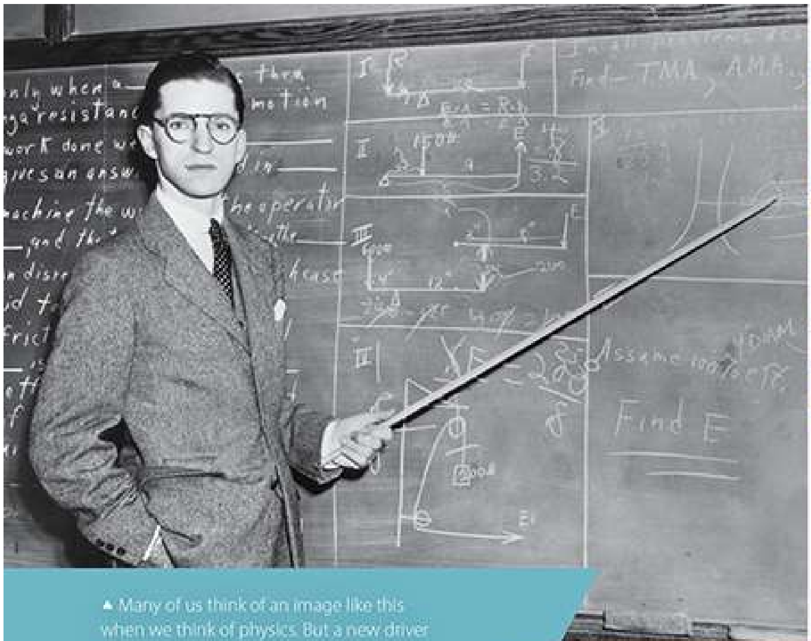



▲ Many of us think of an image like this when we think of physics. But a new driver must master the physics of driving, and a skater might understand some aspects of physics even more than the scientist.

# Everything Is Physics

As students begin their study of physics, there are many thoughts about just what physics is. Some say it is challenging, and there certainly are challenging aspects of the subject. Others say that it is an advanced science; that is true regarding some fields of physics. But in reality physics is very basic. Some physicists enjoy pointing out that everything is physics. What do they mean by that?

Think about what interests you. Is it music? art? photography? sports? hiking? cooking? The list can go on. All these things, actually everything, can be explained using physics. Music is produced when a musician applies a force to his instrument to create a vibration that produces resonance in the instrument. The instrument carries energy away in the form of sound waves, which then arrive at our ear. The waves transfer energy through the mechanical linkages in the ear to our inner ear. Mechanical waves are produced in the fluid in the cochlea. The cochlea produces electrical signals that move along the auditory nerve to our brain which decodes the music. Physics can be—and is—used to describe each of the steps in this process.

Not all of us are expert musicians, but we are all skilled applied physicists. Whether we walk, run, stand up, sit down, throw something, or catch something, our actions involve physics principles, and our mastery of these activities is evidence of our understanding of physics. So what is the purpose of this textbook? It will help you to understand the physics behind everyday tasks that are grounded in physics, such as walking, running, driving a car, playing an instrument, and playing football. You will learn the theory behind the physics and the mathematics that models the physics. You will become a *theoretical* physicist in addition to being an *applied* physicist. You will see how the Bible accounts for the possibility of physics itself.

▲ The f-stop on a camera is related to light optics—a field of physics.

Though the Bible establishes science's purpose, it is not a physics textbook or a scientific reference book. Nor would we want it to be! Physics and science change, but God's Word is the unchanging basis for a biblical worldview. In contrast, most scientists today work from within a *naturalistic worldview*. They assume that all phenomena have only natural causes and reject the existence of anything supernatural. Thus, naturalistic science is essentially atheistic, even though individual scientists may believe in a god. Do physics and the Bible relate to each other?

- Is physics incompatible with the Bible, or does physics explain the universe that God created?
- Is there a right use of physics from an ethical standpoint?
- What does physics and the Bible teach about the origins of the universe and life?
- Why should a Christian study science, in general, and more specifically, physics?

Through your study of physics, you will learn the answers to these questions.

# Features of This Textbook

This textbook is for you, and we've designed it to help you learn. Flip through the following pages to see its features, which we believe will help you succeed in physics. In the back of the textbook you will see other features, including an appendix section, glossary, index, and periodic table. We've designed this textbook with you in mind. We hope that it will help you appreciate the wonders of God's creation even more.

