1 Motion

1-1 Speed, Velocity, and Acceleration

Speed vs. Velocity

Vocabulary **Distance:** How far something travels.

Vocabulary **Displacement:** How far something travels in a given direction.

Notice that these two terms are very similar. **Distance** is an example of what we call a *scalar* quantity. In other words, it has magnitude, but no direction. **Displacement** is an example of a *vector* quantity because it has both magnitude and direction.

The SI (Système International) unit for distance and displacement is the **meter (m).**

Displacements smaller than a meter may be expressed in units of centimeters (cm) or millimeters (mm). Displacements much larger than a meter may be expressed in units of kilometers (km). See Appendix A for the meanings of these and other common prefixes.

Vocabulary **Speed:** How fast something is moving.

$$\textbf{average speed} = \frac{\textbf{distance traveled}}{\textbf{elapsed time}} \quad \text{or} \quad v_{av} = \frac{d}{\Delta t}$$

Vocabulary **Velocity:** How fast something is moving in a given direction.

$$\textbf{average velocity} = \frac{\textbf{displacement}}{\textbf{elapsed time}} \quad \text{or} \quad \mathbf{v}_{\mathbf{av}} = \frac{\Delta \mathbf{d}}{\Delta t} = \frac{\mathbf{d}_f - \mathbf{d}_o}{t_f - t_o}$$

where d_f and t_f are the final position and time respectively, and d_o and t_o are the initial position and time. The symbol "Δ" (delta) means "change" so $\Delta \mathbf{d}$ is the change in position, or the displacement, while Δt is the change in time.

In this book all vector quantities will be introduced in an equation with **bold type** while all scalar quantities will be introduced in an equation in regular type. Note that speed is a scalar quantity while velocity is a vector quantity.

The SI unit for both speed and velocity is the **meter per second (m/s).**

When traveling in any moving vehicle, you rarely maintain the same velocity throughout an entire trip. If you did, you would travel at a constant speed in a straight line. Instead, speed and direction usually vary during your time of travel.

If you begin and end at the same location but you travel for a great distance in getting there (for example, when you travel in a circle), you have a measurable average speed. However, since your total displacement for such a trip is zero, your average velocity is also zero. In this chapter, both average speed and average velocity will be written as v_{av}. The "av" subscript will be dropped in later chapters.

Acceleration

Vocabulary **Acceleration:** The rate at which the velocity changes during a given amount of time.

$$\textbf{acceleration} = \frac{\textbf{change in velocity}}{\textbf{elapsed time}} \quad \text{or} \quad a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_o}{t_f - t_o}$$

where the terms v_f and v_o mean final velocity and initial velocity, respectively.

The SI unit for acceleration is the **meter per second squared (m/s^2).**

If the final velocity of a moving object is smaller than its initial velocity, the object must be slowing down. A slowing object is sometimes said to have *negative acceleration* because the magnitude of the acceleration is preceded by a negative sign.

Solved Examples

Example 1: Benjamin watches a thunderstorm from his apartment window. He sees the flash of a lightning bolt and begins counting the seconds until he hears the clap of thunder 10. s later. Assume that the speed of sound in air is 340 m/s. How far away was the lightning bolt a) in m? b) in km? (Note: The speed of light, 3.0×10^8 m/s, is considerably faster than the speed of sound. That is why you see the lightning flash so much earlier than you hear the clap of thunder. In actuality, the lightning and thunder clap occur almost simultaneously.)

a. *Given:* $v_{av} = 340$ m/s
$\Delta t = 10.0$ s

Unknown: $\Delta d = ?$
Original equation: $v_{av} = \dfrac{\Delta d}{\Delta t}$

Solve: $\Delta d = v_{av}\Delta t = (340 \text{ m/s})(10. \text{ s}) = \mathbf{3400 \text{ m}}$

b. For numbers this large you may wish to express the final answer in km rather than in m. Because "kilo" means 1000, then 1.000 km = 1000. m.

$$3400 \text{ m} \frac{(1.000 \text{ km})}{1000. \text{ m}} = \mathbf{3.4 \text{ km}}$$

The lightning bolt is 3.4 km away, which is just a little over two miles for those of you who think in English units!

