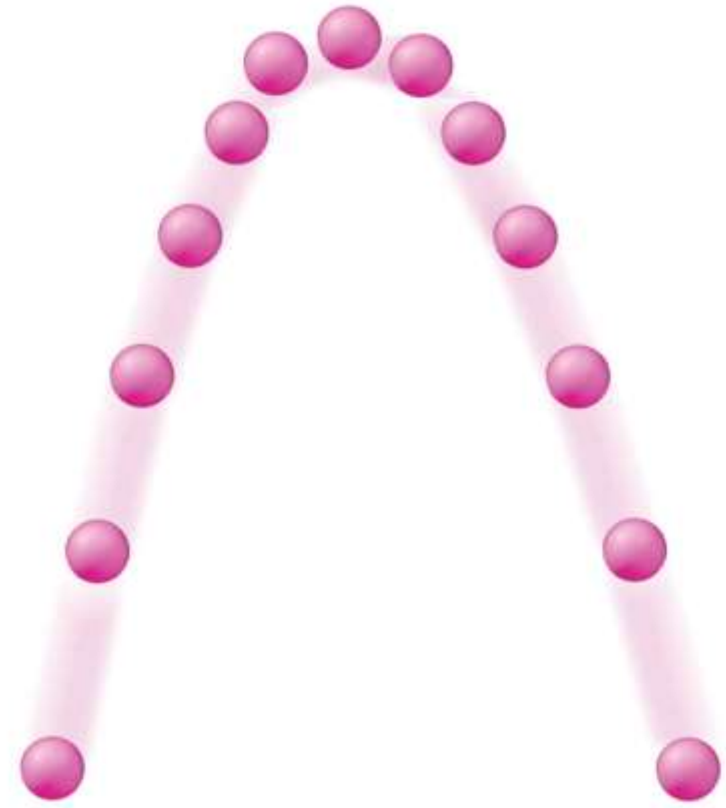
THE BIG IDEA

Projectile motion can be described by the horizontal and vertical components of motion.

PEARSON

In the previous chapter we studied simple straight-line motion—linear motion.

Now we extend these ideas to nonlinear motion—motion along a curved path. Throw a baseball and the path it follows is a combination of constant-velocity horizontal motion and accelerated vertical motion.



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Conceptual Physics

5.1 Vector and Scalar Quantities

A vector quantity includes both magnitude and direction, but a scalar quantity includes only magnitude.

5.1 Vector and Scalar Quantities

A quantity that requires both magnitude and direction for a complete description is a vector quantity.

Velocity is a vector quantity, as is acceleration.

Other quantities, such as momentum, are also vector quantities.

5.1 Vector and Scalar Quantities

A quantity that is completely described by magnitude is a scalar quantity. Scalars can be added, subtracted, multiplied, and divided like ordinary numbers.

- When 3 kg of sand is added to 1 kg of cement, the resulting mixture has a mass of 4 kg.
- When 5 liters of water are poured from a pail that has 8 liters of water in it, the resulting volume is 3 liters.
- If a scheduled 60-minute trip has a 15-minute delay, the trip takes 75 minutes.

5.1 Vector and Scalar Quantities

CONCEPT CHECK

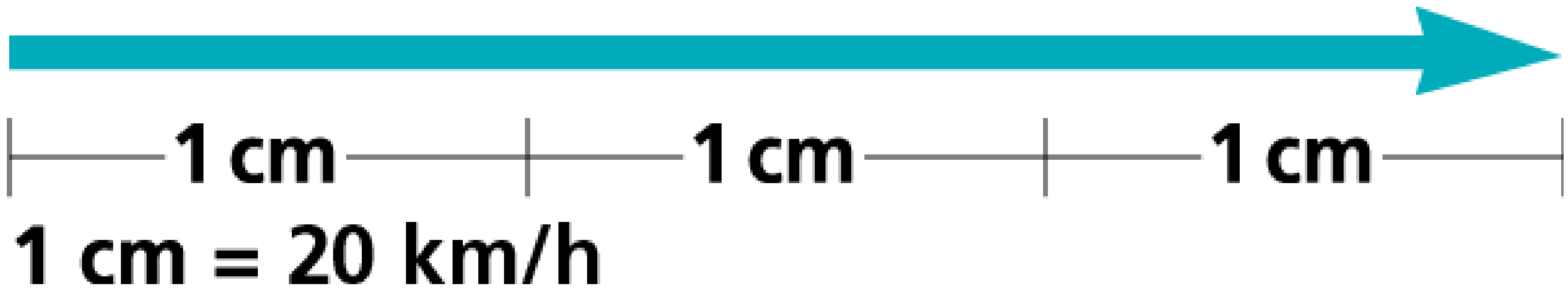
How does a scalar quantity differ from a vector quantity?

5.2 Velocity Vectors

The resultant of two perpendicular vectors is the diagonal of a rectangle constructed with the two vectors as sides.

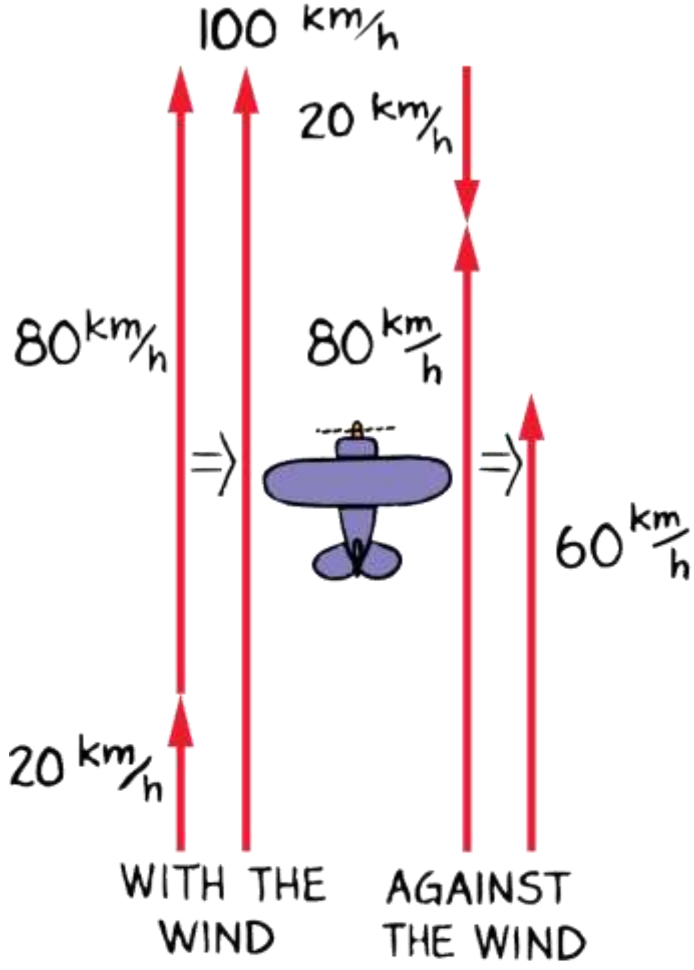
5.2 Velocity Vectors

By using a scale of 1 cm = 20 km/h and drawing a 3-cm-long vector that points to the right, you represent a velocity of 60 km/h to the right (east).



5.2 Velocity Vectors

The airplane's velocity relative to the ground depends on the airplane's velocity relative to the air and on the wind's velocity.



5.2 Velocity Vectors

The velocity of something is often the result of combining two or more other velocities.

- If a small airplane is flying north at 80 km/h relative to the surrounding air and a tailwind blows north at a velocity of 20 km/h, the plane travels 100 kilometers in one hour relative to the ground below.
- What if the plane flies into the wind rather than with the wind? The velocity vectors are now in opposite directions.

The resulting speed of the airplane is 60 km/h.

