{a} = \vec{g}$:

$$\vec{r}_f = \vec{r}_i + \vec{v}_i t + \frac{1}{2} \vec{g} t^2 \quad (4.10)$$



ACTIVE FIGURE 4.7

The parabolic path of a projectile that leaves the origin with a velocity \vec{v}_i . The velocity vector \vec{v} changes with time in both magnitude and direction. This change is the result of acceleration in the negative y direction. The x component of velocity remains constant in time because there is no acceleration along the horizontal direction. The y component of velocity is zero at the peak of the path.

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¹ This assumption is reasonable as long as the range of motion is small compared with the radius of the Earth (6.4×10^6 m). In effect, this assumption is equivalent to assuming that the Earth is flat over the range of motion considered.

² This assumption is generally *not* justified, especially at high velocities. In addition, any spin imparted to a projectile, such as that applied when a pitcher throws a curve ball, can give rise to some very interesting effects associated with aerodynamic forces, which will be discussed in Chapter 14.

PITFALL PREVENTION 4.2 Acceleration at the Highest Point

As discussed in Pitfall Prevention 2.8, many people claim that the acceleration of a projectile at the topmost point of its trajectory is zero. This mistake arises from confusion between zero vertical velocity and zero acceleration. If the projectile were to experience zero acceleration at the highest point, its velocity at that point would not change; rather, the projectile would move horizontally at constant speed from then on! That does not happen, however, because the acceleration is *not* zero anywhere along the trajectory.



The Telegraph Colour Library/Getty Images

A welder cuts holes through a heavy metal construction beam with a hot torch. The sparks generated in the process follow parabolic paths.

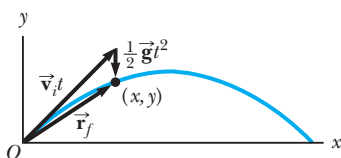


Figure 4.8 The position vector \vec{r}_f of a projectile launched from the origin whose initial velocity at the origin is \vec{v}_i . The vector $\vec{v}_i t$ would be the displacement of the projectile if gravity were absent, and the vector $\frac{1}{2} \vec{g} t^2$ is its vertical displacement from a straight-line path due to its downward gravitational acceleration.

where the initial x and y components of the velocity of the projectile are

$$v_{xi} = v_i \cos \theta_i \quad v_{yi} = v_i \sin \theta_i \quad (4.11)$$

The expression in Equation 4.10 is plotted in Figure 4.8, for a projectile launched from the origin, so that $\vec{r}_i = 0$. The final position of a particle can be considered to be the superposition of its initial position \vec{r}_i ; the term $\vec{v}_i t$, which is its displacement if no acceleration were present; and the term $\frac{1}{2} \vec{g} t^2$ that arises from its acceleration due to gravity. In other words, if there were no gravitational acceleration, the particle would continue to move along a straight path in the direction of \vec{v}_i . Therefore, the vertical distance $\frac{1}{2} \vec{g} t^2$ through which the particle “falls” off the straight-line path is the same distance that an object dropped from rest would fall during the same time interval.

In Section 4.2, we stated that two-dimensional motion with constant acceleration can be analyzed as a combination of two independent motions in the x and y directions, with accelerations a_x and a_y . Projectile motion can also be handled in this way, with zero acceleration in the x direction and a constant acceleration in the y direction, $a_y = -g$. Therefore, **when analyzing projectile motion, model it to be the superposition of two motions: (1) motion of a particle under constant velocity in the horizontal direction and (2) motion of a particle under constant acceleration (free fall) in the vertical direction.** The horizontal and vertical components of a projectile’s motion are completely independent of each other and can be handled separately, with time t as the common variable for both components.

Quick Quiz 4.2 (i) As a projectile thrown upward moves in its parabolic path (such as in Fig. 4.8), at what point along its path are the velocity and acceleration vectors for the projectile perpendicular to each other? (a) nowhere (b) the highest point (c) the launch point (ii) From the same choices, at what point are the velocity and acceleration vectors for the projectile parallel to each other?

Horizontal Range and Maximum Height of a Projectile

Let us assume a projectile is launched from the origin at $t_i = 0$ with a positive v_{yi} component as shown in Figure 4.9 and returns to the same horizontal level. Two points are especially interesting to analyze: the peak point \textcircled{A} , which has Cartesian coordinates $(R/2, h)$, and the point \textcircled{B} , which has coordinates $(R, 0)$. The distance R is called the *horizontal range* of the projectile, and the distance h is its *maximum height*. Let us find h and R mathematically in terms of v_i , θ_i , and g .

We can determine h by noting that at the peak $v_{y\textcircled{A}} = 0$. Therefore, we can use the y component of Equation 4.8 to determine the time $t_{\textcircled{A}}$ at which the projectile reaches the peak:

$$\begin{aligned} v_{yf} &= v_{yi} + a_y t \\ 0 &= v_i \sin \theta_i - g t_{\textcircled{A}} \\ t_{\textcircled{A}} &= \frac{v_i \sin \theta_i}{g} \end{aligned}$$

Substituting this expression for $t_{\textcircled{A}}$ into the y component of Equation 4.9 and replacing $y = y_{\textcircled{A}}$ with h , we obtain an expression for h in terms of the magnitude and direction of the initial velocity vector:

$$\begin{aligned} h &= (v_i \sin \theta_i) \frac{v_i \sin \theta_i}{g} - \frac{1}{2} g \left(\frac{v_i \sin \theta_i}{g} \right)^2 \\ h &= \frac{v_i^2 \sin^2 \theta_i}{2g} \end{aligned} \quad (4.12)$$

The range R is the horizontal position of the projectile at a time that is twice the time at which it reaches its peak, that is, at time $t_{\textcircled{B}} = 2t_{\textcircled{A}}$. Using the x compo-

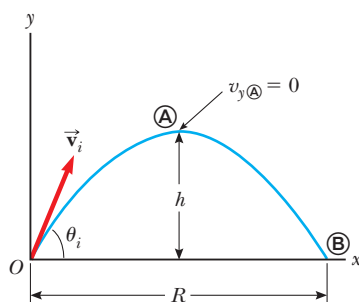
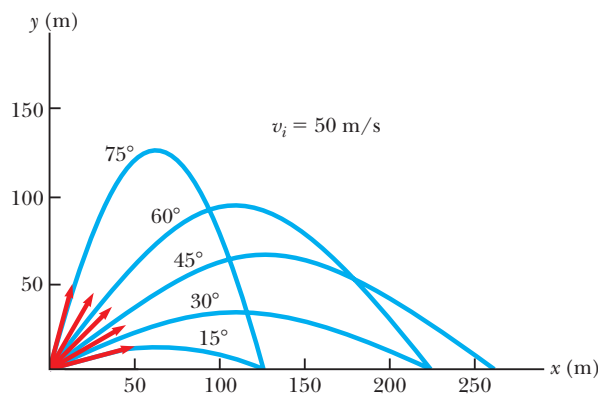


Figure 4.9 A projectile launched over a flat surface from the origin at $t_i = 0$ with an initial velocity \vec{v}_i . The maximum height of the projectile is h , and the horizontal range is R . At \textcircled{A} , the peak of the trajectory, the particle has coordinates $(R/2, h)$.

**ACTIVE FIGURE 4.10**

A projectile launched over a flat surface from the origin with an initial speed of 50 m/s at various angles of projection. Notice that complementary values of θ_i result in the same value of R (range of the projectile).

Sign in at www.thomsonedu.com and go to ThomsonNOW to vary the projection angle, observe the effect on the trajectory, and measure the flight time.

nent of Equation 4.9, noting that $v_{xi} = v_{x\oplus} = v_i \cos \theta_i$, and setting $x_{\oplus} = R$ at $t = 2t_{\oplus}$, we find that

$$\begin{aligned} R &= v_{xi}t_{\oplus} = (v_i \cos \theta_i)2t_{\oplus} \\ &= (v_i \cos \theta_i) \frac{2v_i \sin \theta_i}{g} = \frac{2v_i^2 \sin \theta_i \cos \theta_i}{g} \end{aligned}$$

Using the identity $\sin 2\theta = 2 \sin \theta \cos \theta$ (see Appendix B.4), we can write R in the more compact form

$$R = \frac{v_i^2 \sin 2\theta_i}{g} \quad (4.13)$$

The maximum value of R from Equation 4.13 is $R_{\max} = v_i^2/g$. This result makes sense because the maximum value of $\sin 2\theta_i$ is 1, which occurs when $2\theta_i = 90^\circ$. Therefore, R is a maximum when $\theta_i = 45^\circ$.

Active Figure 4.10 illustrates various trajectories for a projectile having a given initial speed but launched at different angles. As you can see, the range is a maximum for $\theta_i = 45^\circ$. In addition, for any θ_i other than 45° , a point having Cartesian coordinates $(R, 0)$ can be reached by using either one of two complementary values of θ_i , such as 75° and 15° . Of course, the maximum height and time of flight for one of these values of θ_i are different from the maximum height and time of flight for the complementary value.

Quick Quiz 4.3 Rank the launch angles for the five paths in Active Figure 4.10 with respect to time of flight, from the shortest time of flight to the longest.

PROBLEM-SOLVING STRATEGY

Projectile Motion

We suggest you use the following approach when solving projectile motion problems:

1. *Conceptualize.* Think about what is going on physically in the problem. Establish the mental representation by imagining the projectile moving along its trajectory.
2. *Categorize.* Confirm that the problem involves a particle in free fall and that air resistance is neglected. Select a coordinate system with x in the horizontal direction and y in the vertical direction.
3. *Analyze.* If the initial velocity vector is given, resolve it into x and y components. Treat the horizontal motion and the vertical motion independently. Analyze the

PITFALL PREVENTION 4.3

The Height and Range Equations

Equation 4.13 is useful for calculating R only for a symmetric path as shown in Active Figure 4.10. If the path is not symmetric, *do not use this equation*. The general expressions given by Equations 4.8 and 4.9 are the *more important* results because they give the position and velocity components of *any* particle moving in two dimensions at *any* time t .

horizontal motion of the projectile as a particle under constant velocity. Analyze the vertical motion of the projectile as a particle under constant acceleration.

4. *Finalize.* Once you have determined your result, check to see if your answers are consistent with the mental and pictorial representations and that your results are realistic.

EXAMPLE 4.2 The Long Jump

A long jumper (Fig. 4.11) leaves the ground at an angle of 20.0° above the horizontal and at a speed of 11.0 m/s.

(A) How far does he jump in the horizontal direction?

SOLUTION

Conceptualize The arms and legs of a long jumper move in a complicated way, but we will ignore this motion. We conceptualize the motion of the long jumper as equivalent to that of a simple projectile.

Categorize We categorize this example as a projectile motion problem. Because the initial speed and launch angle are given and because the final height is the same as the initial height, we further categorize this problem as satisfying the conditions for which Equations 4.12 and 4.13 can be used. This approach is the most direct way to analyze this problem, although the general methods that have been described will always give the correct answer.

Analyze

Use Equation 4.13 to find the range of the jumper:

$$R = \frac{v_i^2 \sin 2\theta_i}{g} = \frac{(11.0 \text{ m/s})^2 \sin 2(20.0^\circ)}{9.80 \text{ m/s}^2} = 7.94 \text{ m}$$

(B) What is the maximum height reached?

SOLUTION

Analyze

Find the maximum height reached by using Equation 4.12:

$$h = \frac{v_i^2 \sin^2 \theta_i}{2g} = \frac{(11.0 \text{ m/s})^2 (\sin 20.0^\circ)^2}{2(9.80 \text{ m/s}^2)} = 0.722 \text{ m}$$

Finalize Find the answers to parts (A) and (B) using the general method. The results should agree. Treating the long jumper as a particle is an oversimplification. Nevertheless, the values obtained are consistent with experience in sports. We can model a complicated system such as a long jumper as a particle and still obtain results that are reasonable.



Figure 4.11 (Example 4.2) Mike Powell, current holder of the world long-jump record of 8.95 m.