Example 2: On May 28, 2000, Juan Montoya became the first Colombian citizen to win the Indianapolis 500. Montoya completed the race in a time of 2.98 h. What was Montoya's average speed during the 500.-mi race? (Note: Generally the unit "miles" is not used in physics exercises. However, the Indianapolis 500 is a race that is measured in miles, so the mile is appropriate here. Don't forget, the SI unit for distance is the meter.)

Given: $d = 500.$ mi
$\Delta t = 2.98$ h

Unknown: $v_{av} = ?$
Original equation: $\Delta t = \frac{\Delta d}{v}$

Solve: $\Delta t = \frac{\Delta d}{v} = \frac{500. \text{ mi}}{2.98 \text{ h}} = 168 \text{ mi/h}$

Example 3: The slowest animal ever discovered was a crab found in the Red Sea. It traveled with an average speed of 5.70 km/y. How long would it take this crab to travel 100. km?

Given: $\Delta d = 100.$ km
$v_{av} = 5.70$ km/y

Unknown: $\Delta t = ?$
Original equation: $\Delta t = \frac{\Delta d}{v_{av}}$

Solve: $\Delta t = \frac{\Delta d}{v_{av}} = \frac{100. \text{ km}}{5.70 \text{ km/y}} = \mathbf{17.5 \text{ y}}$ A long time!

Example 4: Tiffany, who is opening in a new Broadway show, has some limo trouble in the city. With only 8.0 minutes until curtain time, she hails a cab and they speed off to the theater down a 1000.-m-long one-way street at a speed of 25 m/s. At the end of the street the cab driver waits at a traffic light for 1.5 min and then turns north onto a 1700.-m.-long traffic-filled avenue on which he is able to travel at a speed of only 10.0 m/s. Finally, this brings them to the theater. a) Does Tiffany arrive before the theater lights dim? b) Draw a distance vs. time graph of the situation.

Solution: First, break this exercise down into segments and solve each segment independently.

Segment 1: (one-way street)

Given: $\Delta d = 1000.$ m
$v_{av} = 25$ m/s

Unknown: $\Delta t = ?$
Original equation: $v_{av} = \frac{\Delta d}{\Delta t}$

Solve: $\Delta t = \frac{\Delta d}{v_{av}} = \frac{1000. \text{ m}}{25 \text{ m/s}} = 40. \text{ s}$

Segment 2: (traffic light)

Given: $\Delta t = 1.5$ min $\quad (1.5 \text{ min})\dfrac{(60.\text{ s})}{(1.0 \text{ min})} = 90.\text{ s}$

Segment 3: (traffic-filled avenue)

Given: $\Delta d = 1700.\text{ m}$ $\quad$ *Unknown:* $\Delta t = ?$

$v_{av} = 10.0 \text{ m/s}$ $\quad$ *Original equation:* $v_{av} = \dfrac{\Delta d}{\Delta t}$

Solve: $\Delta t = \dfrac{\Delta d}{v_{av}} = \dfrac{1700.\text{ m}}{10.0 \text{ m/s}} = 170.\text{ s}$

total time $= 40.\text{ s} + 90.\text{ s} + 170.\text{ s} = 300.\text{ s}$ $\quad (300.\text{ s})\dfrac{(1.0 \text{ min})}{(60.\text{ s})} = \mathbf{5.0\ min}$

Yes, she not only makes it to the show in time, but she even has 3.0 minutes to spare to put on her costume and make-up.