5.2 Velocity Vectors

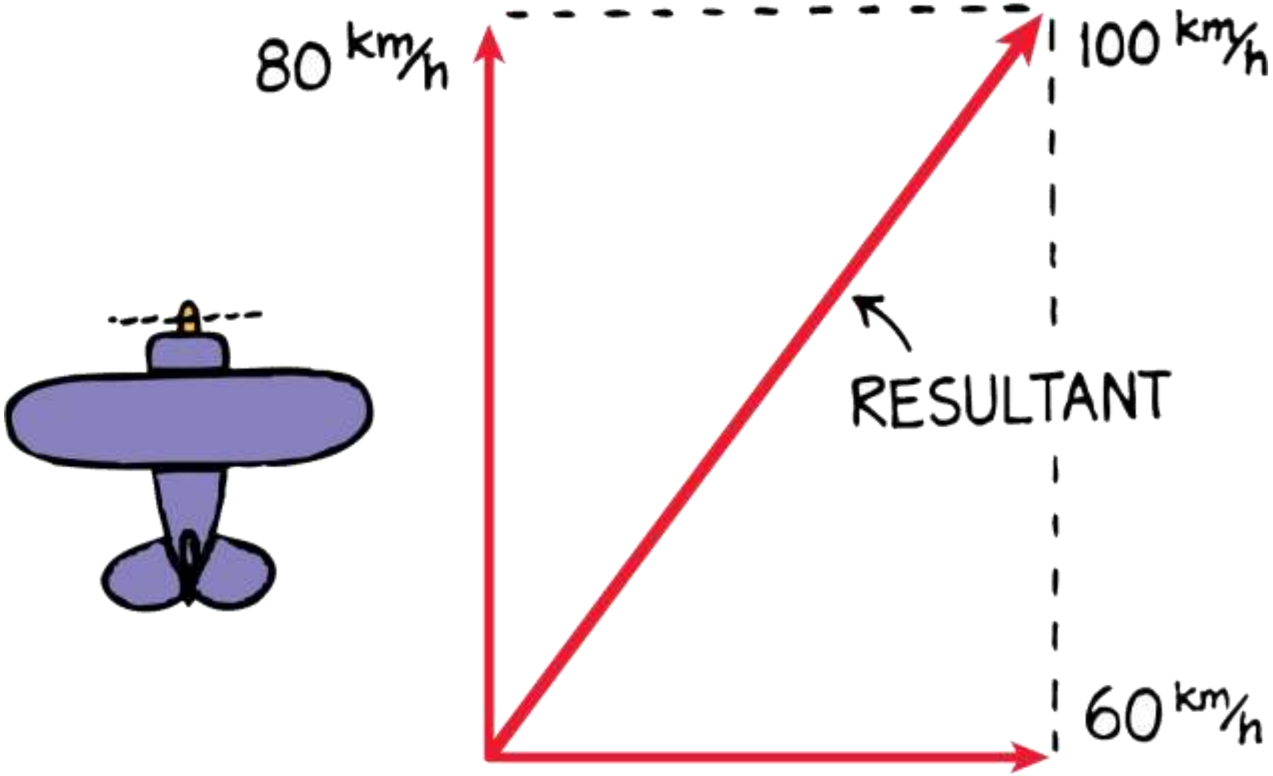
Now consider an 80-km/h airplane flying north caught in a strong crosswind of 60 km/h blowing from west to east.

The plane's speed relative to the ground can be found by adding the two vectors.

The result of adding these two vectors, called the *resultant,* is the diagonal of the rectangle described by the two vectors.

5.2 Velocity Vectors

An 80-km/h airplane flying in a 60-km/h crosswind has a resultant speed of 100 km/h relative to the ground.

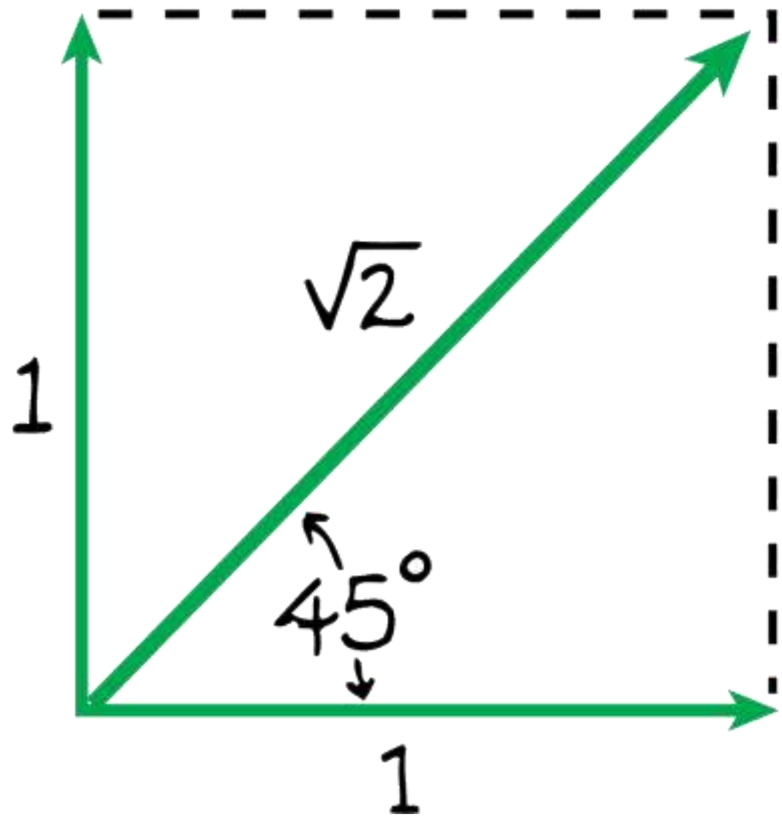


5.2 Velocity Vectors

The 3-unit and 4-unit vectors at right angles add to produce a resultant vector of 5 units, at 37° from the horizontal.

5.2 Velocity Vectors

The diagonal of a square is $\sqrt{2}$, or 1.414, times the length of one of its sides.



5.2 Velocity Vectors

think!

Suppose that an airplane normally flying at 80 km/h encounters wind at a right angle to its forward motion—a crosswind. Will the airplane fly faster or slower than 80 km/h?

5.2 Velocity Vectors

think!

Suppose that an airplane normally flying at 80 km/h encounters wind at a right angle to its forward motion—a crosswind. Will the airplane fly faster or slower than 80 km/h?

Answer: A crosswind would increase the speed of the airplane and blow it off course by a predictable amount.

5.2 Velocity Vectors

CONCEPT CHECK

What is the resultant of two perpendicular vectors?

5.3 Components of Vectors

The perpendicular components of a vector are independent of each other.

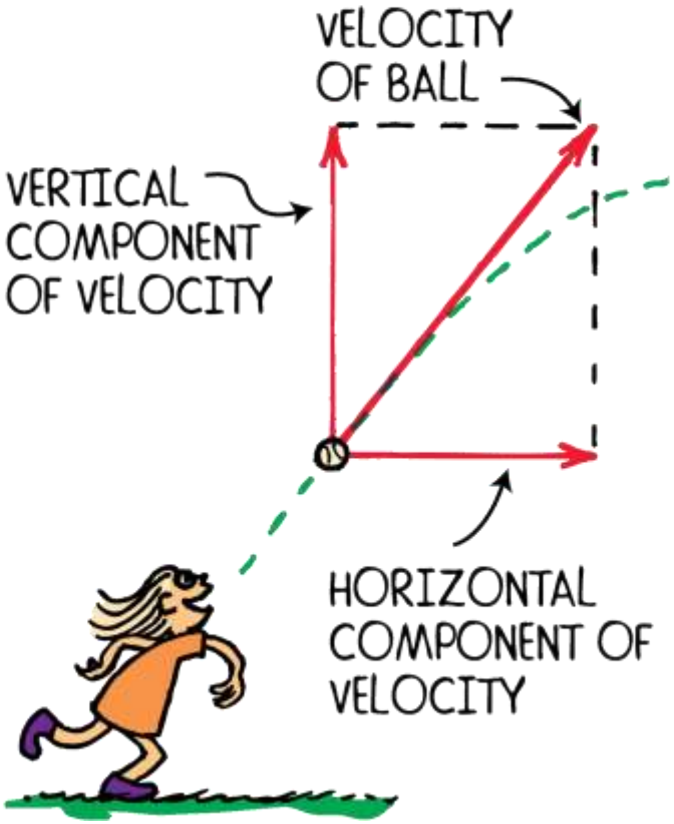
5.3 Components of Vectors

Often we will need to change a single vector into an equivalent set of two *component* vectors at right angles to each other:

- Any vector can be “resolved” into two component vectors at right angles to each other.
- Two vectors at right angles that add up to a given vector are known as the **components** of the given vector.
- The process of determining the components of a vector is called **resolution.**

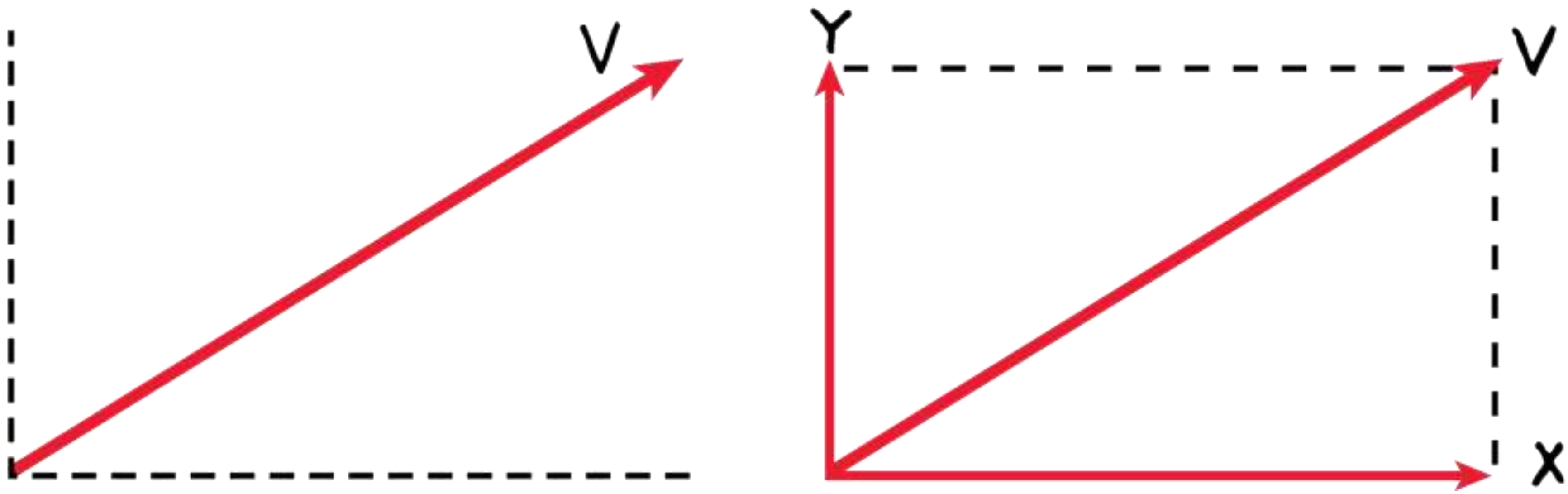
5.3 Components of Vectors

A ball's velocity can be resolved into horizontal and vertical components.