Mike Powell/Allsport/Getty Images

EXAMPLE 4.3 A Bull's-Eye Every Time

In a popular lecture demonstration, a projectile is fired at a target in such a way that the projectile leaves the gun at the same time the target is dropped from rest. Show that if the gun is initially aimed at the stationary target, the projectile hits the falling target as shown in Figure 4.12a.

SOLUTION

Conceptualize We conceptualize the problem by studying Figure 4.12a. Notice that the problem does not ask for numerical values. The expected result must involve an algebraic argument.

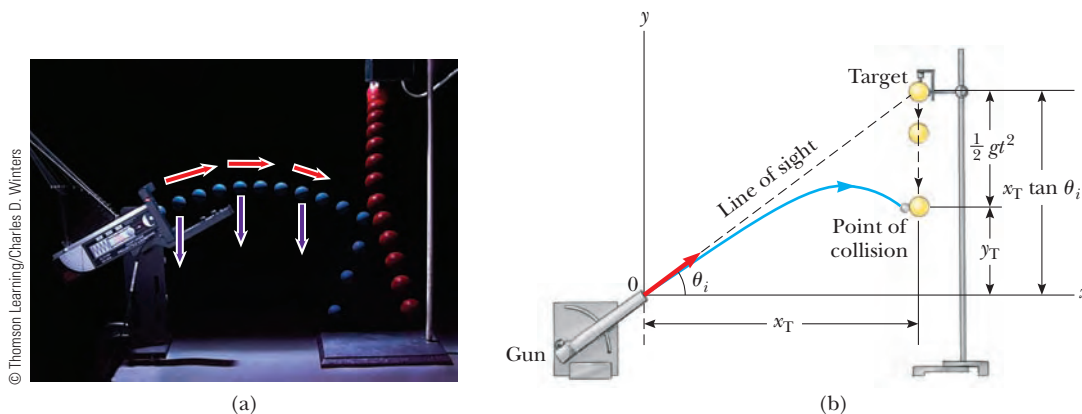


Figure 4.12 (Example 4.3) (a) Multiflash photograph of the projectile–target demonstration. If the gun is aimed directly at the target and is fired at the same instant the target begins to fall, the projectile will hit the target. Notice that the velocity of the projectile (red arrows) changes in direction and magnitude, whereas its downward acceleration (violet arrows) remains constant. (b) Schematic diagram of the projectile–target demonstration.

Categorize Because both objects are subject only to gravity, we categorize this problem as one involving two objects in free fall, the target moving in one dimension and the projectile moving in two.

Analyze The target T is modeled as a particle under constant acceleration in one dimension. Figure 4.12b shows that the initial y coordinate y_T of the target is $x_T \tan \theta_i$ and its initial velocity is zero. It falls with acceleration $a_y = -g$. The projectile P is modeled as a particle under constant acceleration in the y direction and a particle under constant velocity in the x direction.

Write an expression for the y coordinate of the target at any moment after release, noting that its initial velocity is zero:

$$(1) \quad y_T = y_{iT} + (0)t - \frac{1}{2}gt^2 = x_T \tan \theta_i - \frac{1}{2}gt^2$$

Write an expression for the y coordinate of the projectile at any moment:

$$(2) \quad y_P = y_{iP} + v_{yiP}t - \frac{1}{2}gt^2 = 0 + (v_{iP} \sin \theta_i)t - \frac{1}{2}gt^2 = (v_{iP} \sin \theta_i)t - \frac{1}{2}gt^2$$

Write an expression for the x coordinate of the projectile at any moment:

$$x_P = x_{iP} + v_{xiP}t = 0 + (v_{iP} \cos \theta_i)t = (v_{iP} \cos \theta_i)t$$

Solve this expression for time as a function of the horizontal position of the projectile:

$$t = \frac{x_P}{v_{iP} \cos \theta_i}$$

Substitute this expression into Equation (2):

$$(3) \quad y_P = (v_{iP} \sin \theta_i) \left(\frac{x_P}{v_{iP} \cos \theta_i} \right) - \frac{1}{2}gt^2 = x_P \tan \theta_i - \frac{1}{2}gt^2$$

Compare Equations (1) and (3). We see that when the x coordinates of the projectile and target are the same—that is, when $x_T = x_P$ —their y coordinates given by Equations (1) and (3) are the same and a collision results.

Finalize Note that a collision can result only when $v_{iP} \sin \theta_i \geq \sqrt{gd/2}$, where d is the initial elevation of the target above the floor. If $v_{iP} \sin \theta_i$ is less than this value, the projectile strikes the floor before reaching the target.

EXAMPLE 4.4 That's Quite an Arm!

A stone is thrown from the top of a building upward at an angle of 30.0° to the horizontal with an initial speed of 20.0 m/s as shown in Figure 4.13. The height of the building is 45.0 m .

(A) How long does it take the stone to reach the ground?

SOLUTION

Conceptualize Study Figure 4.13, in which we have indicated the trajectory and various parameters of the motion of the stone.

Categorize We categorize this problem as a projectile motion problem. The stone is modeled as a particle under constant acceleration in the y direction and a particle under constant velocity in the x direction.

Analyze We have the information $x_i = y_i = 0$, $y_f = -45.0$ m, $a_y = -g$, and $v_i = 20.0$ m/s (the numerical value of y_f is negative because we have chosen the top of the building as the origin).

Find the initial x and y components of the stone's velocity:

Express the vertical position of the stone from the vertical component of Equation 4.9:

Substitute numerical values:

Solve the quadratic equation for t :

(B) What is the speed of the stone just before it strikes the ground?

SOLUTION

Use the y component of Equation 4.8 with $t = 4.22$ s to obtain the y component of the velocity of the stone just before it strikes the ground:

Substitute numerical values:

Use this component with the horizontal component $v_{xf} = v_{xi} = 17.3$ m/s to find the speed of the stone at $t = 4.22$ s:

Finalize Is it reasonable that the y component of the final velocity is negative? Is it reasonable that the final speed is larger than the initial speed of 20.0 m/s?

What If? What if a horizontal wind is blowing in the same direction as the stone is thrown and it causes the stone to have a horizontal acceleration component $a_x = 0.500$ m/s²? Which part of this example, (A) or (B), will have a different answer?

Answer Recall that the motions in the x and y directions are independent. Therefore, the horizontal wind cannot affect the vertical motion. The vertical motion determines the time of the projectile in the air, so the answer to part (A) does not change. The wind causes the horizontal velocity component to increase with time, so the final speed will be larger in part (B). Taking $a_x = 0.500$ m/s², we find $v_{xf} = 19.4$ m/s and $v_f = 36.9$ m/s.

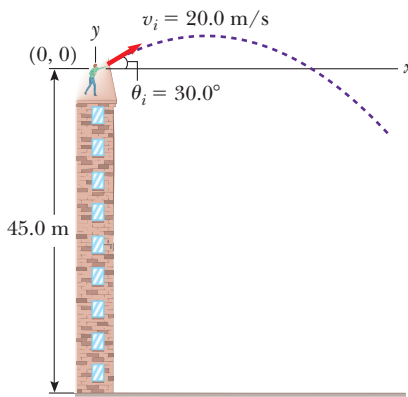


Figure 4.13 (Example 4.4) A stone is thrown from the top of a building.

$$v_{xi} = v_i \cos \theta_i = (20.0 \text{ m/s}) \cos 30.0^\circ = 17.3 \text{ m/s}$$

$$v_{yi} = v_i \sin \theta_i = (20.0 \text{ m/s}) \sin 30.0^\circ = 10.0 \text{ m/s}$$

$$y_f = y_i + v_{yi}t + \frac{1}{2}a_y t^2$$

$$-45.0 \text{ m} = 0 + (10.0 \text{ m/s})t + \frac{1}{2}(-9.80 \text{ m/s}^2)t^2$$

$$t = 4.22 \text{ s}$$

$$v_{yf} = v_{yi} + a_y t$$

$$v_{yf} = 10.0 \text{ m/s} + (-9.80 \text{ m/s}^2)(4.22 \text{ s}) = -31.3 \text{ m/s}$$

$$v_f = \sqrt{v_{xf}^2 + v_{yf}^2} = \sqrt{(17.3 \text{ m/s})^2 + (-31.3 \text{ m/s})^2} = 35.8 \text{ m/s}$$

EXAMPLE 4.5 The End of the Ski Jump

A ski jumper leaves the ski track moving in the horizontal direction with a speed of 25.0 m/s as shown in Figure 4.14. The landing incline below her falls off with a slope of 35.0°. Where does she land on the incline?

SOLUTION

Conceptualize We can conceptualize this problem based on memories of observing winter Olympic ski competitions. We estimate the skier to be airborne for perhaps 4 s and to travel a distance of about 100 m horizontally. We

should expect the value of d , the distance traveled along the incline, to be of the same order of magnitude.

Categorize We categorize the problem as one of a particle in projectile motion.

Analyze It is convenient to select the beginning of the jump as the origin. The initial velocity components are $v_{xi} = 25.0$ m/s and $v_{yi} = 0$. From the right triangle in Figure 4.14, we see that the jumper's x and y coordinates at the landing point are given by $x_f = d \cos 35.0^\circ$ and $y_f = -d \sin 35.0^\circ$.

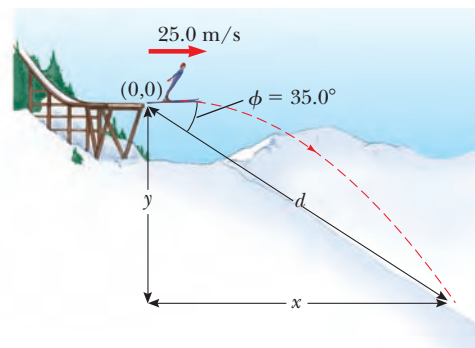


Figure 4.14 (Example 4.5) A ski jumper leaves the track moving in a horizontal direction.

Express the coordinates of the jumper as a function of time:

$$(1) \quad x_f = v_{xi}t = (25.0 \text{ m/s})t$$

$$(2) \quad y_f = v_{yi}t + \frac{1}{2}a_y t^2 = -\frac{1}{2}(9.80 \text{ m/s}^2)t^2$$

Substitute the values of x_f and y_f at the landing point:

$$(3) \quad d \cos 35.0^\circ = (25.0 \text{ m/s})t$$

$$(4) \quad -d \sin 35.0^\circ = -\frac{1}{2}(9.80 \text{ m/s}^2)t^2$$

Solve Equation (3) for t and substitute the result into Equation (4):

$$-d \sin 35.0^\circ = -\frac{1}{2}(9.80 \text{ m/s}^2) \left(\frac{d \cos 35.0^\circ}{25.0 \text{ m/s}} \right)^2$$

Solve for d :

$$d = 109 \text{ m}$$

Evaluate the x and y coordinates of the point at which the skier lands:

$$x_f = d \cos 35.0^\circ = (109 \text{ m}) \cos 35.0^\circ = 89.3 \text{ m}$$

$$y_f = -d \sin 35.0^\circ = -(109 \text{ m}) \sin 35.0^\circ = -62.5 \text{ m}$$

Finalize Let us compare these results with our expectations. We expected the horizontal distance to be on the order of 100 m, and our result of 89.3 m is indeed on this order of magnitude. It might be useful to calculate the time interval that the jumper is in the air and compare it with our estimate of about 4 s.

What If? Suppose everything in this example is the same except the ski jump is curved so that the jumper is projected upward at an angle from the end of the track. Is this design better in terms of maximizing the length of the jump?

Answer If the initial velocity has an upward component, the skier will be in the air longer and should therefore travel further. Tilting the initial velocity vector upward, however, will reduce the horizontal component of the initial velocity. Therefore, angling the end of the ski track upward at a *large* angle may actually *reduce* the distance. Consider the extreme case: the skier is projected at 90° to the horizontal and simply goes up and comes back down at the end of the ski track! This argument suggests that there must be an optimal angle between 0° and 90° that represents a balance between making the flight time longer and the horizontal velocity component smaller.