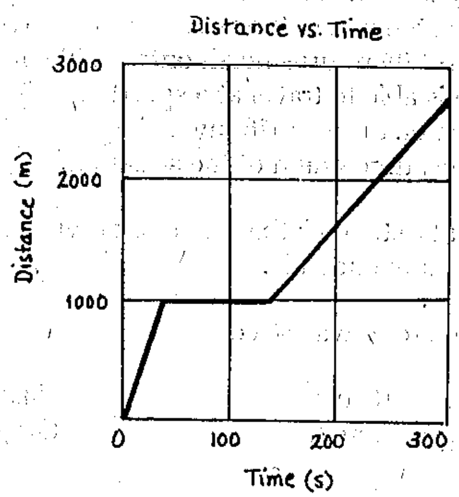
b. The motion of the cab can be described by the following graph.

In Segment 1, the distance of 1000. m was covered in a fairly short amount of time, which means that the cab was traveling quickly. This high speed can be seen as a steep slope on the graph.

In Segment 2, the cab was at rest. Notice that even though the cab did not move, time continued on, resulting in a horizontal line on the graph.

In Segment 3, the distance of 1700. m was covered in a much longer amount of time so the cab was traveling slowly. This low speed is indicated by a slope that is not as steep as that in segment 1.

Remember, all graphs should have titles and the axes should be labeled with the correct units.



Example 5: Grace is driving her sports car at 30 m/s when a ball rolls out into the street in front of her. Grace slams on the brakes and comes to a stop in 3.0 s. What was the acceleration of Grace's car?

Given: $v_o = 30\ \text{m/s}$
$v_f = 0\ \text{m/s}$
$\Delta t = 3.0\ \text{s}$

Unknown: $a = ?$
Original equation: $a = \dfrac{v_f - v_o}{\Delta t}$

Solve: $a = \dfrac{v_f - v_o}{\Delta t} = \dfrac{0\ \text{m/s} - 30\ \text{m/s}}{3.0\ \text{s}} = -10\ \text{m/s}^2$

The negative sign means the car was slowing down.

Practice Exercises

Exercise 1: Hans stands at the rim of the Grand Canyon and yodels down to the bottom. He hears his yodel echo back from the canyon floor 5.20 s later. Assume that the speed of sound in air is 340.0 m/s. How deep is the canyon at this location?

Answer: ________________

Exercise 2: The world speed record on water was set on October 8, 1978 by Ken Warby of Blowering Dam, Australia. If Ken drove his motorboat a distance of 1000. m in 7.045 s, how fast was his boat moving a) in m/s? b) in mi/h?

Answer: **a.** ________________

Answer: **b.** ________________

Exercise 3: According to the World Flying Disk Federation, on April 8, 2000, Jennifer Griffin of Fredericksburg, Virginia threw a Frisbee for a distance of 138.56 m to capture the women's record. If the Frisbee was thrown horizontally with a speed of 13.0 m/s, how long did the Frisbee remain aloft?

Answer: ____________________

Exercise 4: It is now 10:29 a.m., but when the bell rings at 10:30 a.m. Suzette will be late for French class for the third time this week. She must get from one side of the school to the other by hurrying down three different hallways. She runs down the first hallway, a distance of 35.0 m, at a speed of 3.50 m/s. The second hallway is filled with students, and she covers its 48.0-m length at an average speed of 1.20 m/s. The final hallway is empty, and Suzette sprints its 60.0-m length at a speed of 5.00 m/s. a) Does Suzette make it to class on time or does she get detention for being late again? b) Draw a distance vs. time graph of the situation.

Answer: **a.** ____________________

Exercise 5: A jumbo jet taxiing down the runway receives word that it must return to the gate to pick up an important passenger who was late to his connecting flight. The jet is traveling at 45.0 m/s when the pilot receives the message. What is the acceleration of the plane if it takes the pilot 5.00 s to bring the plane to a halt?

Answer: ____________________

Exercise 6: While driving his sports car at 20.0 m/s down a four-lane highway, Eddie comes up behind a slow-moving dump truck and decides to pass it in the left-hand lane. If Eddie can accelerate at 5.00 m/s^2, how long will it take for him to reach a speed of 30.0 m/s?