5.3 Components of Vectors

Vectors X and Y are the horizontal and vertical components of a vector V.



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5.3 Components of Vectors

CONCEPT CHECK

How do components of a vector affect each other?

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5.4 Projectile Motion

- The horizontal component of motion for a projectile is just like the horizontal motion of a ball rolling freely along a level surface without friction.
- The vertical component of a projectile's velocity is like the motion for a freely falling object.

5.4 Projectile Motion

A **projectile** is any object that moves through the air or space, acted on only by gravity (and air resistance, if any).

A cannonball shot from a cannon, a stone thrown into the air, a ball rolling off the edge of a table, a spacecraft circling Earth—all of these are examples of projectiles.

5.4 Projectile Motion

Projectiles near the surface of Earth follow a curved path that at first seems rather complicated.

These paths are surprisingly simple when we look at the horizontal and vertical components of motion separately.

5.4 Projectile Motion

Projectile motion can be separated into components.

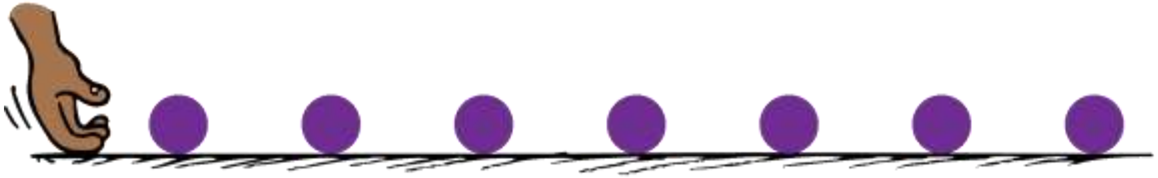
a. Roll a ball along a horizontal surface, and its velocity is constant because no component of gravitational force acts horizontally.

5.4 Projectile Motion

Projectile motion can be separated into components.

a. Roll a ball along a horizontal surface, and its velocity is constant because no component of gravitational force acts horizontally.

b. Drop it, and it accelerates downward and covers a greater vertical distance each second.



5.4 Projectile Motion

Most important, the horizontal component of motion for a projectile is completely independent of the vertical component of motion.

Each component is independent of the other.

Their combined effects produce the variety of curved paths that projectiles follow.

5.4 Projectile Motion

CONCEPT CHECK

Describe the components of projectile motion.

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5.5 Projectiles Launched Horizontally

The downward motion of a horizontally launched projectile is the same as that of free fall.

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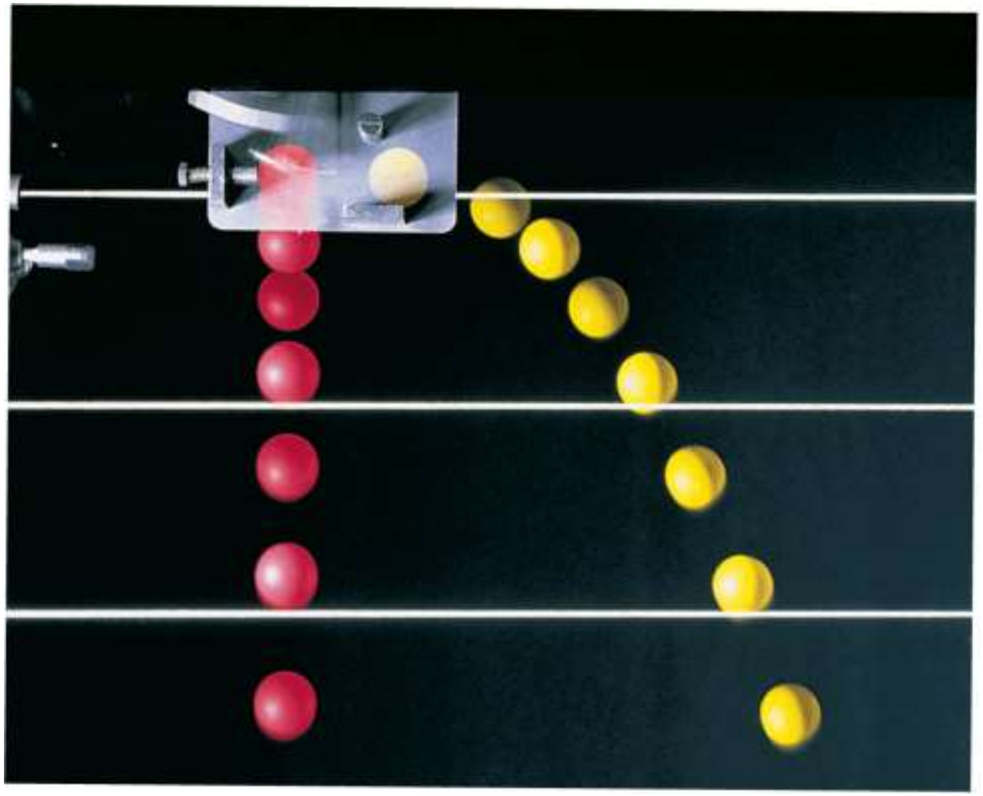
5.5 Projectiles Launched Horizontally

A strobe-light photo of two balls released simultaneously–one ball drops freely while the other one is projected horizontally.



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5.5 Projectiles Launched Horizontally

There are two important things to notice in the photo of two balls falling simultaneously:

- The ball's horizontal component of motion remains constant. Gravity acts only downward, so the only acceleration of the ball is downward.
- Both balls fall the same vertical distance in the same time. The vertical distance fallen has nothing to do with the horizontal component of motion.

5.5 Projectiles Launched Horizontally

The ball moves the same horizontal distance in the equal time intervals because no horizontal component of force is acting on it.

The path traced by a projectile accelerating in the vertical direction while moving at constant horizontal velocity is a *parabola.*

When air resistance is small enough to neglect, the curved paths are parabolic.

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5.5 Projectiles Launched Horizontally

think!

At the instant a horizontally pointed cannon is fired, a cannonball held at the cannon's side is released and drops to the ground. Which cannonball strikes the ground first, the one fired from the cannon or the one dropped?

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5.5 Projectiles Launched Horizontally

think!

At the instant a horizontally pointed cannon is fired, a cannonball held at the cannon's side is released and drops to the ground. Which cannonball strikes the ground first, the one fired from the cannon or the one dropped?

Answer: Both cannonballs fall the same vertical distance with the same acceleration *g* and therefore strike the ground at the same time.

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5.5 Projectiles Launched Horizontally

CONCEPT CHECK

Describe the downward motion of a horizontally launched projectile.

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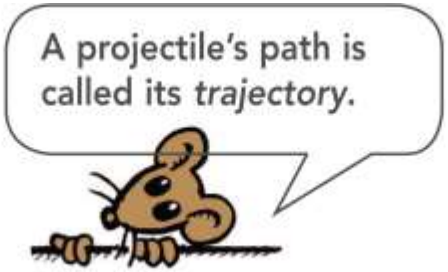
5.6 Projectiles Launched at an Angle

The vertical distance a projectile falls below an imaginary straight-line path increases continually with time and is equal to 5t^2 meters.

PEARSON

5.6 Projectiles Launched at an Angle

No matter the angle at which a projectile is launched, the vertical distance of fall beneath the idealized straight-line path (dashed straight lines) is the same for equal times.



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5.6 Projectiles Launched at an Angle

The dashed straight lines show the ideal trajectories of the stones if there were no gravity.