Let us find this optimal angle mathematically. We modify equations (1) through (4) in the following way,

assuming that the skier is projected at an angle θ with respect to the horizontal over a landing incline sloped with an arbitrary angle ϕ :

$$(1) \text{ and } (3) \quad \rightarrow \quad x_f = (v_i \cos \theta)t = d \cos \phi$$

$$(2) \text{ and } (4) \quad \rightarrow \quad y_f = (v_i \sin \theta)t - \frac{1}{2}gt^2 = -d \sin \phi$$

By eliminating the time t between these equations and using differentiation to maximize d in terms of θ , we arrive (after several steps; see Problem 62) at the following equation for the angle θ that gives the maximum value of d :

$$\theta = 45^\circ - \frac{\phi}{2}$$

For the slope angle in Figure 4.14, $\phi = 35.0^\circ$; this equation results in an optimal launch angle of $\theta = 27.5^\circ$. For a slope angle of $\phi = 0^\circ$, which represents a horizontal plane, this equation gives an optimal launch angle of $\theta = 45^\circ$, as we would expect (see Active Figure 4.10).

PITFALL PREVENTION 4.4**Acceleration of a Particle in Uniform Circular Motion**

Remember that acceleration in physics is defined as a change in the *velocity*, not a change in the *speed* (contrary to the everyday interpretation). In circular motion, the velocity vector is changing in direction, so there is indeed an acceleration.

4.4 The Particle in Uniform Circular Motion

Figure 4.15a shows a car moving in a circular path with *constant speed* v . Such motion, called **uniform circular motion**, occurs in many situations. Because it occurs so often, this type of motion is recognized as an analysis model called the **particle in uniform circular motion**. We discuss this model in this section.

It is often surprising to students to find that **even though an object moves at a constant speed in a circular path, it still has an acceleration**. To see why, consider the defining equation for acceleration, $\vec{a} = d\vec{v}/dt$ (Eq. 4.5). Notice that the acceleration depends on the change in the *velocity*. Because velocity is a vector quantity, an acceleration can occur in two ways, as mentioned in Section 4.1: by a change in the *magnitude* of the velocity and by a change in the *direction* of the velocity. The latter situation occurs for an object moving with constant speed in a circular path. The velocity vector is always tangent to the path of the object and perpendicular to the radius of the circular path.

We now show that the acceleration vector in uniform circular motion is always perpendicular to the path and always points toward the center of the circle. If that were not true, there would be a component of the acceleration parallel to the path and therefore parallel to the velocity vector. Such an acceleration component would lead to a change in the speed of the particle along the path. This situation, however, is inconsistent with our setup of the situation: the particle moves with constant speed along the path. Therefore, for *uniform* circular motion, the acceleration vector can only have a component perpendicular to the path, which is toward the center of the circle.

Let us now find the magnitude of the acceleration of the particle. Consider the diagram of the position and velocity vectors in Figure 4.15b. The figure also shows the vector representing the change in position $\Delta\vec{r}$ for an arbitrary time interval. The particle follows a circular path of radius r , part of which is shown by the dashed curve. The particle is at \textcircled{A} at time t_i , and its velocity at that time is \vec{v}_i ; it is at \textcircled{B} at some later time t_f , and its velocity at that time is \vec{v}_f . Let us also assume \vec{v}_i and \vec{v}_f differ only in direction; their magnitudes are the same (that is, $v_i = v_f = v$ because it is *uniform* circular motion).

In Figure 4.15c, the velocity vectors in Figure 4.15b have been redrawn tail to tail. The vector $\Delta\vec{v}$ connects the tips of the vectors, representing the vector addition $\vec{v}_f = \vec{v}_i + \Delta\vec{v}$. In both Figures 4.15b and 4.15c, we can identify triangles that help us analyze the motion. The angle $\Delta\theta$ between the two position vectors in Figure 4.15b is the same as the angle between the velocity vectors in Figure 4.15c because the velocity vector \vec{v} is always perpendicular to the position vector \vec{r} . Therefore, the two triangles are *similar*. (Two triangles are similar if the angle between any two sides is the same for both triangles and if the ratio of the lengths of these sides is the same.) We can now write a relationship between the lengths of the sides for the two triangles in Figures 4.15b and 4.15c:

$$\frac{|\Delta\vec{v}|}{v} = \frac{|\Delta\vec{r}|}{r}$$

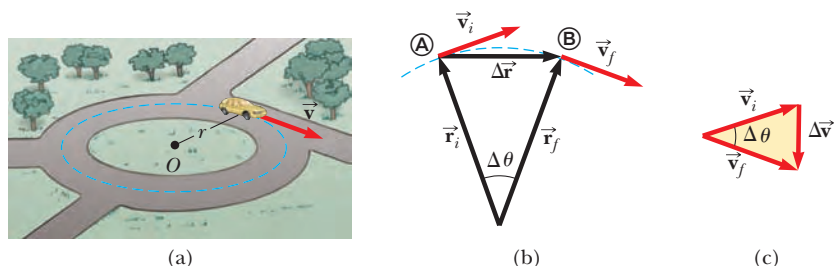


Figure 4.15 (a) A car moving along a circular path at constant speed experiences uniform circular motion. (b) As a particle moves from \textcircled{A} to \textcircled{B} , its velocity vector changes from \vec{v}_i to \vec{v}_f . (c) The construction for determining the direction of the change in velocity $\Delta\vec{v}$, which is toward the center of the circle for small $\Delta\vec{r}$.

where $v = v_i = v_f$ and $r = r_i = r_f$. This equation can be solved for $|\Delta\vec{v}|$, and the expression obtained can be substituted into Equation 4.4, $\vec{a}_{\text{avg}} = \Delta\vec{v}/\Delta t$, to give the magnitude of the average acceleration over the time interval for the particle to move from Ⓐ to Ⓑ:

$$|\vec{a}_{\text{avg}}| = \frac{|\Delta\vec{v}|}{|\Delta t|} = \frac{v}{r} \frac{|\Delta\vec{r}|}{\Delta t}$$

Now imagine that points Ⓐ and Ⓑ in Figure 4.15b become extremely close together. As Ⓐ and Ⓑ approach each other, Δt approaches zero, $|\Delta\vec{r}|$ approaches the distance traveled by the particle along the circular path, and the ratio $|\Delta\vec{r}|/\Delta t$ approaches the speed v . In addition, the average acceleration becomes the instantaneous acceleration at point Ⓐ. Hence, in the limit $\Delta t \rightarrow 0$, the magnitude of the acceleration is

$$a_c = \frac{v^2}{r} \quad (4.14)$$

An acceleration of this nature is called a **centripetal acceleration** (*centripetal* means *center-seeking*). The subscript on the acceleration symbol reminds us that the acceleration is centripetal.

In many situations, it is convenient to describe the motion of a particle moving with constant speed in a circle of radius r in terms of the **period** T , which is defined as the time interval required for one complete revolution of the particle. In the time interval T , the particle moves a distance of $2\pi r$, which is equal to the circumference of the particle's circular path. Therefore, because its speed is equal to the circumference of the circular path divided by the period, or $v = 2\pi r/T$, it follows that

$$T = \frac{2\pi r}{v} \quad (4.15)$$

Quick Quiz 4.4 A particle moves in a circular path of radius r with speed v . It then increases its speed to $2v$ while traveling along the same circular path. (i) The centripetal acceleration of the particle has changed by what factor (choose one)? (a) 0.25 (b) 0.5 (c) 2 (d) 4 (e) impossible to determine (ii) From the same choices, by what factor has the period of the particle changed?

EXAMPLE 4.6 The Centripetal Acceleration of the Earth

What is the centripetal acceleration of the Earth as it moves in its orbit around the Sun?

SOLUTION

Conceptualize Think about a mental image of the Earth in a circular orbit around the Sun. We will model the Earth as a particle and approximate the Earth's orbit as circular (it's actually slightly elliptical, as we discuss in Chapter 13).

Categorize The Conceptualize step allows us to categorize this problem as one of a particle in uniform circular motion.

Analyze We do not know the orbital speed of the Earth to substitute into Equation 4.14. With the help of Equation 4.15, however, we can recast Equation 4.14 in terms of the period of the Earth's orbit, which we know is one year, and the radius of the Earth's orbit around the Sun, which is 1.496×10^{11} m.

Combine Equations 4.14 and 4.15:

$$a_c = \frac{v^2}{r} = \frac{\left(\frac{2\pi r}{T}\right)^2}{r} = \frac{4\pi^2 r}{T^2}$$

Substitute numerical values:

$$a_c = \frac{4\pi^2(1.496 \times 10^{11} \text{ m})}{(1 \text{ yr})^2} \left(\frac{1 \text{ yr}}{3.156 \times 10^7 \text{ s}}\right)^2 = 5.93 \times 10^{-3} \text{ m/s}^2$$

Finalize This acceleration is much smaller than the free-fall acceleration on the surface of the Earth. An important thing we learned here is the technique of replacing the speed v in Equation 4.14 in terms of the period T of the motion.

PITFALL PREVENTION 4.5

Centripetal Acceleration Is Not Constant

We derived the magnitude of the centripetal acceleration vector and found it to be constant for uniform circular motion, but *the centripetal acceleration vector is not constant*. It always points toward the center of the circle, but it continuously changes direction as the object moves around the circular path.

◀ Centripetal acceleration

◀ Period of circular motion

4.5 Tangential and Radial Acceleration

Let us consider the motion of a particle along a smooth, curved path where the velocity changes both in direction and in magnitude as described in Active Figure 4.16. In this situation, the velocity vector is always tangent to the path; the acceleration vector \vec{a} , however, is at some angle to the path. At each of three points (A), (B), and (C) in Active Figure 4.16, we draw dashed circles that represent the curvature of the actual path at each point. The radius of the circles is equal to the path's radius of curvature at each point.

As the particle moves along the curved path in Active Figure 4.16, the direction of the total acceleration vector \vec{a} changes from point to point. At any instant, this vector can be resolved into two components based on an origin at the center of the dashed circle corresponding to that instant: a radial component a_r along the radius of the circle and a tangential component a_t perpendicular to this radius. The total acceleration vector \vec{a} can be written as the vector sum of the component vectors:

Total acceleration ►
$$\vec{a} = \vec{a}_r + \vec{a}_t \quad (4.16)$$

The tangential acceleration component causes a change in the speed v of the particle. This component is parallel to the instantaneous velocity, and its magnitude is given by

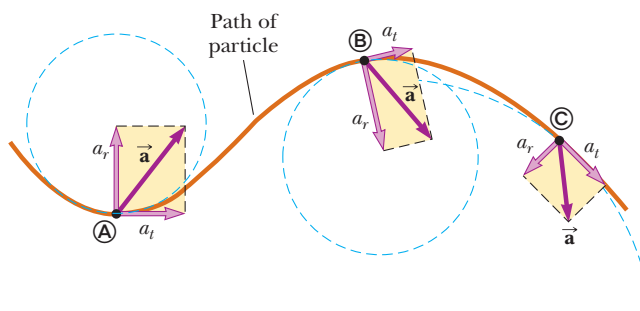
Tangential acceleration ►
$$a_t = \left| \frac{dv}{dt} \right| \quad (4.17)$$

The radial acceleration component arises from a change in direction of the velocity vector and is given by

Radial acceleration ►
$$a_r = -a_c = -\frac{v^2}{r} \quad (4.18)$$

where r is the radius of curvature of the path at the point in question. We recognize the radial component of the acceleration as the centripetal acceleration discussed in Section 4.4. The negative sign in Equation 4.18 indicates that the direction of the centripetal acceleration is toward the center of the circle representing the radius of curvature. The direction is opposite that of the radial unit vector \hat{r} , which always points away from the origin at the center of the circle.

Because \vec{a}_r and \vec{a}_t are perpendicular component vectors of \vec{a} , it follows that the magnitude of \vec{a} is $a = \sqrt{a_r^2 + a_t^2}$. At a given speed, a_r is large when the radius of curvature is small (as at points (A) and (B) in Fig. 4.16) and small when r is large (as at point (C)). The direction of \vec{a}_t is either in the same direction as \vec{v} (if v is increasing) or opposite \vec{v} (if v is decreasing).