Answer: ____________________

Exercise 7: Vivian is walking to the hairdresser's at 1.3 m/s when she glances at her watch and realizes that she is going to be late for her appointment. Vivian gradually quickens her pace at a rate of 0.090 m/s^2. a) What is Vivian's speed after 10.0 s? b) At this speed, is Vivian walking, jogging, or running very fast?

Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 8: A torpedo fired from a submerged submarine is propelled through the water with a speed of 20.00 m/s and explodes upon impact with a target 2000.0 m away. If the sound of the impact is heard 101.4 s after the torpedo was fired, what is the speed of sound in water? (Because the torpedo is held at a constant speed by its propeller, the effect of water resistance can be neglected.)

Answer: ____________________

1-2 Free Fall

Vocabulary **Free Fall:** The movement of an object in response to a gravitational attraction.

When an object is released, it falls toward the earth due to the gravitational attraction the earth provides. As the object falls, it will accelerate at a constant rate of 9.8 m/s^2 regardless of its mass. However, to make calculations more expedient and easier to do without a calculator, this number will be written as $g = 10.0\ m/s^2$ throughout this book.

There are many different ways to solve free fall exercises. The sign convention used may be chosen by you or your teacher. In this book, the downward direction will be positive, and anything falling downward will be written with a positive velocity and position; anything moving upward will be represented with a negative velocity and position. Remember: Gravity *always* acts to pull an object down, so the gravitational acceleration, g, will always be written as a positive number regardless of which direction the object is moving.

The displacement of a falling object in a given amount of time is written as

$$\Delta d = v_o \Delta t + \left(\frac{1}{2}\right) g \Delta t^2$$

The final velocity of a falling object can be represented by the equation

$$v_f^2 = v_o^2 + 2g\Delta d$$

or by the earlier equation, $a = (v_f - v_o)/\Delta t$, rewritten as $v_f = v_o + a\Delta t$, or

$$v_f = v_o + g\Delta t$$

Note that the term "g" in all of these exercises can be written as "a" if you use a constant acceleration other than gravity. Therefore, these equations can be used for objects moving horizontally as well as vertically.

It is common to neglect air resistance in most free fall exercises (including those in this book), although in real life, air resistance is a factor that must be taken into account. This book will also assume that the initial speed of all objects in free fall is zero, unless otherwise specified.

Solved Examples

Example 6: King Kong carries Fay Wray up the 321-m-tall Empire State Building. At the top of the skyscraper, Fay Wray's shoe falls from her foot. How fast will the shoe be moving when it hits the ground?

Given: $v_o = 0\ \text{m/s}$
$g = 10.0\ \text{m/s}^2$
$\Delta d = 321\ \text{m}$

Unknown: $v_f = ?$
Original equation: $v_f^2 = v_o^2 + 2g\Delta d$

Solve: $v_f = \sqrt{v_o^2 + 2g\Delta d} = \sqrt{0 + 2(10.0\ \text{m/s}^2)(321\ \text{m})} = \sqrt{6420\ \text{m}^2/\text{s}^2}$
$= \mathbf{80.1\ m/s}$

Example 7: The Steamboat Geyser in Yellowstone National Park, Wyoming is capable of shooting its hot water up from the ground with a speed of 48.0 m/s. How high can this geyser shoot?

Solution: Remember, the geyser is shooting **up;** therefore it must have a negative initial velocity.

Given: $v_o = -48.0\ \text{m/s}$
$v_f = 0\ \text{m/s}$
$g = 10.0\ \text{m/s}^2$

Unknown: $\Delta d = ?$
Original equation: $v_f^2 = v_o^2 + 2g\Delta d$

Solve: $\Delta d = \dfrac{v_f^2 - v_o^2}{2g} = \dfrac{(0\ \text{m/s})^2 - (-48.0\ \text{m/s})^2}{2(10.0\ \text{m/s}^2)} = \mathbf{-115\ m}$

As you might expect, the final answer has a negative displacement. This means that the total distance the water has traveled is measured up from the ground.