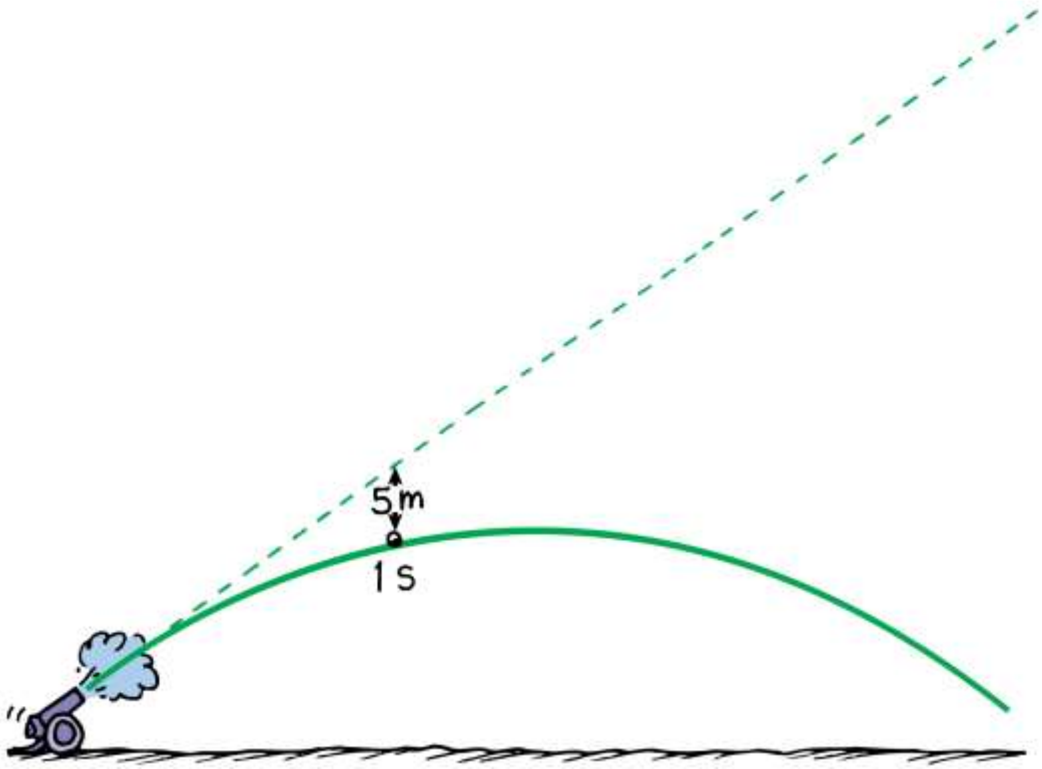
Notice that the vertical distance that the stone falls beneath the idealized straight-line paths is the same for equal times.

This vertical distance is independent of what's happening horizontally.

PEARSON

5.6 Projectiles Launched at an Angle

With no gravity the projectile would follow the straight-line path (dashed line). But because of gravity it falls beneath this line the same vertical distance it would fall if it were released from rest.



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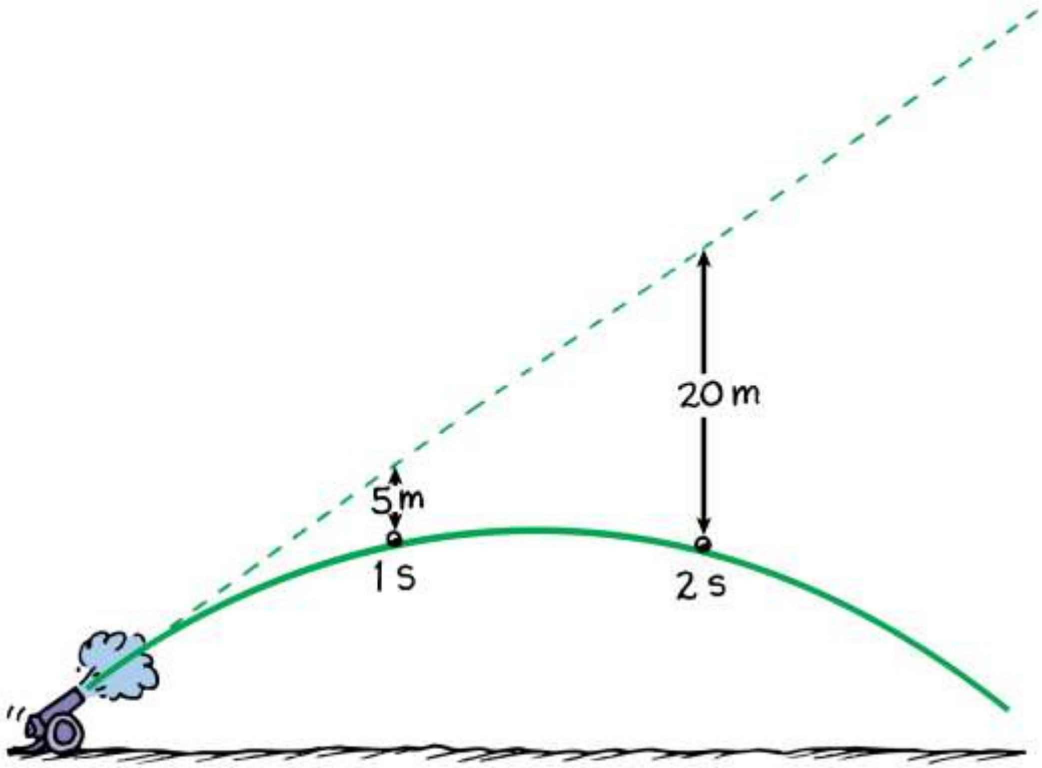

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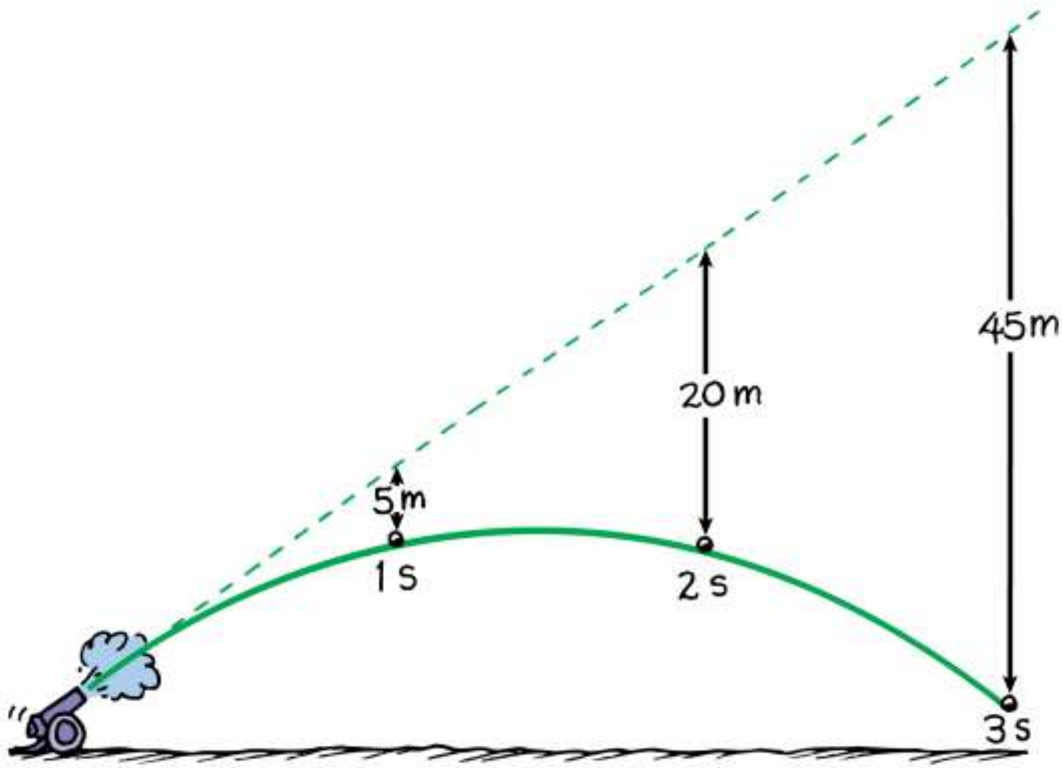
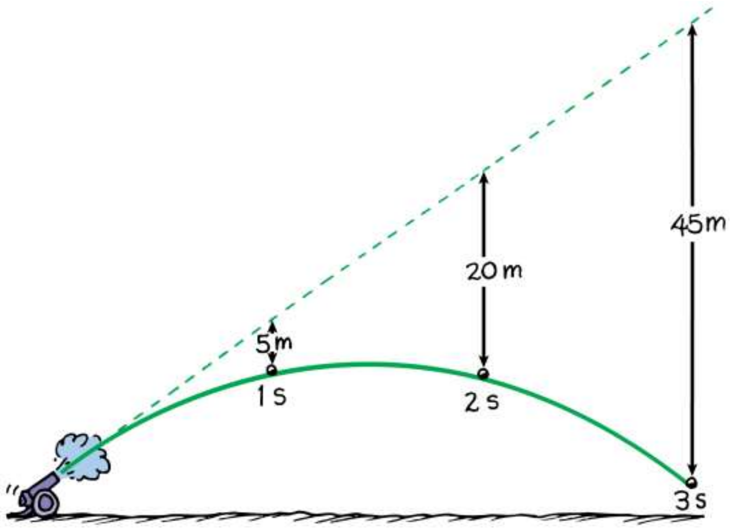


5.6 Projectiles Launched at an Angle

If there were no gravity the cannonball would follow the straight-line path shown by the dashed line.