ACTIVE FIGURE 4.16

The motion of a particle along an arbitrary curved path lying in the xy plane. If the velocity vector \vec{v} (always tangent to the path) changes in direction and magnitude, the components of the acceleration \vec{a} are a tangential component a_t and a radial component a_r .

Sign in at www.thomsonedu.com and go to ThomsonNOW to study the acceleration components of a roller-coaster car.

In uniform circular motion, where v is constant, $a_t = 0$ and the acceleration is always completely radial as described in Section 4.4. In other words, uniform circular motion is a special case of motion along a general curved path. Furthermore, if the direction of \vec{v} does not change, there is no radial acceleration and the motion is one dimensional (in this case, $a_r = 0$, but a_t may not be zero).

Quick Quiz 4.5 A particle moves along a path and its speed increases with time. (i) In which of the following cases are its acceleration and velocity vectors parallel? (a) when the path is circular (b) when the path is straight (c) when the path is a parabola (d) never (ii) From the same choices, in which case are its acceleration and velocity vectors perpendicular everywhere along the path?

EXAMPLE 4.7 Over the Rise

A car exhibits a constant acceleration of 0.300 m/s^2 parallel to the roadway. The car passes over a rise in the roadway such that the top of the rise is shaped like a circle of radius 500 m . At the moment the car is at the top of the rise, its velocity vector is horizontal and has a magnitude of 6.00 m/s . What are the magnitude and direction of the total acceleration vector for the car at this instant?

SOLUTION

Conceptualize Conceptualize the situation using Figure 4.17a and any experiences you have had in driving over rises on a roadway.

Categorize Because the accelerating car is moving along a curved path, we categorize this problem as one involving a particle experiencing both tangential and radial acceleration. We recognize that it is a relatively simple substitution problem.

The radial acceleration is given by Equation 4.18, with $v = 6.00 \text{ m/s}$ and $r = 500 \text{ m}$. The radial acceleration vector is directed straight downward, and the tangential acceleration vector has magnitude 0.300 m/s^2 and is horizontal.

Evaluate the radial acceleration:

$$a_r = -\frac{v^2}{r} = -\frac{(6.00 \text{ m/s})^2}{500 \text{ m}} = -0.0720 \text{ m/s}^2$$

Find the magnitude of \vec{a} :

$$\begin{aligned} \sqrt{a_r^2 + a_t^2} &= \sqrt{(-0.0720 \text{ m/s}^2)^2 + (0.300 \text{ m/s}^2)^2} \\ &= 0.309 \text{ m/s}^2 \end{aligned}$$

Find the angle ϕ (see Fig. 4.17b) between \vec{a} and the horizontal:

$$\phi = \tan^{-1} \frac{a_r}{a_t} = \tan^{-1} \left(\frac{-0.0720 \text{ m/s}^2}{0.300 \text{ m/s}^2} \right) = -13.5^\circ$$

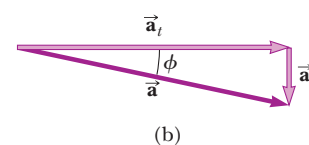
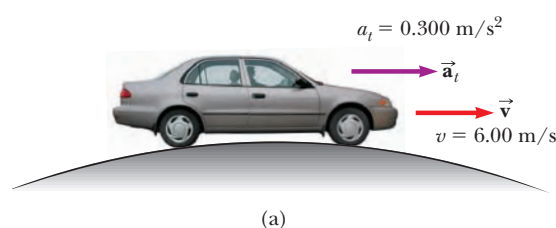


Figure 4.17 (Example 4.7) (a) A car passes over a rise that is shaped like a circle. (b) The total acceleration vector \vec{a} is the sum of the tangential and radial acceleration vectors \vec{a}_t and \vec{a}_r .

4.6 Relative Velocity and Relative Acceleration

In this section, we describe how observations made by different observers in different frames of reference are related to one another. A frame of reference can be described by a Cartesian coordinate system for which an observer is at rest with respect to the origin.

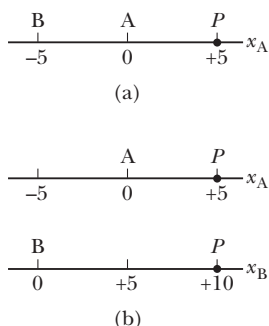


Figure 4.18 Different observers make different measurements. (a) Observer A is located at the origin, and Observer B is at a position of -5 . Both observers measure the position of a particle at P . (b) If both observers see themselves at the origin of their own coordinate system, they disagree on the value of the position of the particle at P .

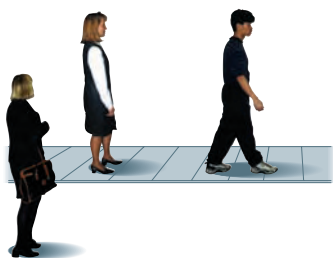


Figure 4.19 Two observers measure the speed of a man walking on a moving beltway. The woman standing on the beltway sees the man moving with a slower speed than does the woman observing from the stationary floor.

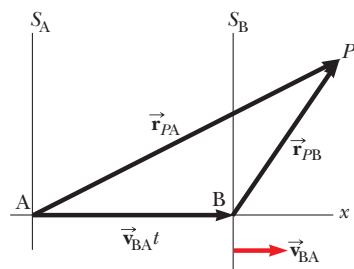


Figure 4.20 A particle located at P is described by two observers, one in the fixed frame of reference S_A and the other in the frame S_B , which moves to the right with a constant velocity \vec{v}_{BA} . The vector \vec{r}_{PA} is the particle's position vector relative to S_A , and \vec{r}_{PB} is its position vector relative to S_B .

Galilean velocity transformation ▶

Let us conceptualize a sample situation in which there will be different observations for different observers. Consider the two observers A and B along the number line in Figure 4.18a. Observer A is located at the origin of a one-dimensional x_A axis, while observer B is at the position $x_A = -5$. We denote the position variable as x_A because observer A is at the origin of this axis. Both observers measure the position of point P , which is located at $x_A = +5$. Suppose observer B decides that he is located at the origin of an x_B axis as in Figure 4.18b. Notice that the two observers disagree on the value of the position of point P . Observer A claims point P is located at a position with a value of $+5$, whereas observer B claims it is located at a position with a value of $+10$. Both observers are correct, even though they make different measurements. Their measurements differ because they are making the measurement from different frames of reference.

Imagine now that observer B in Figure 4.18b is moving to the right along the x_B axis. Now the two measurements are even more different. Observer A claims point P remains at rest at a position with a value of $+5$, whereas observer B claims the position of P continuously changes with time, even passing him and moving behind him! Again, both observers are correct, with the difference in their measurements arising from their different frames of reference.

We explore this phenomenon further by considering two observers watching a man walking on a moving beltway at an airport in Figure 4.19. The woman standing on the moving beltway sees the man moving at a normal walking speed. The woman observing from the stationary floor sees the man moving with a higher speed because the beltway speed combines with his walking speed. Both observers look at the same man and arrive at different values for his speed. Both are correct; the difference in their measurements results from the relative velocity of their frames of reference.

In a more general situation, consider a particle located at point P in Figure 4.20. Imagine that the motion of this particle is being described by two observers, observer A in a reference frame S_A fixed relative to Earth and a second observer B in a reference frame S_B moving to the right relative to S_A (and therefore relative to Earth) with a constant velocity \vec{v}_{BA} . In this discussion of relative velocity, we use a double-subscript notation; the first subscript represents what is being observed, and the second represents who is doing the observing. Therefore, the notation \vec{v}_{BA} means the velocity of observer B (and the attached frame S_B) as measured by observer A. With this notation, observer B measures A to be moving to the left with a velocity $\vec{v}_{AB} = -\vec{v}_{BA}$. For purposes of this discussion, let us place each observer at her or his respective origin.

We define the time $t = 0$ as the instant at which the origins of the two reference frames coincide in space. Therefore, at time t , the origins of the reference frames will be separated by a distance $v_{BA}t$. We label the position P of the particle relative to observer A with the position vector \vec{r}_{PA} and that relative to observer B with the position vector \vec{r}_{PB} , both at time t . From Figure 4.20, we see that the vectors \vec{r}_{PA} and \vec{r}_{PB} are related to each other through the expression

$$\vec{r}_{PA} = \vec{r}_{PB} + \vec{v}_{BA}t \tag{4.19}$$

By differentiating Equation 4.19 with respect to time, noting that \vec{v}_{BA} is constant, we obtain

$$\begin{aligned} \frac{d\vec{r}_{PA}}{dt} &= \frac{d\vec{r}_{PB}}{dt} + \vec{v}_{BA} \\ \vec{u}_{PA} &= \vec{u}_{PB} + \vec{v}_{BA} \end{aligned} \tag{4.20}$$

where \vec{u}_{PA} is the velocity of the particle at P measured by observer A and \vec{u}_{PB} is its velocity measured by B. (We use the symbol \vec{u} for particle velocity rather than \vec{v} , which is used for the relative velocity of two reference frames.) Equations 4.19 and 4.20 are known as **Galilean transformation equations**. They relate the position and

velocity of a particle as measured by observers in relative motion. Notice the pattern of the subscripts in Equation 4.20. When relative velocities are added, the inner subscripts (B) are the same and the outer ones (P, A) match the subscripts on the velocity on the left of the equation.

Although observers in two frames measure different velocities for the particle, they measure the *same acceleration* when \vec{v}_{BA} is constant. We can verify that by taking the time derivative of Equation 4.20:

$$\frac{d\vec{u}_{PA}}{dt} = \frac{d\vec{u}_{PB}}{dt} + \frac{d\vec{v}_{BA}}{dt}$$

Because \vec{v}_{BA} is constant, $d\vec{v}_{BA}/dt = 0$. Therefore, we conclude that $\vec{a}_{PA} = \vec{a}_{PB}$ because $\vec{a}_{PA} = d\vec{u}_{PA}/dt$ and $\vec{a}_{PB} = d\vec{u}_{PB}/dt$. That is, **the acceleration of the particle measured by an observer in one frame of reference is the same as that measured by any other observer moving with constant velocity relative to the first frame.**

EXAMPLE 4.8 A Boat Crossing a River

A boat crossing a wide river moves with a speed of 10.0 km/h relative to the water. The water in the river has a uniform speed of 5.00 km/h due east relative to the Earth.

(A) If the boat heads due north, determine the velocity of the boat relative to an observer standing on either bank.

SOLUTION

Conceptualize Imagine moving across a river while the current pushes you down the river. You will not be able to move directly across the river, but will end up downstream as suggested in Figure 4.21a.

Categorize Because of the separate velocities of you and the river, we can categorize this problem as one involving relative velocities.

Analyze We know \vec{v}_{br} , the velocity of the *boat* relative to the *river*, and \vec{v}_{rE} , the velocity of the *river* relative to the *Earth*. What we must find is \vec{v}_{bE} , the velocity of the *boat* relative to the *Earth*. The relationship between these three quantities is $\vec{v}_{bE} = \vec{v}_{br} + \vec{v}_{rE}$. The terms in the equation must be manipulated as vector quantities; the vectors are shown in Figure 4.21a. The quantity \vec{v}_{br} is due north; \vec{v}_{rE} is due east; and the vector sum of the two, \vec{v}_{bE} , is at an angle θ as defined in Figure 4.21a.

Find the speed v_{bE} of the boat relative to the Earth using the Pythagorean theorem:

$$\begin{aligned} v_{bE} &= \sqrt{v_{br}^2 + v_{rE}^2} = \sqrt{(10.0 \text{ km/h})^2 + (5.00 \text{ km/h})^2} \\ &= 11.2 \text{ km/h} \end{aligned}$$

Find the direction of \vec{v}_{bE} :

$$\theta = \tan^{-1}\left(\frac{v_{rE}}{v_{br}}\right) = \tan^{-1}\left(\frac{5.00}{10.0}\right) = 26.6^\circ$$

Finalize The boat is moving at a speed of 11.2 km/h in the direction 26.6° east of north relative to the Earth. Notice that the speed of 11.2 km/h is faster than your boat speed of 10.0 km/h. The current velocity adds to yours to give you a larger speed. Notice in Figure 4.21a that your resultant velocity is at an angle to the direction straight across the river, so you will end up downstream, as we predicted.