Example 8: A baby blue jay sits in a tall tree awaiting the arrival of its dinner. As the mother lands on the nest, she drops a worm toward the hungry chick's mouth, but the worm misses and falls from the nest to the ground in 1.50 s. How high up is the nest?

Given: $v_o = 0\ \text{m/s}$
$g = 10.0\ \text{m/s}^2$
$t = 1.50\ \text{s}$

Unknown: $\Delta d = ?$
Original equation: $\Delta d = v_o\Delta t + \left(\frac{1}{2}\right)g\Delta t^2$

Solve: $\Delta d = v_o\Delta t + \left(\frac{1}{2}\right)g\Delta t^2 = 0 + \left(\frac{1}{2}\right)(10.0\ \text{m/s}^2)(1.50\ \text{s})^2 = \mathbf{11.3\ m}$

Example 9: A giraffe, who stands 6.00 m tall, bites a branch off a tree to chew on the leaves, and he lets the branch fall to the ground. How long does it take the branch to hit the ground?

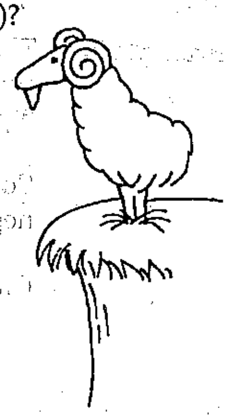
Given: $\Delta d = 6.00\ \text{m}$
$g = 10.0\ \text{m/s}^2$
$v_o = 0\ \text{m/s}$

Unknown: $\Delta t = ?$
Original equation: $\Delta d = v_o\Delta t + \left(\frac{1}{2}\right)g\Delta t^2$

Solve: $\Delta t = \sqrt{\dfrac{2\Delta d}{g}} = \sqrt{\dfrac{2(6.00\ \text{m})}{10.0\ \text{m/s}^2}} = \sqrt{1.20\ \text{s}^2} = \mathbf{1.10\ s}$

Practice Exercises

Exercise 9: Billy, a mountain goat, is rock climbing on his favorite slope one sunny spring morning when a rock comes hurtling toward him from a ledge 40.0 m above. Billy ducks and avoids injury. a) How fast is the rock traveling when it passes Billy? b) How does this speed compare to that of a car traveling down the highway at the speed limit of 25 m/s (equivalent to 55 mi/h)?



Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 10: Reverend Northwick climbs to the church belfry one morning to determine the height of the church. From an outside balcony he drops a book and observes that it takes 2.00 s to strike the ground below. a) How high is the balcony of the church belfry? b) Why would it be difficult to determine the height of the belfry balcony if the Reverend dropped only one page out of the book?

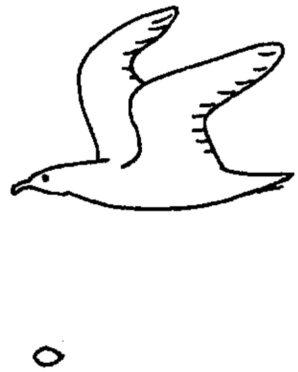
Answer: **a.** ____________________

Answer: **b.** ____________________

Exercise 11: How long is Tina, a ballerina, in the air when she leaps straight up with a speed of 1.8 m/s?

Answer: ____________________

Exercise 12: In order to open the clam it catches, a seagull will drop the clam repeatedly onto a hard surface from high in the air until the shell cracks. If a seagull flies to a height of 25 m, how long will the clam take to fall?



Answer: ____________________

Exercise 13: At Six Flags Great Adventure Amusement Park in New Jersey, a popular ride known as "Free Fall" carries passengers up to a height of 33.5 m and drops them to the ground inside a small cage. How fast are the passengers going at the bottom of this exhilarating journey?