The vertical distance it falls *beneath any point on the dashed line* is the same vertical distance it would fall if it were dropped from rest:

$$d = \frac{1}{2}gt^2$$



5.6 Projectiles Launched at an Angle

Height

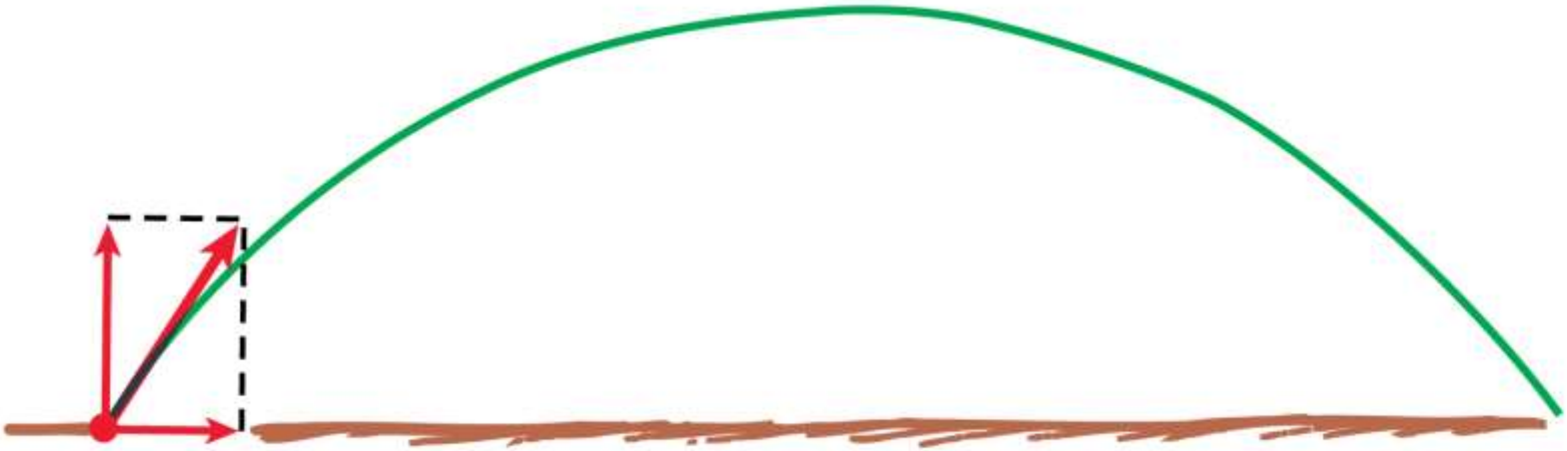
For the component vectors of the cannonball's motion, the horizontal component is always the same and only the vertical component changes.

At the top of the path the vertical component shrinks to zero, so the velocity there *is* the same as the horizontal component of velocity at all other points.

Everywhere else the magnitude of velocity is greater, just as the diagonal of a rectangle is greater than either of its sides.

5.6 Projectiles Launched at an Angle

The velocity of a projectile is shown at various points along its path. Notice that the vertical component changes while the horizontal component does not. Air resistance is neglected.



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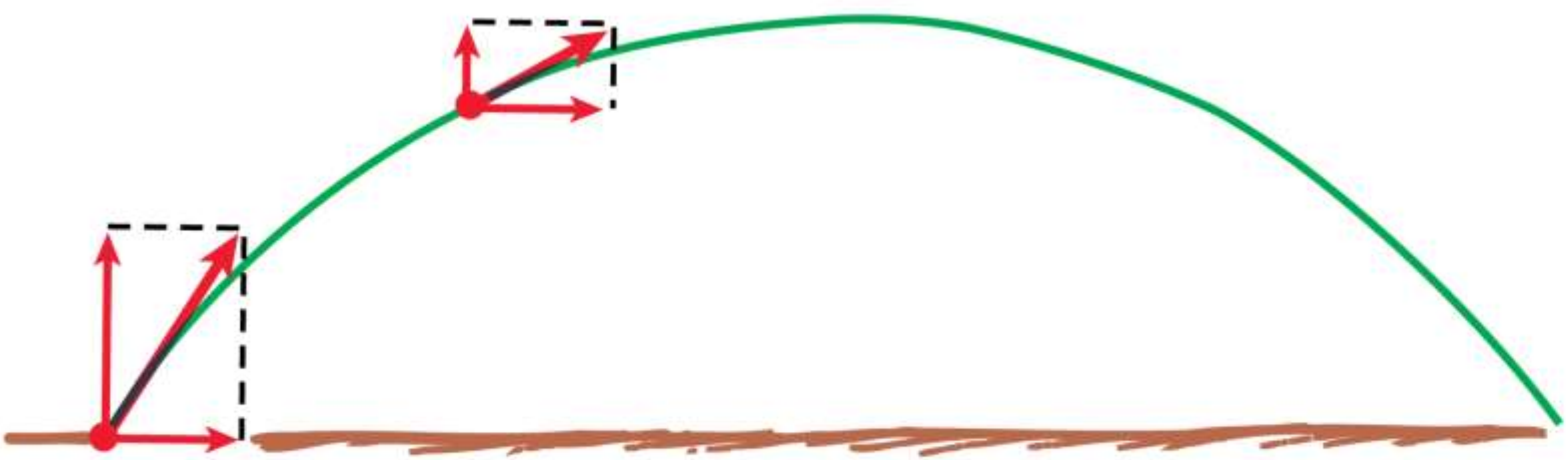

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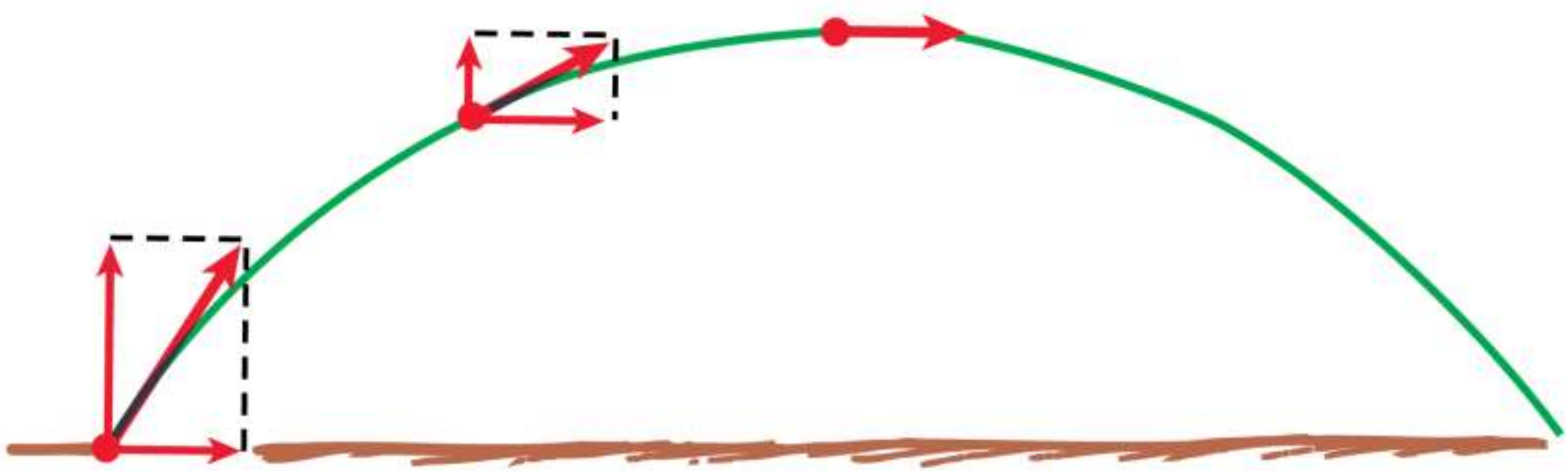