(B) If the boat travels with the same speed of 10.0 km/h relative to the river and is to travel due north as shown in Figure 4.21b, what should its heading be?

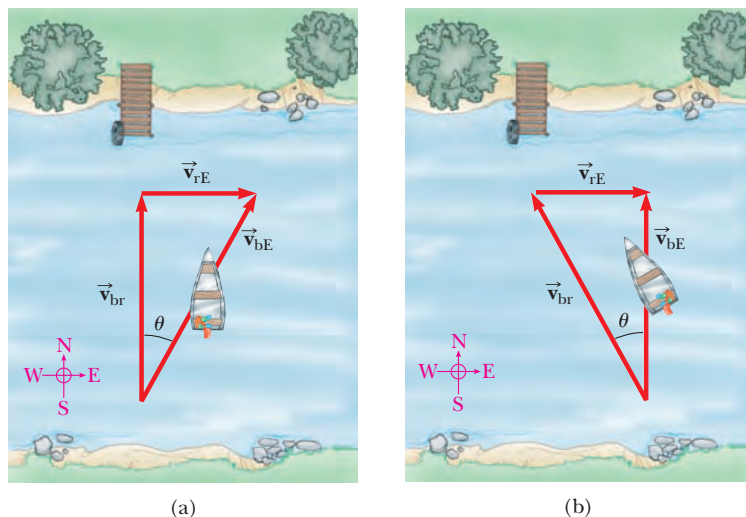


Figure 4.21 (Example 4.8) (a) A boat aims directly across a river and ends up downstream. (b) To move directly across the river, the boat must aim upstream.

SOLUTION

Conceptualize/Categorize This question is an extension of part (A), so we have already conceptualized and categorized the problem. One new feature of the conceptualization is that we must now aim the boat upstream so as to go straight across the river.

Analyze The analysis now involves the new triangle shown in Figure 4.21b. As in part (A), we know \vec{v}_{rE} and the magnitude of the vector \vec{v}_{br} , and we want \vec{v}_{bE} to be directed across the river. Notice the difference between the triangle in Figure 4.21a and the one in Figure 4.21b: the hypotenuse in Figure 4.21b is no longer \vec{v}_{bE} .

Use the Pythagorean theorem to find v_{bE} :
$$v_{bE} = \sqrt{v_{br}^2 - v_{rE}^2} = \sqrt{(10.0 \text{ km/h})^2 - (5.00 \text{ km/h})^2} = 8.66 \text{ km/h}$$

Find the direction in which the boat is heading:
$$\theta = \tan^{-1}\left(\frac{v_{rE}}{v_{bE}}\right) = \tan^{-1}\left(\frac{5.00}{8.66}\right) = 30.0^\circ$$

Finalize The boat must head upstream so as to travel directly northward across the river. For the given situation, the boat must steer a course 30.0° west of north. For faster currents, the boat must be aimed upstream at larger angles.

What If? Imagine that the two boats in parts (A) and (B) are racing across the river. Which boat arrives at the opposite bank first?

Answer In part (A), the velocity of 10 km/h is aimed directly across the river. In part (B), the velocity that is directed across the river has a magnitude of only 8.66 km/h. Therefore, the boat in part (A) has a larger velocity component directly across the river and arrives first.

Summary

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DEFINITIONS

The **displacement vector** $\Delta\vec{r}$ for a particle is the difference between its final position vector and its initial position vector:

$$\Delta\vec{r} \equiv \vec{r}_f - \vec{r}_i \quad (4.1)$$

The **average velocity** of a particle during the time interval Δt is defined as the displacement of the particle divided by the time interval:

$$\vec{v}_{\text{avg}} \equiv \frac{\Delta\vec{r}}{\Delta t} \quad (4.2)$$

The **instantaneous velocity** of a particle is defined as the limit of the average velocity as Δt approaches zero:

$$\vec{v} \equiv \lim_{\Delta t \rightarrow 0} \frac{\Delta\vec{r}}{\Delta t} = \frac{d\vec{r}}{dt} \quad (4.3)$$

The **average acceleration** of a particle is defined as the change in its instantaneous velocity vector divided by the time interval Δt during which that change occurs:

$$\vec{a}_{\text{avg}} \equiv \frac{\vec{v}_f - \vec{v}_i}{t_f - t_i} = \frac{\Delta\vec{v}}{\Delta t} \quad (4.4)$$

The **instantaneous acceleration** of a particle is defined as the limiting value of the average acceleration as Δt approaches zero:

$$\vec{a} \equiv \lim_{\Delta t \rightarrow 0} \frac{\Delta\vec{v}}{\Delta t} = \frac{d\vec{v}}{dt} \quad (4.5)$$

Projectile motion is one type of two-dimensional motion under constant acceleration, where $a_x = 0$ and $a_y = -g$.

A particle moving in a circle of radius r with constant speed v is in **uniform circular motion**. For such a particle, the **period** of its motion is

$$T = \frac{2\pi r}{v} \quad (4.15)$$

CONCEPTS AND PRINCIPLES

If a particle moves with *constant* acceleration \vec{a} and has velocity \vec{v}_i and position \vec{r}_i at $t = 0$, its velocity and position vectors at some later time t are

$$\vec{v}_f = \vec{v}_i + \vec{a}t \tag{4.8}$$

$$\vec{r}_f = \vec{r}_i + \vec{v}_i t + \frac{1}{2}\vec{a}t^2 \tag{4.9}$$

For two-dimensional motion in the xy plane under constant acceleration, each of these vector expressions is equivalent to two component expressions: one for the motion in the x direction and one for the motion in the y direction.

It is useful to think of projectile motion in terms of a combination of two analysis models: (1) the particle under constant velocity model in the x direction and (2) the particle under constant acceleration model in the vertical direction with a constant downward acceleration of magnitude $g = 9.80 \text{ m/s}^2$.

A particle in uniform circular motion undergoes a radial acceleration \vec{a} , because the direction of \vec{v} changes in time. This acceleration is called **centripetal acceleration**, and its direction is always toward the center of the circle.

If a particle moves along a curved path in such a way that both the magnitude and the direction of \vec{v} change in time, the particle has an acceleration vector that can be described by two component vectors: (1) a radial component vector \vec{a}_r that causes the change in direction of \vec{v} and (2) a tangential component vector \vec{a}_t that causes the change in magnitude of \vec{v} . The magnitude of \vec{a}_r is v^2/r , and the magnitude of \vec{a}_t is $|dv/dt|$.

The velocity \vec{u}_{PA} of a particle measured in a fixed frame of reference S_A can be related to the velocity \vec{u}_{PB} of the same particle measured in a moving frame of reference S_B by

$$\vec{u}_{PA} = \vec{u}_{PB} + \vec{v}_{BA} \tag{4.20}$$

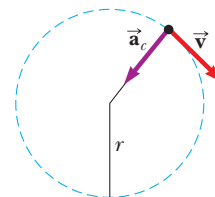
where \vec{v}_{BA} is the velocity of S_B relative to S_A .

ANALYSIS MODEL FOR PROBLEM SOLVING

Particle in Uniform Circular Motion If a particle moves in a circular path of radius r with a constant speed v , the magnitude of its centripetal acceleration is given by

$$a_c = \frac{v^2}{r} \tag{4.14}$$

and the period of the particle's motion is given by Equation 4.15.



Questions

denotes answer available in *Student Solutions Manual/Study Guide*; **O** denotes objective question

1. **O** Figure Q4.1 shows a bird's-eye view of a car going around a highway curve. As the car moves from point 1 to point 2, its speed doubles. Which vector (a) through (g) shows the direction of the car's average acceleration between these two points?
2. If you know the position vectors of a particle at two points along its path and also know the time interval during which it moved from one point to the other, can you determine the particle's instantaneous velocity? Its average velocity? Explain.
3. Construct motion diagrams showing the velocity and acceleration of a projectile at several points along its path, assuming (a) the projectile is launched horizontally

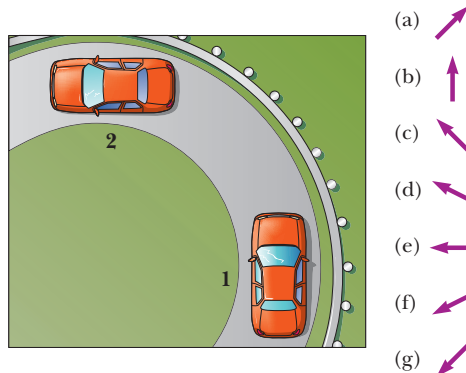


Figure Q4.1

and (b) the projectile is launched at an angle θ with the horizontal.

4. **O** Entering his dorm room, a student tosses his book bag to the right and upward at an angle of 45° with the horizontal. Air resistance does not affect the bag. It moves through point **A** immediately after it leaves his hand, through point **B** at the top of its flight, and through point **C** immediately before it lands on his top bunk bed. **(i)** Rank the following horizontal and vertical velocity components from the largest to the smallest. Note that zero is larger than a negative number. If two quantities are equal, show them as equal in your list. If any quantity is equal to zero, show that fact in your list. (a) $v_{\text{A}x}$ (b) $v_{\text{A}y}$ (c) $v_{\text{B}x}$ (d) $v_{\text{B}y}$ (e) $v_{\text{C}x}$ (f) $v_{\text{C}y}$ **(ii)** Similarly, rank the following acceleration components. (a) $a_{\text{A}x}$ (b) $a_{\text{A}y}$ (c) $a_{\text{B}x}$ (d) $a_{\text{B}y}$ (e) $a_{\text{C}x}$ (f) $a_{\text{C}y}$
5. A spacecraft drifts through space at a constant velocity. Suddenly a gas leak in the side of the spacecraft gives it a constant acceleration in a direction perpendicular to the initial velocity. The orientation of the spacecraft does not change, so the acceleration remains perpendicular to the original direction of the velocity. What is the shape of the path followed by the spacecraft in this situation?
6. **O** In which of the following situations is the moving object appropriately modeled as a projectile? Choose all correct answers. (a) A shoe is tossed in an arbitrary direction. (b) A jet airplane crosses the sky with its engines thrusting the plane forward. (c) A rocket leaves the launch pad. (d) A rocket moves through the sky, at much less than the speed of sound, after its fuel has been used up. (e) A diver throws a stone under water.
7. A projectile is launched at some angle to the horizontal with some initial speed v_i , and air resistance is negligible. Is the projectile a freely falling body? What is its acceleration in the vertical direction? What is its acceleration in the horizontal direction?
8. **O** State which of the following quantities, if any, remain constant as a projectile moves through its parabolic trajectory: (a) speed (b) acceleration (c) horizontal component of velocity (d) vertical component of velocity
9. **O** A projectile is launched on the Earth with a certain initial velocity and moves without air resistance. Another projectile is launched with the same initial velocity on the Moon, where the acceleration due to gravity is $1/6$ as large. **(i)** How does the range of the projectile on the Moon compare with that of the projectile on the Earth? (a) $1/6$ as large (b) the same (c) $\sqrt{6}$ times larger (d) 6 times larger (e) 36 times larger **(ii)** How does the maximum altitude of the projectile on the Moon compare with that of the projectile on the Earth? Choose from the same possibilities (a) through (e).
10. Explain whether or not the following particles have an acceleration: (a) a particle moving in a straight line with constant speed and (b) a particle moving around a curve with constant speed.
11. Describe how a driver can steer a car traveling at constant speed so that (a) the acceleration is zero or (b) the magnitude of the acceleration remains constant.
12. **O** A rubber stopper on the end of a string is swung steadily in a horizontal circle. In one trial, it moves at speed v in a circle of radius r . In a second trial, it moves at a higher speed $3v$ in a circle of radius $3r$. **(i)** In this second trial, its acceleration is (choose one) (a) the same as in the first trial (b) three times larger (c) one-third as large (d) nine times larger (e) one-ninth as large **(ii)** In the second trial, how does its period compare with its period in the first trial? Choose your answers from the same possibilities (a) through (e).
13. An ice skater is executing a figure eight, consisting of two equal, tangent circular paths. Throughout the first loop she increases her speed uniformly, and during the second loop she moves at a constant speed. Draw a motion diagram showing her velocity and acceleration vectors at several points along the path of motion.
14. **O** A certain light truck can go around a curve having a radius of 150 m with a maximum speed of 32.0 m/s. To have the same acceleration, at what maximum speed can it go around a curve having a radius of 75.0 m? (a) 64 m/s (b) 45 m/s (c) 32 m/s (d) 23 m/s (e) 16 m/s (f) 8 m/s
15. **O** Galileo suggested the idea for this question: A sailor drops a wrench from the top of a sailboat's vertical mast while the boat is moving rapidly and steadily straight forward. Where will the wrench hit the deck? (a) ahead of the base of the mast (b) at the base of the mast (c) behind the base of the mast (d) on the windward side of the base of the mast
16. **O** A girl, moving at 8 m/s on rollerblades, is overtaking a boy moving at 5 m/s as they both skate on a straight path. The boy tosses a ball backward toward the girl, giving it speed 12 m/s relative to him. What is the speed of the ball relative to the girl, who catches it? (a) $(8 + 5 + 12)$ m/s (b) $(8 - 5 - 12)$ m/s (c) $(8 + 5 - 12)$ m/s (d) $(8 - 5 + 12)$ m/s (e) $(-8 + 5 + 12)$ m/s

Problems

WebAssign The Problems from this chapter may be assigned online in WebAssign.