Answer: ____________________

Exercise 14: A unique type of basketball is played on the planet Zarth. During the game, a player flies above the basket and drops the ball in from a height of 10 m. If the ball takes 5.0 s to fall, find the acceleration due to gravity on Zarth.

Answer: ____________________

Additional Exercises

A-1: During an Apollo moon landing, reflecting panels were placed on the moon. This allowed earth-based astronomers to shoot laser beams at the moon's surface to determine its distance. The reflected laser beam was observed 2.52 s after the laser pulse was sent. If the speed of light is 3.00×10^8 m/s, what was the distance between the astronomers and the moon?

A-2: The peregrine falcon is the world's fastest known bird and has been clocked diving downward toward its prey at constant vertical velocity of 97.2 m/s. If the falcon dives straight down from a height of 100. m, how much time does this give a rabbit below to consider his next move as the falcon begins his descent?

A-3: The Kentucky Derby, the first of three horse races for the triple crown, was won on May 7, 2000 by Fusaichi Pegasus with a time of 121.1 s. If the race covers 2011.25 m, what was Fusaichi Pegasus' average speed in a) m/s? b) mi/h?

A-4: For years, the posted highway speed limit was 88.5 km/h (55 mi/h) but now some rural stretches of highway have posted speed limits of 104.6 km/h (65 mi/h). In Maine, the distance from Portland to Bangor is 215 km. How much time can be saved in traveling from Portland to Bangor at this higher speed limit?

A-5: A tortoise and a hare are in a road race to defend the honor of their breeds. The tortoise crawls the entire 1000.-m distance at a speed of 0.2000 m/s while the rabbit runs the first 200.0 m at 2.000 m/s. The rabbit then stops to take a nap for 1.300 h and awakens to finish the last 800.0 m with an average speed of 3.000 m/s. a) Who wins the race and by how much time? b) Draw a graph of distance vs. time for the situation.

A-6: Two physics professors challenge each other to a 100.-m race across the football field. The loser will grade the winner's physics labs for one month. Dr. Nelson runs the race in 10.40 s. Dr. Bray runs the first 25.0 m with an average speed of 10.0 m/s, the next 50.0 m with an average speed of 9.50 m/s, and the last 25.0 m with an average speed of 11.1 m/s. Who gets stuck grading physics labs for the next month?

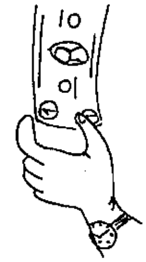
A-7: A caterpillar crawling up a leaf slows from 0.75 cm/s to 0.50 cm/s at a rate of -0.05 cm/s^2. How long does it take the caterpillar to make the change?

A-8: In the Wizard of Oz, Dorothy awakens in Munchkinland where her house has been blown by a tornado. If the house fell from a height of 3000. m, with what speed did it hit the Wicked Witch of the East when it landed?

A-9: The Tambora volcano on the island of Sumbawa, Indonesia has been known to throw ash into the air with a speed of 625 m/s during an eruption. a) How high could this volcanic plume have risen? b) On Venus, where the acceleration due to gravity is slightly less than on Earth, would this volcanic plume rise higher or not as high as it does on Earth?

A-10: Chief Boolie, the jungle dweller, is out hunting for dinner when a coconut falls from a tree and lands on his toe. If the nut fell for 1.4 s, how fast was it traveling when it hit Chief Boolie's toe?

A-11: Here is a bet that you are almost sure to win! Try dropping a dollar bill through a friend's fingers and offer to let her keep it if she can catch it. The bill should be started just at the finger level and your friend shouldn't have any advanced warning when it is going to drop. A dollar bill has a length of 15.5 cm and human reaction time is rarely less than 0.20 s. Do the necessary calculations—why is this almost a sure bet?