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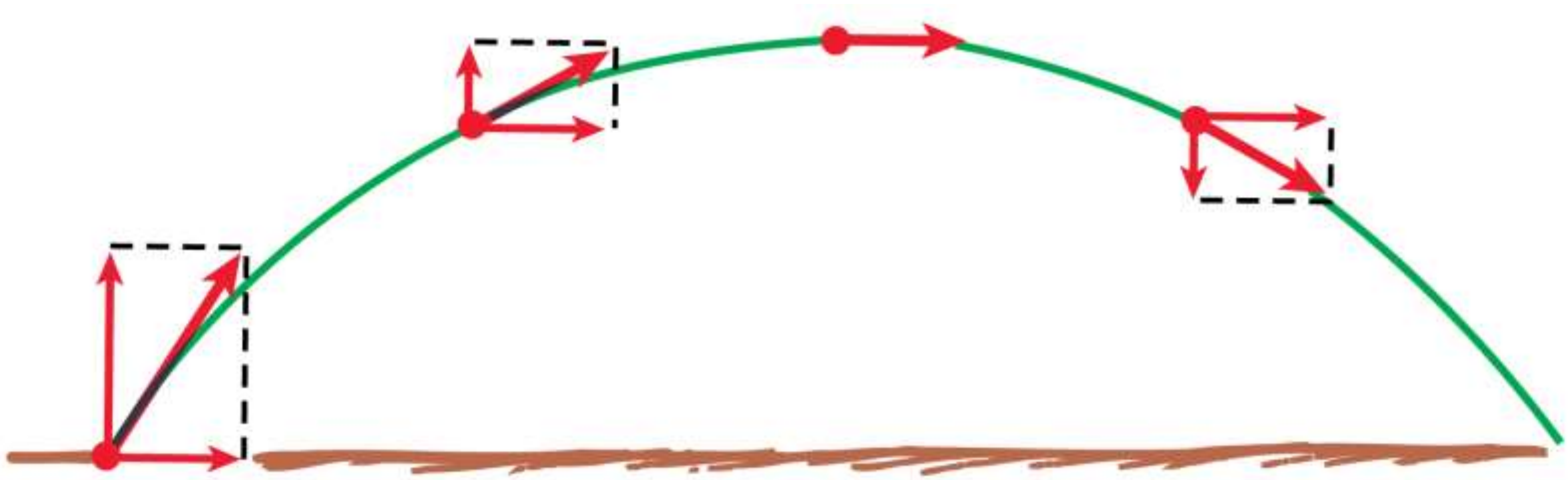

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5.6 Projectiles Launched at an Angle

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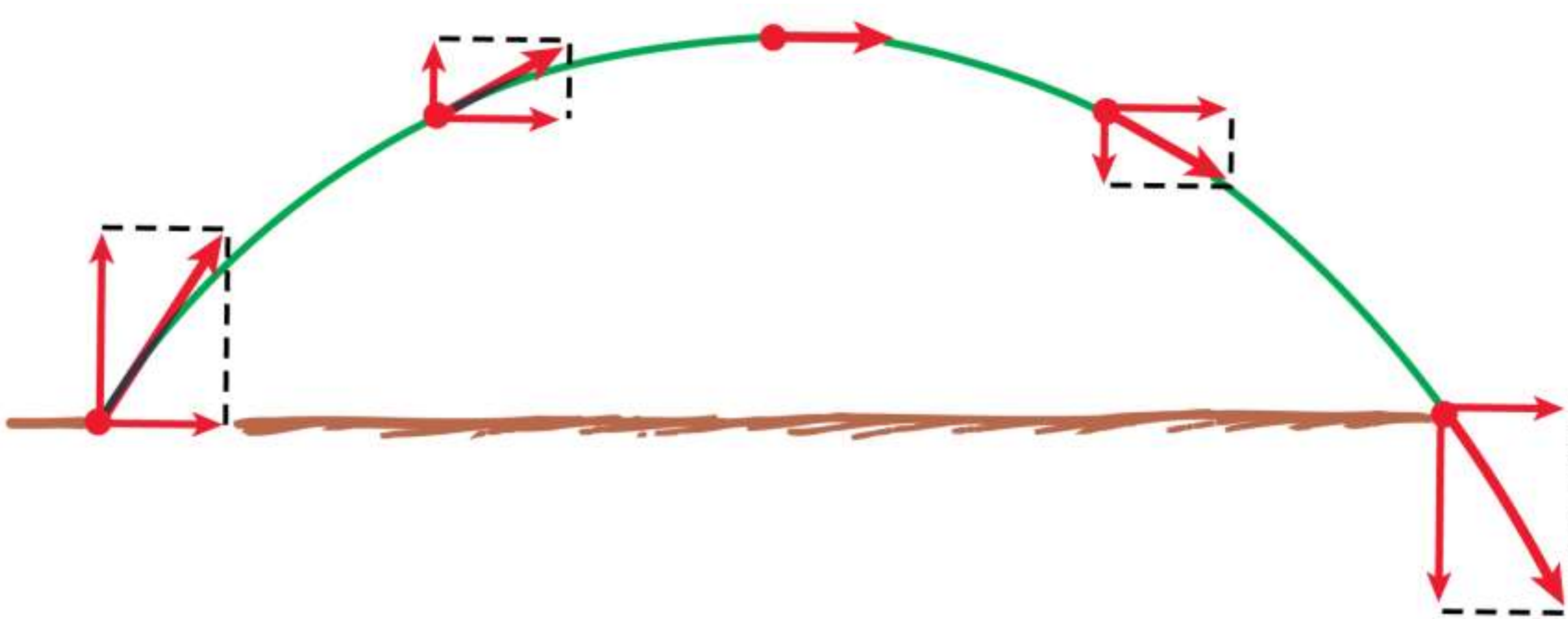

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5.6 Projectiles Launched at an Angle

Range

The angle at which the projectile is launched affects the distance that it travels.

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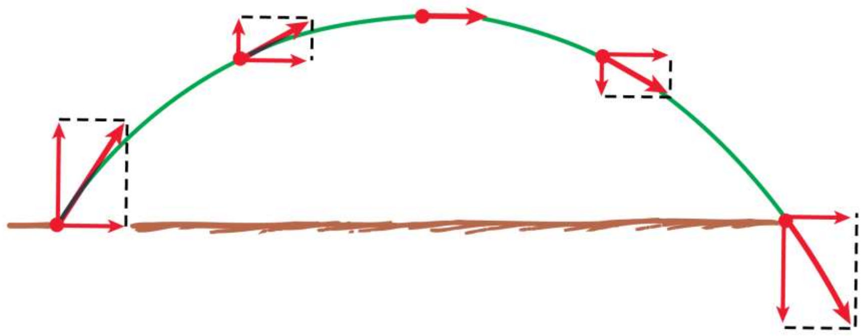
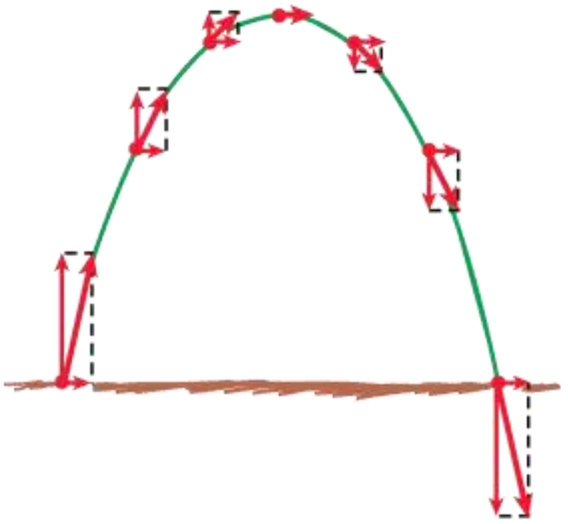
5.6 Projectiles Launched at an Angle

Both projectiles have the same launching speed.

The initial velocity vector has a greater vertical component than when the projection angle is less. This greater component results in a higher path.

The horizontal component is less, so the range is less.





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5.6 Projectiles Launched at an Angle