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1, 2, 3 denotes straightforward, intermediate, challenging; \square denotes full solution available in *Student Solutions Manual/Study Guide*; \blacktriangle denotes coached solution with hints available at www.thomsonedu.com; \blacksquare denotes developing symbolic reasoning; \bullet denotes asking for qualitative reasoning; \blacksquare denotes computer useful in solving problem

Section 4.1 The Position, Velocity, and Acceleration Vectors

1. ▲ A motorist drives south at 20.0 m/s for 3.00 min, then turns west and travels at 25.0 m/s for 2.00 min, and finally travels northwest at 30.0 m/s for 1.00 min. For this 6.00-min trip, find (a) the total vector displacement, (b) the average speed, and (c) the average velocity. Let the positive x axis point east.
2. A golf ball is hit off a tee at the edge of a cliff. Its x and y coordinates as functions of time are given by the following expressions:

$$x = (18.0 \text{ m/s})t$$

$$y = (4.00 \text{ m/s})t - (4.90 \text{ m/s}^2)t^2$$

- (a) Write a vector expression for the ball's position as a function of time, using the unit vectors \hat{i} and \hat{j} . By taking derivatives, obtain expressions for (b) the velocity vector \vec{v} as a function of time and (c) the acceleration vector \vec{a} as a function of time. Next use unit-vector notation to write expressions for (d) the position, (e) the velocity, and (f) the acceleration of the golf ball, all at $t = 3.00$ s.
3. When the Sun is directly overhead, a hawk dives toward the ground with a constant velocity of 5.00 m/s at 60.0° below the horizontal. Calculate the speed of its shadow on the level ground.
4. ● The coordinates of an object moving in the xy plane vary with time according to $x = -(5.00 \text{ m}) \sin(\omega t)$ and $y = (4.00 \text{ m}) - (5.00 \text{ m})\cos(\omega t)$, where ω is a constant and t is in seconds. (a) Determine the components of velocity and components of acceleration of the object at $t = 0$. (b) Write expressions for the position vector, the velocity vector, and the acceleration vector of the object at any time $t > 0$. (c) Describe the path of the object in an xy plot.

Section 4.2 Two-Dimensional Motion with Constant Acceleration

5. A fish swimming in a horizontal plane has velocity $\vec{v}_i = (4.00\hat{i} + 1.00\hat{j}) \text{ m/s}$ at a point in the ocean where the position relative to a certain rock is $\vec{r}_i = (10.0\hat{i} - 4.00\hat{j}) \text{ m}$. After the fish swims with constant acceleration for 20.0 s, its velocity is $\vec{v} = (20.0\hat{i} - 5.00\hat{j}) \text{ m/s}$. (a) What are the components of the acceleration? (b) What is the direction of the acceleration with respect to unit vector \hat{i} ? (c) If the fish maintains constant acceleration, where is it at $t = 25.0$ s, and in what direction is it moving?
6. The vector position of a particle varies in time according to the expression $\vec{r} = (3.00\hat{i} - 6.00t^2\hat{j}) \text{ m}$. (a) Find expressions for the velocity and acceleration of the particle as functions of time. (b) Determine the particle's position and velocity at $t = 1.00$ s.
7. What if the acceleration is not constant? A particle starts from the origin with velocity $5\hat{i} \text{ m/s}$ at $t = 0$ and moves in the xy plane with a varying acceleration given by $\vec{a} = (6\sqrt{t}\hat{j}) \text{ m/s}^2$, where t is in s. (a) Determine the vector velocity of the particle as a function of time. (b) Determine the position of the particle as a function of time.
8. A particle initially located at the origin has an acceleration of $\vec{a} = 3.00\hat{j} \text{ m/s}^2$ and an initial velocity of $\vec{v}_i = 5.00\hat{i} \text{ m/s}$.

Find (a) the vector position and velocity of the particle at any time t and (b) the coordinates and speed of the particle at $t = 2.00$ s.

Section 4.3 Projectile Motion

Note: Ignore air resistance in all problems. Take $g = 9.80 \text{ m/s}^2$ at the Earth's surface.

9. ▲ In a local bar, a customer slides an empty beer mug down the counter for a refill. The bartender is momentarily distracted and does not see the mug, which slides off the counter and strikes the floor 1.40 m from the base of the counter. If the height of the counter is 0.860 m, (a) with what velocity did the mug leave the counter? (b) What was the direction of the mug's velocity just before it hit the floor?
10. In a local bar, a customer slides an empty beer mug down the counter for a refill. The bartender is just deciding to go home and rethink his life, so he does not see the mug. It slides off the counter and strikes the floor at distance d from the base of the counter. The height of the counter is h . (a) With what velocity did the mug leave the counter? (b) What was the direction of the mug's velocity just before it hit the floor?
11. To start an avalanche on a mountain slope, an artillery shell is fired with an initial velocity of 300 m/s at 55.0° above the horizontal. It explodes on the mountainside 42.0 s after firing. What are the x and y coordinates of the shell where it explodes, relative to its firing point?
12. ● A rock is thrown upward from the level ground in such a way that the maximum height of its flight is equal to its horizontal range d . (a) At what angle θ is the rock thrown? (b) **What If?** Would your answer to part (a) be different on a different planet? Explain. (c) What is the range d_{max} the rock can attain if it is launched at the same speed but at the optimal angle for maximum range?
13. A projectile is fired in such a way that its horizontal range is equal to three times its maximum height. What is the angle of projection?
14. A firefighter, a distance d from a burning building, directs a stream of water from a fire hose at angle θ_i above the horizontal as shown in Figure P4.14. If the initial speed of the stream is v_i , at what height h does the water strike the building?

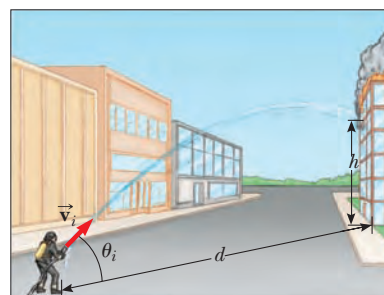


Figure P4.14

15. A ball is tossed from an upper-story window of a building. The ball is given an initial velocity of 8.00 m/s at an angle of 20.0° below the horizontal. It strikes the ground 3.00 s later. (a) How far horizontally from the base of the

building does the ball strike the ground? (b) Find the height from which the ball was thrown. (c) How long does it take the ball to reach a point 10.0 m below the level of launching?

16. A landscape architect is planning an artificial waterfall in a city park. Water flowing at 1.70 m/s will leave the end of a horizontal channel at the top of a vertical wall 2.35 m high, and from there the water falls into a pool. (a) Will the space behind the waterfall be wide enough for a pedestrian walkway? (b) To sell her plan to the city council, the architect wants to build a model to standard scale, one-twelfth actual size. How fast should the water flow in the channel in the model?
17. **▲** A placekicker must kick a football from a point 36.0 m (about 40 yards) from the goal, and half the crowd hopes the ball will clear the crossbar, which is 3.05 m high. When kicked, the ball leaves the ground with a speed of 20.0 m/s at an angle of 53.0° to the horizontal. (a) By how much does the ball clear or fall short of clearing the crossbar? (b) Does the ball approach the crossbar while still rising or while falling?
18. A dive-bomber has a velocity of 280 m/s at an angle θ below the horizontal. When the altitude of the aircraft is 2.15 km, it releases a bomb, which subsequently hits a target on the ground. The magnitude of the displacement from the point of release of the bomb to the target is 3.25 km. Find the angle θ .
19. A playground is on the flat roof of a city school, 6.00 m above the street below. The vertical wall of the building is 7.00 m high, forming a 1 m-high railing around the playground. A ball has fallen to the street below, and a passerby returns it by launching it at an angle of 53.0° above the horizontal at a point 24.0 m from the base of the building wall. The ball takes 2.20 s to reach a point vertically above the wall. (a) Find the speed at which the ball was launched. (b) Find the vertical distance by which the ball clears the wall. (c) Find the distance from the wall to the point on the roof where the ball lands.
20. A basketball star covers 2.80 m horizontally in a jump to dunk the ball (Fig. P4.20a). His motion through space can be modeled precisely as that of a particle at his *center of mass*, which we will define in Chapter 9. His center of mass is at elevation 1.02 m when he leaves the floor. It reaches a maximum height of 1.85 m above the floor and is at elevation 0.900 m when he touches down again. Determine (a) his time of flight (his “hang time”), (b) his horizontal and (c) vertical velocity components at the instant of takeoff, and (d) his takeoff angle. (e) For comparison, determine the hang time of a whitetail deer making



Figure P4.20

ing a jump (Fig. P4.20b) with center-of-mass elevations $y_i = 1.20$ m, $y_{\max} = 2.50$ m, and $y_f = 0.700$ m.

21. A soccer player kicks a rock horizontally off a 40.0-m-high cliff into a pool of water. If the player hears the sound of the splash 3.00 s later, what was the initial speed given to the rock? Assume the speed of sound in air is 343 m/s.
22. **●** The motion of a human body through space can be modeled as the motion of a particle at the body’s center of mass, as we will study in Chapter 9. The components of the position of an athlete’s center of mass from the beginning to the end of a certain jump are described by the two equations

$$x_f = 0 + (11.2 \text{ m/s})(\cos 18.5^\circ)t$$

$$0.360 \text{ m} = 0.840 \text{ m} + (11.2 \text{ m/s})(\sin 18.5^\circ)t - \frac{1}{2}(9.80 \text{ m/s}^2)t^2$$

where t is the time at which the athlete lands after taking off at $t = 0$. Identify (a) his vector position and (b) his vector velocity at the takeoff point. (c) The world long-jump record is 8.95 m. How far did the athlete jump in this problem? (d) Describe the shape of the trajectory of his center of mass.

23. A fireworks rocket explodes at height h , the peak of its vertical trajectory. It throws out burning fragments in all directions, but all at the same speed v . Pellets of solidified metal fall to the ground without air resistance. Find the smallest angle that the final velocity of an impacting fragment makes with the horizontal.

Section 4.4 The Particle in Uniform Circular Motion

Note: Problems 10 and 12 in Chapter 6 can also be assigned with this section and the next.

24. From information on the endpapers of this book, compute the radial acceleration of a point on the surface of the Earth at the equator, owing to the rotation of the Earth about its axis.
25. **▲** The athlete shown in Figure P4.25 rotates a 1.00-kg discus along a circular path of radius 1.06 m. The maximum speed of the discus is 20.0 m/s. Determine the magnitude of the maximum radial acceleration of the discus.