**1 Chapter Opener**
short articles that highlight issues and developments in physics that demonstrate how physics intersects with your life


**2 Essential Question**
the big question that you will learn about in a section

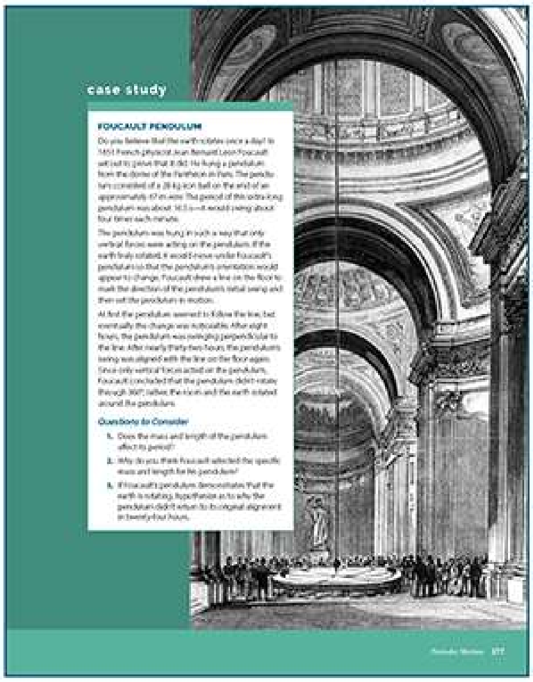
**3 Key Questions**
the smaller questions that you can ask along the way through a section to help you answer the essential question

**4 Vocabulary Terms**
the key terms that will be introduced in a section

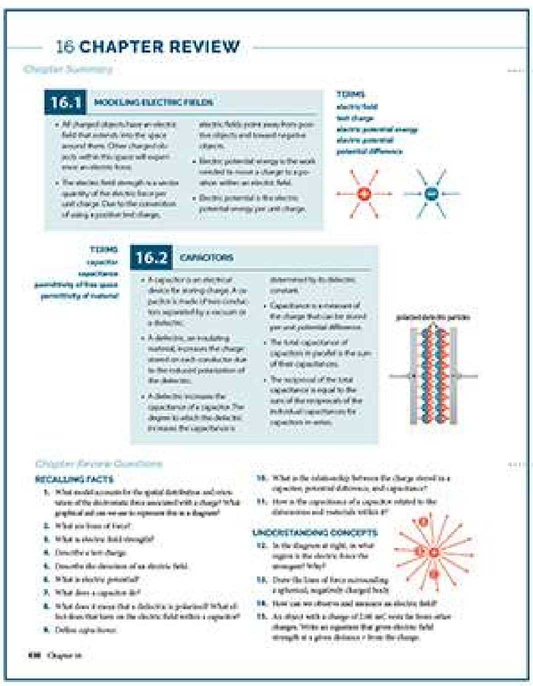
**5 ConnectConcepts**
short text connecting the current chapter to previously learned material

**6 Bold-Faced Terms**
vocabulary terms that you need to know

**7 Italicized Terms**
terms that will be defined later in the textbook or that are important terms in other scientific fields