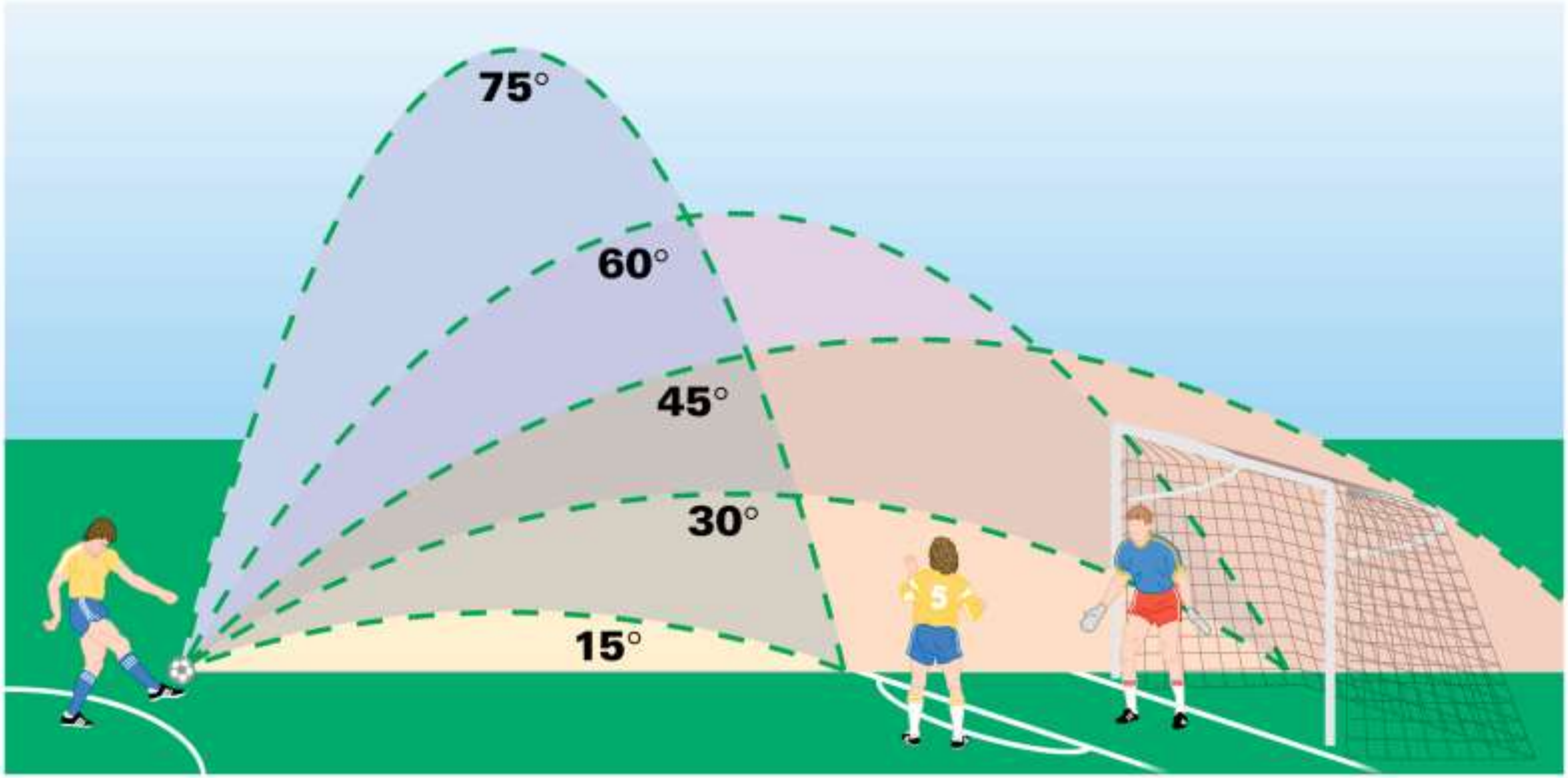
Horizontal Ranges

Projectiles that are launched at the same speed but at different angles reach different heights (altitude) above the ground.

They also travel different horizontal distances, that is, they have different *horizontal ranges.*

5.6 Projectiles Launched at an Angle

The paths of projectiles launched at the same speed but at different angles. The paths neglect air resistance.

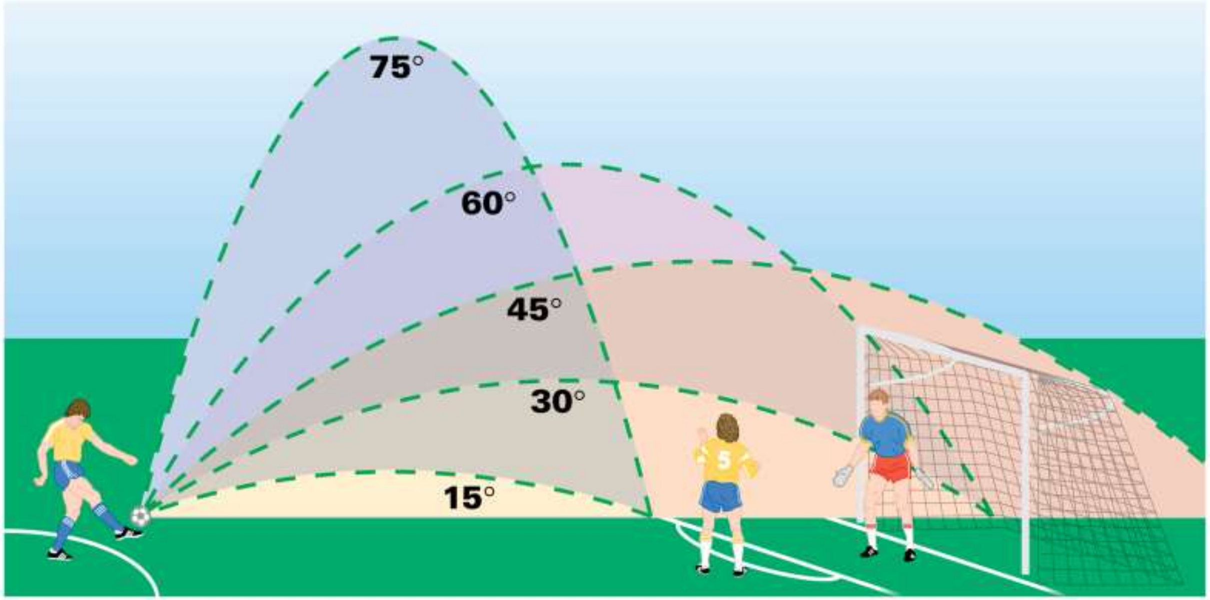


5.6 Projectiles Launched at an Angle

The same range is obtained for two different projection angles—angles that add up to 90°.

An object thrown into the air at an angle of 60° will have the same range as at 30° with the same speed.

Maximum range is usually attained at an angle of 45°.



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5.6 Projectiles Launched at an Angle

Maximum range is attained when the ball is batted at an angle of nearly 45°.

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5.6 Projectiles Launched at an Angle

Speed

Without air resistance, a projectile will reach maximum height in the same time it takes to fall from that height to the ground.

The deceleration due to gravity going up is the same as the acceleration due to gravity coming down.

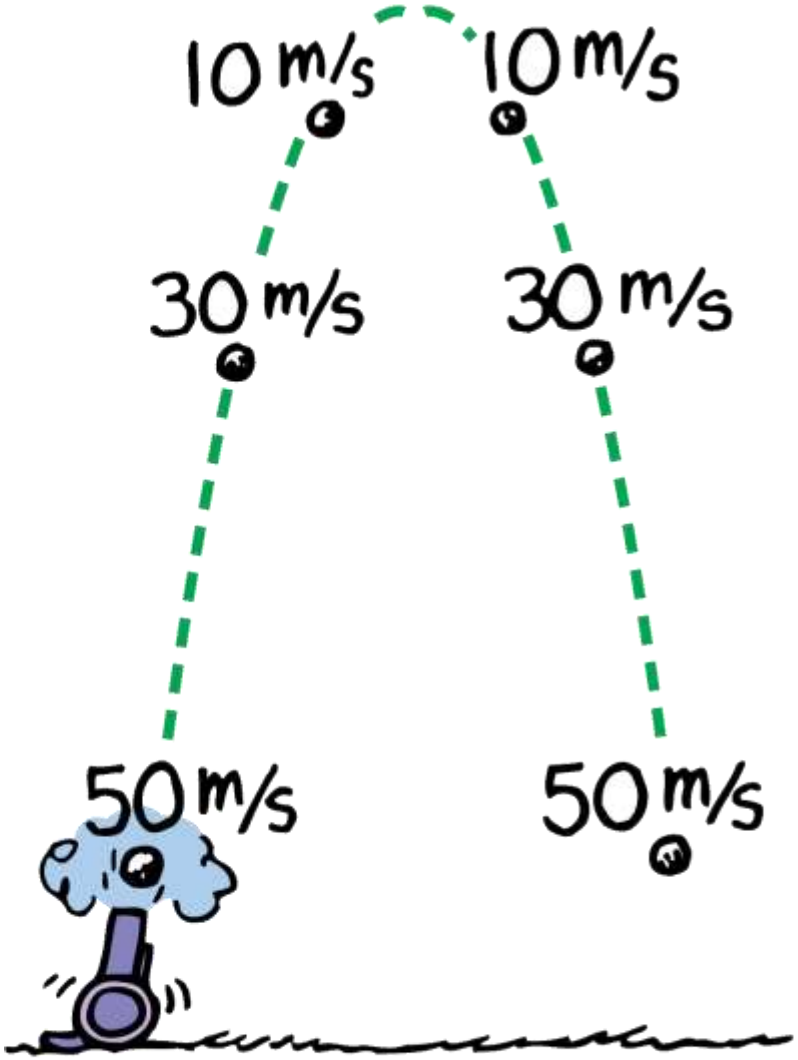
The projectile hits the ground with the same speed it had when it was projected upward from the ground.