Figure P4.25

26. As their booster rockets separate, space shuttle astronauts typically feel accelerations up to $3g$, where $g = 9.80 \text{ m/s}^2$. In their training, astronauts ride in a device in which they experience such an acceleration as a centripetal acceleration. Specifically, the astronaut is fastened securely at the end of a mechanical arm that then turns at constant

speed in a horizontal circle. Determine the rotation rate, in revolutions per second, required to give an astronaut a centripetal acceleration of $3.00g$ while in circular motion with radius 9.45 m .

27. Young David who slew Goliath experimented with slings before tackling the giant. He found he could revolve a sling of length 0.600 m at the rate of 8.00 rev/s . If he increased the length to 0.900 m , he could revolve the sling only 6.00 times per second. (a) Which rate of rotation gives the greater speed for the stone at the end of the sling? (b) What is the centripetal acceleration of the stone at 8.00 rev/s ? (c) What is the centripetal acceleration at 6.00 rev/s ?

Section 4.5 Tangential and Radial Acceleration

28. ● (a) Could a particle moving with instantaneous speed 3.00 m/s on a path with radius of curvature 2.00 m have an acceleration of magnitude 6.00 m/s^2 ? (b) Could it have $|\vec{a}| = 4.00\text{ m/s}^2$? In each case, if the answer is yes, explain how it can happen; if the answer is no, explain why not.
29. A train slows down as it rounds a sharp horizontal turn, slowing from 90.0 km/h to 50.0 km/h in the 15.0 s that it takes to round the bend. The radius of the curve is 150 m . Compute the acceleration at the moment the train speed reaches 50.0 km/h . Assume it continues to slow down at this time at the same rate.
30. A ball swings in a vertical circle at the end of a rope 1.50 m long. When the ball is 36.9° past the lowest point on its way up, its total acceleration is $(-22.5\hat{i} + 20.2\hat{j})\text{ m/s}^2$. At that instant, (a) sketch a vector diagram showing the components of its acceleration, (b) determine the magnitude of its radial acceleration, and (c) determine the speed and velocity of the ball.
31. Figure P4.31 represents the total acceleration of a particle moving clockwise in a circle of radius 2.50 m at a certain instant of time. At this instant, find (a) the radial acceleration, (b) the speed of the particle, and (c) its tangential acceleration.

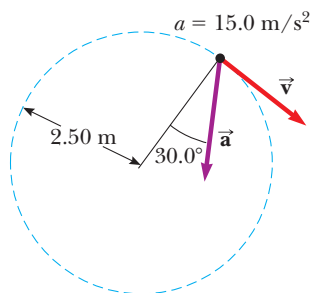


Figure P4.31

32. A race car starts from rest on a circular track. The car increases its speed at a constant rate a_t as it goes once around the track. Find the angle that the total acceleration of the car makes—with the radius connecting the center of the track and the car—at the moment the car completes the circle.

Section 4.6 Relative Velocity and Relative Acceleration

33. A car travels due east with a speed of 50.0 km/h . Raindrops are falling at a constant speed vertically with respect to the Earth. The traces of the rain on the side windows of the car make an angle of 60.0° with the vertical. Find the velocity of the rain with respect to (a) the car and (b) the Earth.
34. Heather in her Corvette accelerates at the rate of $(300\hat{i} - 2.00\hat{j})\text{ m/s}^2$, while Jill in her Jaguar accelerates at $(1.00\hat{i} + 3.00\hat{j})\text{ m/s}^2$. They both start from rest at the origin of an xy coordinate system. After 5.00 s , (a) what is Heather's speed with respect to Jill, (b) how far apart are they, and (c) what is Heather's acceleration relative to Jill?
35. A river has a steady speed of 0.500 m/s . A student swims upstream a distance of 1.00 km and swims back to the starting point. If the student can swim at a speed of 1.20 m/s in still water, how long does the trip take? Compare this answer with the time interval required for the trip if the water were still.
36. How long does it take an automobile traveling in the left lane at 60.0 km/h to pull alongside a car traveling in the same direction in the right lane at 40.0 km/h if the cars' front bumpers are initially 100 m apart?
37. Two swimmers, Alan and Beth, start together at the same point on the bank of a wide stream that flows with a speed v . Both move at the same speed c (where $c > v$), relative to the water. Alan swims downstream a distance L and then upstream the same distance. Beth swims so that her motion relative to the Earth is perpendicular to the banks of the stream. She swims the distance L and then back the same distance so that both swimmers return to the starting point. Which swimmer returns first? *Note:* First guess the answer.
38. ● A farm truck moves due north with a constant velocity of 9.50 m/s on a limitless horizontal stretch of road. A boy riding on the back of the truck throws a can of soda upward and catches the projectile at the same location on the truck bed, but 16.0 m farther down the road. (a) In the frame of reference of the truck, at what angle to the vertical does the boy throw the can? (b) What is the initial speed of the can relative to the truck? (c) What is the shape of the can's trajectory as seen by the boy? (d) An observer on the ground watches the boy throw the can and catch it. In this observer's ground frame of reference, describe the shape of the can's path and determine the initial velocity of the can.
39. A science student is riding on a flatcar of a train traveling along a straight horizontal track at a constant speed of 10.0 m/s . The student throws a ball into the air along a path that he judges to make an initial angle of 60.0° with the horizontal and to be in line with the track. The student's professor, who is standing on the ground nearby, observes the ball to rise vertically. How high does she see the ball rise?
40. ● A bolt drops from the ceiling of a moving train car that is accelerating northward at a rate of 2.50 m/s^2 . (a) What is the acceleration of the bolt relative to the train car? (b) What is the acceleration of the bolt relative to the Earth? (c) Describe the trajectory of the bolt as seen by

an observer inside the train car. (d) Describe the trajectory of the bolt as seen by an observer fixed on the Earth.

41. A Coast Guard cutter detects an unidentified ship at a distance of 20.0 km in the direction 15.0° east of north. The ship is traveling at 26.0 km/h on a course at 40.0° east of north. The Coast Guard wishes to send a speedboat to intercept the vessel and investigate it. If the speedboat travels 50.0 km/h, in what direction should it head? Express the direction as a compass bearing with respect to due north.

Additional Problems

42. *The "Vomit Comet."* In zero-gravity astronaut training and equipment testing, NASA flies a KC135A aircraft along a parabolic flight path. As shown in Figure P4.42, the aircraft climbs from 24 000 ft to 31 000 ft, where it enters the zero- g parabola with a velocity of 143 m/s nose high at 45.0° and exits with velocity 143 m/s at 45.0° nose low. During this portion of the flight, the aircraft and objects inside its padded cabin are in free fall; they have gone ballistic. The aircraft then pulls out of the dive with an upward acceleration of $0.800g$, moving in a vertical circle with radius 4.13 km. (During this portion of the flight, occupants of the aircraft perceive an acceleration of $1.8g$.) What are the aircraft's (a) speed and (b) altitude at the top of the maneuver? (c) What is the time interval spent in zero gravity? (d) What is the speed of the aircraft at the bottom of the flight path?
43. An athlete throws a basketball upward from the ground, giving it speed 10.6 m/s at an angle of 55.0° above the horizontal. (a) What is the acceleration of the basketball at the highest point in its trajectory? (b) On its way down, the basketball hits the rim of the basket, 3.05 m above the floor. It bounces straight up with one-half the speed with which it hit the rim. What height above the floor does the basketball reach on this bounce?
44. ● (a) An athlete throws a basketball toward the east, with initial speed 10.6 m/s at an angle of 55.0° above the horizontal. Just as the basketball reaches the highest point of its trajectory, it hits an eagle (the mascot of the opposing team) flying horizontally west. The ball bounces back horizontally west with 1.50 times the speed it had just before their collision. How far behind the player who threw it does the ball land? (b) This situation is not covered in the

rule book, so the officials turn the clock back to repeat this part of the game. The player throws the ball in the same way. The eagle is thoroughly annoyed and this time intercepts the ball so that, at the same point in its trajectory, the ball again bounces from the bird's beak with 1.50 times its impact speed, moving west at some nonzero angle with the horizontal. Now the ball hits the player's head, at the same location where her hands had released it. Is the angle necessarily positive (that is, above the horizontal), necessarily negative (below the horizontal), or could it be either? Give a convincing argument, either mathematical or conceptual, for your answer.

45. Manny Ramírez hits a home run so that the baseball just clears the top row of bleachers, 21.0 m high, located 130 m from home plate. The ball is hit at an angle of 35.0° to the horizontal, and air resistance is negligible. Find (a) the initial speed of the ball, (b) the time interval required for the ball to reach the bleachers, and (c) the velocity components and the speed of the ball when it passes over the top row. Assume the ball is hit at a height of 1.00 m above the ground.
46. As some molten metal splashes, one droplet flies off to the east with initial velocity v_i at angle θ_i above the horizontal and another droplet flies off to the west with the same speed at the same angle above the horizontal as shown in Figure P4.46. In terms of v_i and θ_i , find the distance between the droplets as a function of time.

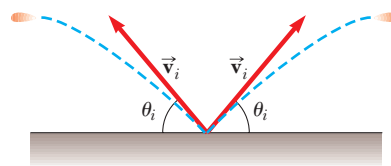


Figure P4.46

47. A pendulum with a cord of length $r = 1.00$ m swings in a vertical plane (Fig. P4.47). When the pendulum is in the two horizontal positions $\theta = 90.0^\circ$ and $\theta = 270^\circ$, its speed is 5.00 m/s. (a) Find the magnitude of the radial acceleration and tangential acceleration for these positions. (b) Draw vector diagrams to determine the direction of the total acceleration for these two positions. (c) Calculate the magnitude and direction of the total acceleration.

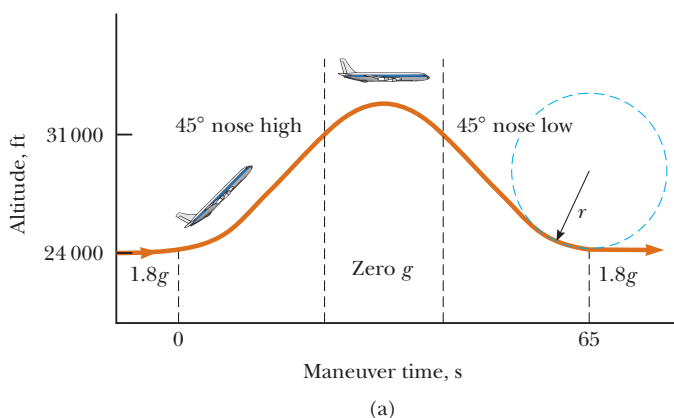


Figure P4.42



Courtesy of NASA

(b)

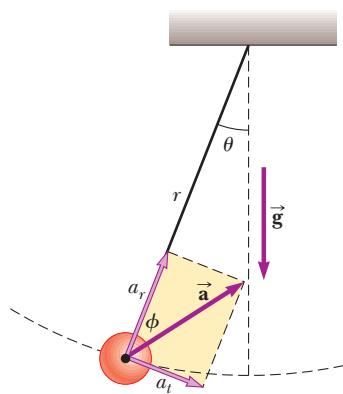


Figure P4.47

48. An astronaut on the surface of the Moon fires a cannon to launch an experiment package, which leaves the barrel moving horizontally. (a) What must be the muzzle speed of the package so that it travels completely around the Moon and returns to its original location? (b) How long does this trip around the Moon take? Assume the free-fall acceleration on the Moon is one-sixth of that on the Earth.
49. ● A projectile is launched from the point $(x = 0, y = 0)$ with velocity $(12.0\hat{i} + 49.0\hat{j})$ m/s, at $t = 0$. (a) Make a table listing the projectile's distance $|\vec{r}|$ from the origin at the end of each second thereafter, for $0 \leq t \leq 10$ s. Tabulating the x and y coordinates and the components of velocity v_x and v_y may also be useful. (b) Observe that the projectile's distance from its starting point increases with time, goes through a maximum, and starts to decrease. Prove that the distance is a maximum when the position vector is perpendicular to the velocity. *Suggestion:* Argue that if \vec{v} is not perpendicular to \vec{r} , then $|\vec{r}|$ must be increasing or decreasing. (c) Determine the magnitude of the maximum distance. Explain your method.
50. ● A spring cannon is located at the edge of a table that is 1.20 m above the floor. A steel ball is launched from the cannon with speed v_0 at 35.0° above the horizontal. (a) Find the horizontal displacement component of the ball to the point where it lands on the floor as a function of v_0 . We write this function as $x(v_0)$. Evaluate x for (b) $v_0 = 0.100$ m/s and for (c) $v_0 = 100$ m/s. (d) Assume v_0 is close to zero but not equal to zero. Show that one term in the answer to part (a) dominates so that the function $x(v_0)$ reduces to a simpler form. (e) If v_0 is very large, what is the approximate form of $x(v_0)$? (f) Describe the overall shape of the graph of the function $x(v_0)$. *Suggestion:* As practice, you could do part (b) before doing part (a).