**8 Case Studies**
opportunities to investigate specific areas in physics to apply what you have learned in a chapter



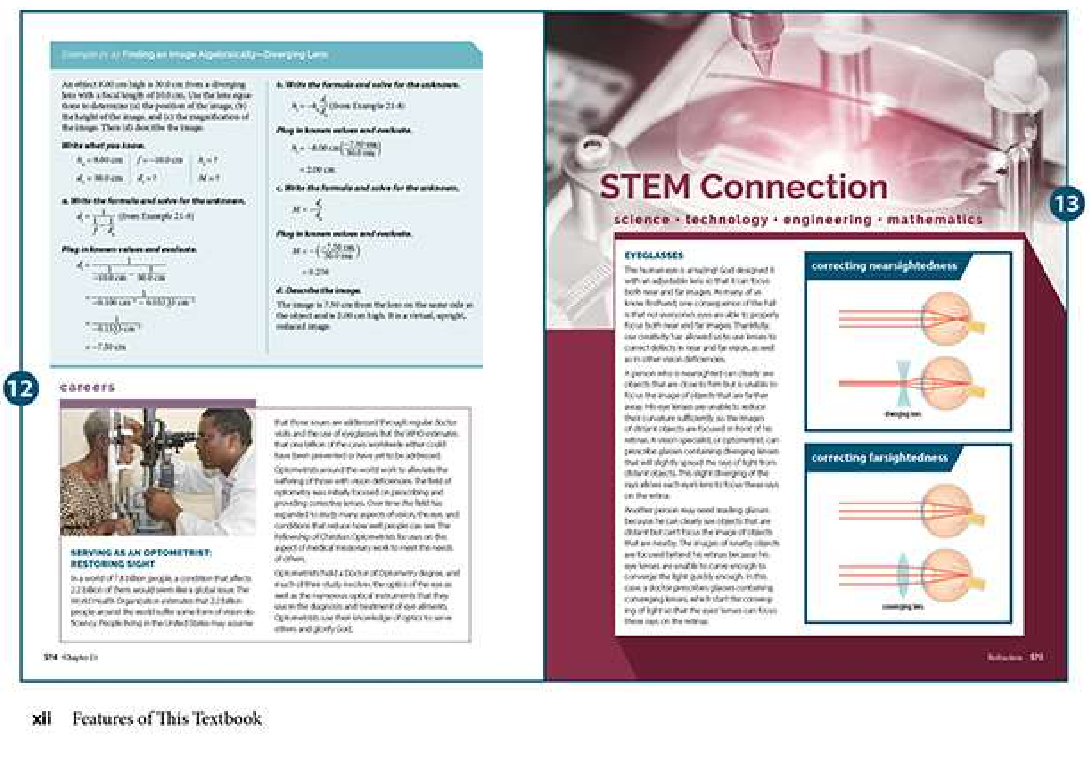

**9 Chapter Summary**
handy statements of the big ideas of the chapter, including vocabulary lists

**10 Review Questions**
questions at the end of each section and chapter that will have you recall facts, demonstrate your understanding of concepts, and cause you to use critical thinking

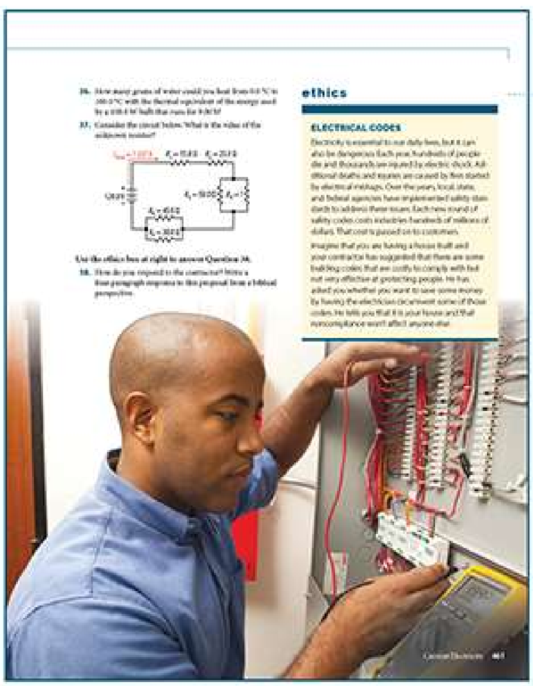
**11** **Mini Labs**
short hands-on activities to get you thinking and working like a scientist

**12** **Career Boxes**
information about careers in physics (that could be yours!) that can be followed to wisely use God's world and help people!

**13** **STEM Connection Boxes**
descriptions of how science, technology, engineering, and mathematics (STEM) work together to solve real-world problems


**14 Worldview Investigation Boxes**
inquiry-based investigations that help you think through controversial areas of physics through the lens of Scripture




**15 Ethics Boxes**
opportunities to apply a biblical worldview to ethical issues in physics

# 4 Motion in Two Dimensions



# 4.1 Kinematics of Two-Dimensional Motion

Areas inhabited by people with the greatest needs are often the most inaccessible. Populated locales devastated and isolated by war or large-scale natural disasters quickly become uninhabitable. Homes are destroyed and utility networks are disrupted. Electricity and clean water supplies are in short supply, and sewage can't be disposed of properly. Roads, bridges, and airfields may be inaccessible, cutting off areas from the outside world. Governmental authority wanes, and local medical establishments may be overwhelmed with patients. The fabric of civilized living unravels. People surviving in such circumstances urgently need water, food, shelter, and medical care. The lack of transportation and communication amplifies these problems. How can humanitarian aid be delivered to such isolated and needy people? As we'll see later in this chapter, physics can help answer that question.