A-12: While repairing a defective radio transmitter located 410 m up on the Skydeck of Chicago's Sears Tower, Lyle drops his hammer that falls all the way to the ground below. a) How long will it take for Lyle's hammer to fall? b) With what speed will the hammer hit the pavement? c) How far will the hammer have fallen after 1.50 s when a janitor watches it pass outside an office window?

A-13: On July 31, 1994, Sergey Bubka of the Ukraine broke his own world pole-vaulting record by attaining a height of 6.14 m. a) How long did it take Bubka to return to the ground from the highest part of his vault? b) Describe how this time compares to the time it took him to go from the ground to the highest point.

A-14: A Christmas tree ball will break if dropped on a hardwood floor with a speed of 2.0 m/s or more. Holly is decorating her Christmas tree when her cat, Trickor, taps a ball, causing it to fall 15 cm from a tree branch to the floor. Does the ball break?

A-15: Perhaps sometime in the future, NASA will develop a program to land a human being on Mars. If you were the first Mars explorer and discovered that when you dropped a hammer it took 0.68 s to fall 0.90 m to the ground, what would you calculate for the gravitational acceleration on Mars?

Challenge Exercises for Further Study

B-1: Seth is doing his student driving with the "Give-Me-A-Brake" driving school and is traveling down the interstate with a speed of 9.0 m/s. Mack is driving his "18-wheeler" down the fast lane at 27.0 m/s when he notices Seth 30.0 m ahead of him in the right lane. a) If Mack and Seth maintain their speeds, how far must Mack travel before he catches up to Seth? b) How long will this take?

B-2: At the 2000 summer Olympics in Sydney Australia, the women's 400-m medley swimming relay was won by the United States. The four U.S. women swam the 100.0-m leg of the race with the following average speeds: Barbara Bedford (backstroke) at 1.6289 m/s, Megan Quann (breaststroke) at 1.5085 m/s, Jenny Thompson (fly) at 1.7467 m/s and Dara Torres (freestyle) at 1.8737 m/s. a) How far was the team's final time from the world record time of 4.028 min. set by the Chinese in 1994? b) Did the American women break the world record, or miss it? c) What was the U.S. team's average speed for the 400.0-m race?

B-3: In 1945, the *Enola Gay*, a B-29 bomber, dropped the atomic bomb from a height of 9450 m over Hiroshima, Japan. If the plane carrying the bomb were traveling with a horizontal velocity of 67.0 m/s, how far horizontally would the bomb have traveled between the point of release and the point where it exploded 513 m above the ground? (To avoid being above the bomb when it exploded, the Enola Gay turned sharply away after the bomb's release.)

B-4: Pepe, the clown, is jumping on a trampoline as Babette, the tightrope walker, above him suddenly loses her balance and falls off the tightrope straight toward Pepe. Pepe has just started upward at 15 m/s when Babette begins to fall. Pepe catches her in midair after 1.0 s. a) How far has Babette fallen when she is caught by Pepe? b) What is Babette's velocity at the time of contact? c) What is Pepe's velocity at the time of contact? d) How far above the trampoline was Babette before she fell?

B-5: Mr. DeFronzo has just learned that he won the Presidential Award for Excellence in Science Teaching. He runs to the open window and throws his red marking pen into the air with an initial upward speed of 5.00 m/s. a) If the window is 12.0 m above the ground, what is the velocity of the pen 1.0 s after it is thrown? b) How far has the pen fallen from its starting position after 2.0 s? c) How long does it take the pen to hit the ground?

B-6: On October 24, 1901 Annie Edson Taylor, a school teacher from Michigan, became the first person to successfully ride over Niagara Falls in a wooden barrel. Assume Annie began her journey at Goat Island, 240. m from the falls, where the water current started her down the Niagara River at 8.00 m/s. During her journey, the current reached 15.0 m/s as it carried Annie over Horseshoe Falls, a drop of 51.0 m. How long was Annie's trip from start to finish?