51. When baseball players throw the ball in from the outfield, they usually allow it to take one bounce before it reaches the infield on the theory that the ball arrives sooner that way. Suppose the angle at which a bounced ball leaves the ground is the same as the angle at which the outfielder threw it as shown in Figure P4.51, but the ball's speed after the bounce is one-half of what it was before the bounce. (a) Assume the ball is always thrown with the same initial speed. At what angle θ should the fielder throw the ball to make it go the same distance D with one bounce (blue path) as a ball thrown upward at 45.0° with

no bounce (green path)? (b) Determine the ratio of the time interval for the one-bounce throw to the flight time for the no-bounce throw.

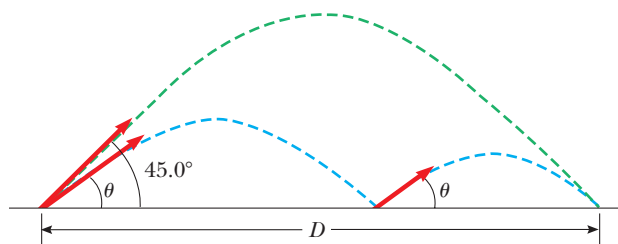


Figure P4.51

52. A truck loaded with cannonball watermelons stops suddenly to avoid running over the edge of a washed-out bridge (Fig. P4.52). The quick stop causes a number of melons to fly off the truck. One melon rolls over the edge with an initial speed $v_i = 10.0$ m/s in the horizontal direction. A cross section of the bank has the shape of the bottom half of a parabola with its vertex at the edge of the road and with the equation $y^2 = 16x$, where x and y are measured in meters. What are the x and y coordinates of the melon when it splatters on the bank?

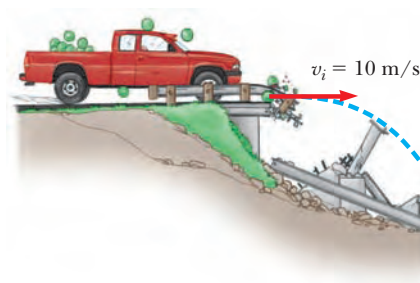


Figure P4.52

53. Your grandfather is copilot of a bomber, flying horizontally over level terrain, with a speed of 275 m/s relative to the ground, at an altitude of 3 000 m. (a) The bombardier releases one bomb. How far will the bomb travel horizontally between its release and its impact on the ground? Ignore the effects of air resistance. (b) Firing from the people on the ground suddenly incapacitates the bombardier before he can call, "Bombs away!" Consequently, the pilot maintains the plane's original course, altitude, and speed through a storm of flak. Where will the plane be when the bomb hits the ground? (c) The plane has a telescopic bombsight set so that the bomb hits the target seen in the sight at the moment of release. At what angle from the vertical was the bombsight set?
54. A person standing at the top of a hemispherical rock of radius R kicks a ball (initially at rest on the top of the rock) to give it horizontal velocity \vec{v}_i as shown in Figure P4.54. (a) What must be its minimum initial speed if the ball is never to hit the rock after it is kicked? (b) With this initial speed, how far from the base of the rock does the ball hit the ground?

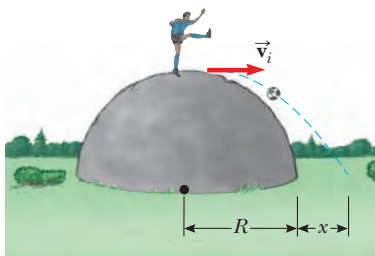


Figure P4.54

55. A hawk is flying horizontally at 10.0 m/s in a straight line, 200 m above the ground. A mouse it has been carrying struggles free from its talons. The hawk continues on its path at the same speed for 2.00 s before attempting to retrieve its prey. To accomplish the retrieval, it dives in a straight line at constant speed and recaptures the mouse 3.00 m above the ground. (a) Assuming no air resistance acts on the mouse, find the diving speed of the hawk. (b) What angle did the hawk make with the horizontal during its descent? (c) For how long did the mouse “enjoy” free fall?
56. The determined coyote is out once more in pursuit of the elusive roadrunner. The coyote wears a pair of Acme jet-powered roller skates, which provide a constant horizontal acceleration of 15.0 m/s^2 (Fig. P4.56). The coyote starts at rest 70.0 m from the brink of a cliff at the instant the roadrunner zips past in the direction of the cliff. (a) Assuming the roadrunner moves with constant speed, determine the minimum speed it must have to reach the cliff before the coyote. At the edge of the cliff, the roadrunner escapes by making a sudden turn, while the coyote continues straight ahead. The coyote’s skates remain horizontal and continue to operate while the coyote is in flight, so its acceleration while in the air is $(15.0\hat{i} - 9.80\hat{j}) \text{ m/s}^2$. (b) The cliff is 100 m above the flat floor of a canyon. Determine where the coyote lands in the canyon. (c) Determine the components of the coyote’s impact velocity.

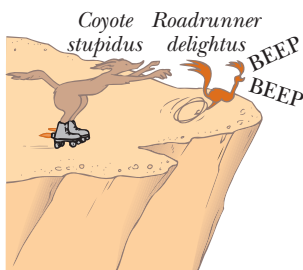


Figure P4.56

57. ▲ A car is parked on a steep incline overlooking the ocean, where the incline makes an angle of 37.0° below the horizontal. The negligent driver leaves the car in neutral, and the parking brakes are defective. Starting from rest at $t = 0$, the car rolls down the incline with a constant acceleration of 4.00 m/s^2 , traveling 50.0 m to the edge of a vertical cliff. The cliff is 30.0 m above the ocean. Find (a) the speed of the car when it reaches the edge of the cliff and the time interval elapsed when it arrives there,

- (b) the velocity of the car when it lands in the ocean, (c) the total time interval that the car is in motion, and (d) the position of the car when it lands in the ocean, relative to the base of the cliff.

58. ● Do not hurt yourself; do not strike your hand against anything. Within these limitations, describe what you do to give your hand a large acceleration. Compute an order-of-magnitude estimate of this acceleration, stating the quantities you measure or estimate and their values.
59. ● A skier leaves the ramp of a ski jump with a velocity of 10.0 m/s, 15.0° above the horizontal, as shown in Figure P4.59. The slope is inclined at 50.0° , and air resistance is negligible. Find (a) the distance from the ramp to where the jumper lands and (b) the velocity components just before the landing. (How do you think the results might be affected if air resistance were included? Note that jumpers lean forward in the shape of an airfoil, with their hands at their sides, to increase their distance. Why does this method work?)

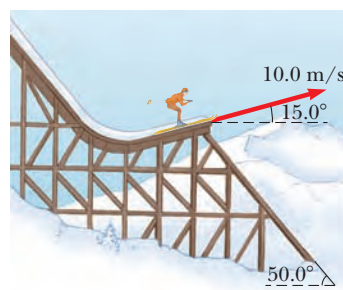


Figure P4.59

60. An angler sets out upstream from Metaline Falls on the Pend Oreille River in northwestern Washington State. His small boat, powered by an outboard motor, travels at a constant speed v in still water. The water flows at a lower constant speed v_w . He has traveled upstream for 2.00 km when his ice chest falls out of the boat. He notices that the chest is missing only after he has gone upstream for another 15.0 min. At that point, he turns around and heads back downstream, all the time traveling at the same speed relative to the water. He catches up with the floating ice chest just as it is about to go over the falls at his starting point. How fast is the river flowing? Solve this problem in two ways. (a) First, use the Earth as a reference frame. With respect to the Earth, the boat travels upstream at speed $v - v_w$ and downstream at $v + v_w$. (b) A second much simpler and more elegant solution is obtained by using the water as the reference frame. This approach has important applications in many more complicated problems; examples are calculating the motion of rockets and satellites and analyzing the scattering of subatomic particles from massive targets.
61. An enemy ship is on the east side of a mountainous island as shown in Figure P4.61. The enemy ship has maneuvered to within 2 500 m of the 1 800-m-high mountain peak and can shoot projectiles with an initial speed of 250 m/s. If the western shoreline is horizontally 300 m from the peak, what are the distances from the western shore at which a ship can be safe from the bombardment of the enemy ship?

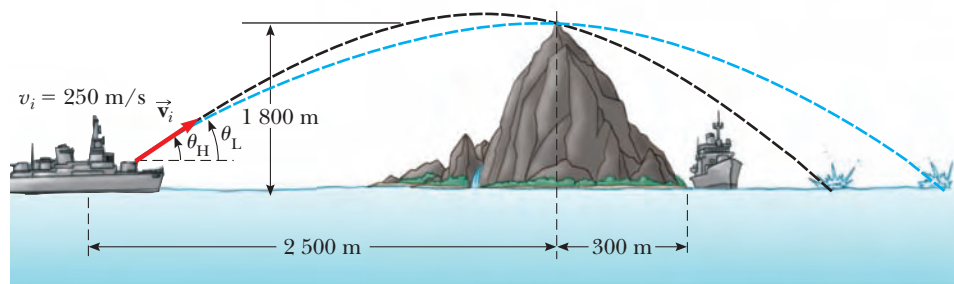


Figure P4.61

62. In the **What If?** section of Example 4.5, it was claimed that the maximum range of a ski jumper occurs for a launch angle θ given by

$$\theta = 45^\circ - \frac{\phi}{2}$$

where ϕ is the angle that the hill makes with the horizontal in Figure 4.14. Prove this claim by deriving this equation.

Answers to Quick Quizzes

- 4.1 (a). Because acceleration occurs whenever the velocity changes in any way—with an increase or decrease in speed, a change in direction, or both—all three controls are accelerators. The gas pedal causes the car to speed up; the brake pedal causes the car to slow down. The steering wheel changes the direction of the velocity vector.
- 4.2 (i), (b). At only one point—the peak of the trajectory—are the velocity and acceleration vectors perpendicular to each other. The velocity vector is horizontal at that point, and the acceleration vector is downward. (ii), (a). The acceleration vector is always directed downward. The velocity vector is never vertical and parallel to the acceleration vector if the object follows a path such as that in Figure 4.8.
- 4.3 15° , 30° , 45° , 60° , 75° . The greater the maximum height, the longer it takes the projectile to reach that altitude and then fall back down from it. So, as the launch angle increases, the time of flight increases.
- 4.4 (i), (d). Because the centripetal acceleration is proportional to the square of the speed of the particle, doubling the speed increases the acceleration by a factor of 4. (ii), (b). The period is inversely proportional to the speed of the particle.
- 4.5 (i), (b). The velocity vector is tangent to the path. If the acceleration vector is to be parallel to the velocity vector, it must also be tangent to the path, which requires that the acceleration vector have no component perpendicular to the path. If the path were to change direction, the acceleration vector would have a radial component, perpendicular to the path. Therefore, the path must remain straight. (ii), (d). If the acceleration vector is to be perpendicular to the velocity vector, it must have no component tangent to the path. On the other hand, if the speed is changing, there *must* be a component of the acceleration tangent to the path. Therefore, the velocity and acceleration vectors are never perpendicular in this situation. They can only be perpendicular if there is no change in the speed.