PEARSON

5.6 Projectiles Launched at an Angle

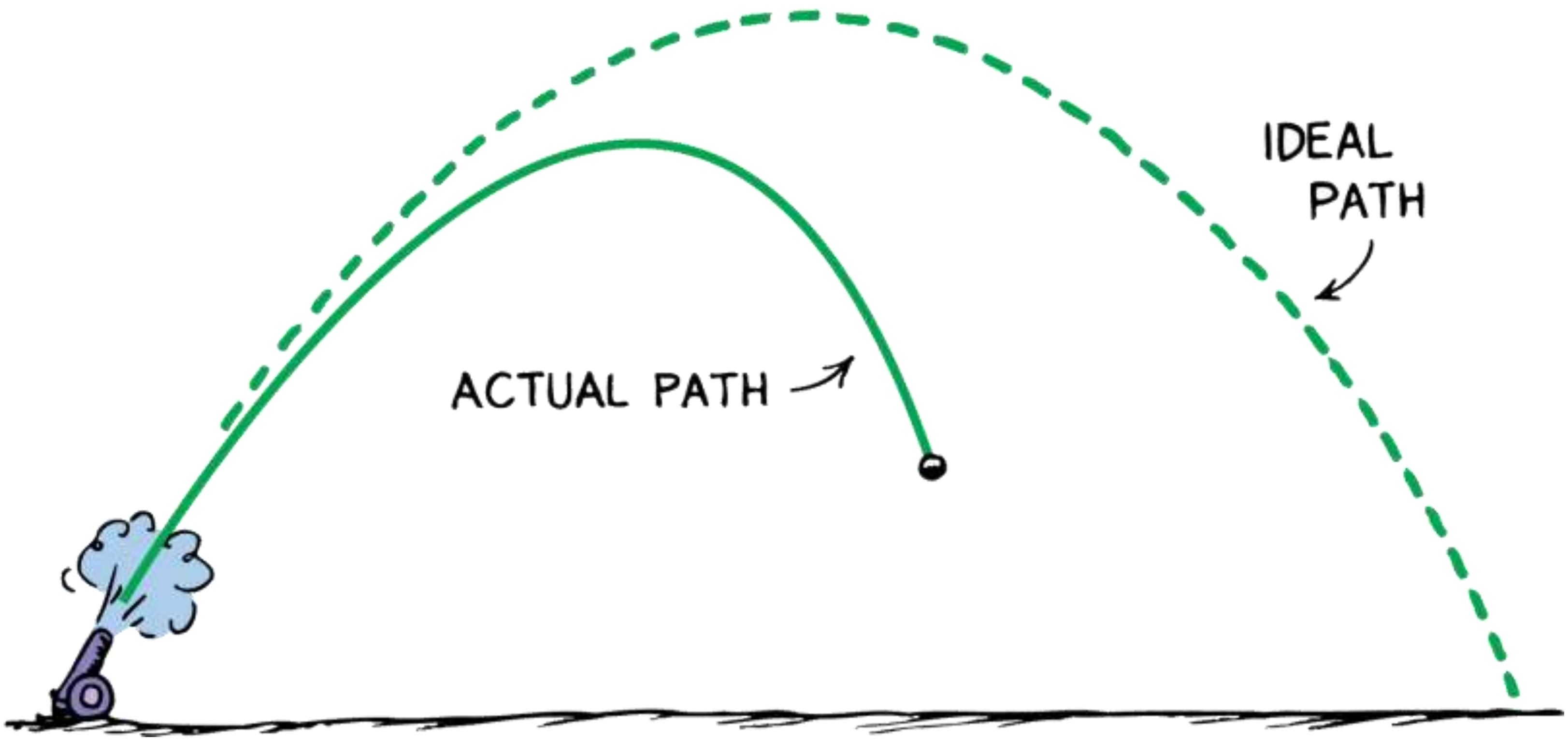
Without air resistance, the speed lost while the cannonball is going up equals the speed gained while it is coming down.

The time to go up equals the time to come down.

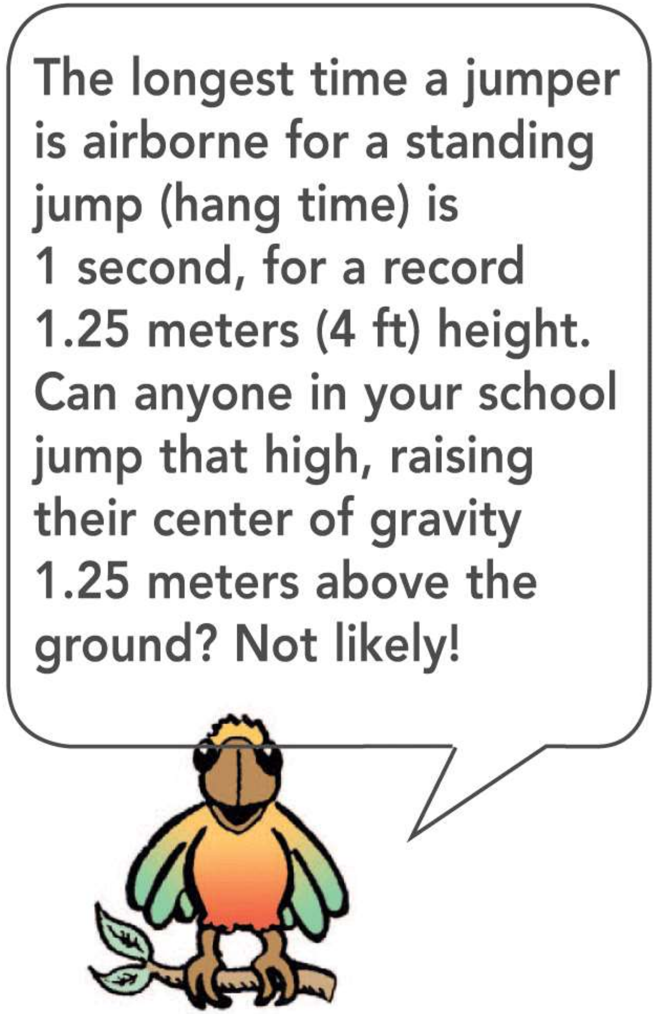


5.6 Projectiles Launched at an Angle

In the presence of air resistance, the path of a high-speed projectile falls below the idealized parabola and follows the solid curve.



5.6 Projectiles Launched at an Angle



5.6 Projectiles Launched at an Angle

think!

A projectile is launched at an angle into the air. Neglecting air resistance, what is its vertical acceleration? Its horizontal acceleration?

5.6 Projectiles Launched at an Angle

think!

A projectile is launched at an angle into the air. Neglecting air resistance, what is its vertical acceleration? Its horizontal acceleration?

Answer: Its vertical acceleration is *g* because the force of gravity is downward. Its horizontal acceleration is zero because no horizontal force acts on it.

5.6 Projectiles Launched at an Angle

think!

At what point in its path does a projectile have minimum speed?

5.6 Projectiles Launched at an Angle

think!

At what point in its path does a projectile have minimum speed?

Answer: The minimum speed of a projectile occurs at the top of its path. If it is launched vertically, its speed at the top is zero. If it is projected at an angle, the vertical component of velocity is still zero at the top, leaving only the horizontal component.

5.6 Projectiles Launched at an Angle

CONCEPT CHECK

Describe how far below an imaginary straight-line path a projectile falls.

Assessment Questions

1. Which of these expresses a vector quantity?
   a. 10 kg
   b. 10 kg to the north
   c. 10 m/s
   d. 10 m/s to the north

Assessment Questions

1. Which of these expresses a vector quantity?
   a. 10 kg
   b. 10 kg to the north
   c. 10 m/s
   d. 10 m/s to the north

Answer: D

Assessment Questions

2. An ultra-light aircraft traveling north at 40 km/h in a 30-km/h crosswind (at right angles) has a groundspeed of
   a. 30 km/h.
   b. 40 km/h.
   c. 50 km/h.
   d. 60 km/h.

Assessment Questions

2. An ultra-light aircraft traveling north at 40 km/h in a 30-km/h crosswind (at right angles) has a groundspeed of

   a. 30 km/h.

   b. 40 km/h.

   c. 50 km/h.

   d. 60 km/h.

Answer: C

Assessment Questions

3. A ball launched into the air at 45° to the horizontal initially has
   a. equal horizontal and vertical components.
   b. components that do not change in flight.
   c. components that affect each other throughout flight.
   d. a greater component of velocity than the vertical component.

Assessment Questions

3. A ball launched into the air at 45° to the horizontal initially has
   a. equal horizontal and vertical components.
   b. components that do not change in flight.
   c. components that affect each other throughout flight.
   d. a greater component of velocity than the vertical component.

Answer: A

Assessment Questions

4. When no air resistance acts on a fast-moving baseball, its acceleration is
   a. downward, *g*.
   b. due to a combination of constant horizontal motion and accelerated downward motion.
   c. opposite to the force of gravity.
   d. at right angles.

Assessment Questions

4. When no air resistance acts on a fast-moving baseball, its acceleration is
   a. downward, *g*.
   b. due to a combination of constant horizontal motion and accelerated downward motion.
   c. opposite to the force of gravity.
   d. at right angles.

Answer: A

Assessment Questions

5. When no air resistance acts on a projectile, its horizontal acceleration is
   a. *g*.
   b. at right angles to *g*.
   c. upward, *g*.
   d. zero.

Assessment Questions

5. When no air resistance acts on a projectile, its horizontal acceleration is

   a. *g*.

   b. at right angles to *g*.

   c. upward, *g*.

   d. zero.

Answer: D

Assessment Questions

6. Without air resistance, the time for a vertically tossed ball to return to where it was thrown is
   a. 10 m/s for every second in the air.
   b. the same as the time going upward.
   c. less than the time going upward.
   d. more than the time going upward.

Assessment Questions

6. Without air resistance, the time for a vertically tossed ball to return to where it was thrown is
   a. 10 m/s for every second in the air.
   b. the same as the time going upward.
   c. less than the time going upward.
   d. more than the time going upward.

Answer: B