***How does a pilot correct for the wind?***

**QUESTIONS**

- How can we identify the positions of objects?
- How are vectors used to solve problems in kinematics?

**TERMS**

none

**ConnectConcepts**

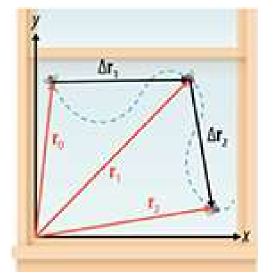
In this chapter we will be connecting the concepts of kinematics from Chapter 2 with the vector operations from Chapter 3.

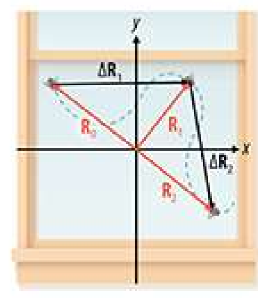
## Position Vectors in Two Dimensions

Analyzing position and motion in two dimensions is only slightly more complicated than analyzing one-dimensional motion. Positions, displacements, velocities, and accelerations in two dimensions are all vector quantities that can be resolved into their components. Components can be analyzed using the equations of motion derived in Chapter 2.

In straight-line motion, we located an object by its position on a one-dimensional number line using coordinates. In two-dimensional motion position is typically determined using the rectangular Cartesian coordinate system. By convention, the $x$-axis is horizontal and the $y$-axis is vertical.

Position in two dimensions is determined by the position vector ($\mathbf{r}$). The tail of the position vector is at the origin of the coordinate system, and the head is at the object's location. The diagram at right shows the path of a fly on a window pane. At time $t_0$, the fly is at the tip of $\mathbf{r}_0$; at time $t_1$, the fly is at the tip of $\mathbf{r}_1$; at time $t_2$, the fly is at the tip of $\mathbf{r}_2$. The origin is at the lower left corner of the window. The next figure shows the same path of the fly, but now the origin is at the center of the window. Although the positions of the fly are identical, the position vectors are different when measured from the different reference points. Recall from Chapter 2 that a frame of reference is simply the coordinate system within which motion is measured or observed. In theory, an infinite number of reference frames is possible.




## Displacement in Two Dimensions

The displacement of an object is its change in position represented by the difference vector $\Delta\mathbf{r}$. The displacement for an interval of time is

$$\Delta\mathbf{r} = \mathbf{r}_f - \mathbf{r}_i,$$

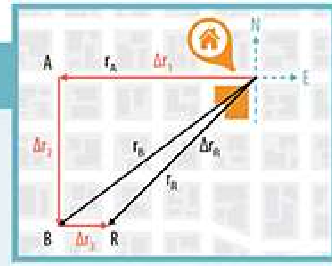
where $\mathbf{r}_f$ is the final position vector and $\mathbf{r}_i$ is the initial position vector. For instance, the fly's displacement ($\Delta\mathbf{r}_1$) for the interval $t_0$ to $t_1$ in the first figure is

$$\Delta\mathbf{r}_1 = \mathbf{r}_1 - \mathbf{r}_0;$$

for the second it is

$$\Delta\mathbf{R}_1 = \mathbf{R}_1 - \mathbf{R}_0.$$

The displacement is the same no matter which reference frame is used. Recall from Chapter 3 that we can also calculate a resultant vector by doing vector addition with the individual vectors. So a total displacement may be found by finding the change in position or adding the displacement vectors. The approach we take will depend on the problem.




### *Example 4-1* Determining Two-Dimensional Displacement

A jogger starts from home and jogs 400 m west to corner A, turns and jogs 300 m south to corner B, and then turns east and jogs for another 100 m before stopping to rest at point R. Using the jogger's home as the origin of the coordinate system, we draw the jogger's complete path and the position vectors to A, B, and R.

a. What is the jogger's displacement from corner A to corner B?

b. What is his displacement from home to the resting spot?

c. What is the total distance that he jogged?

***Write what you know.***

Refer to the figure above.

***Write the formula and solve for the unknown.***

a. $\Delta\mathbf{r}_2 = \mathbf{r}_B - \mathbf{r}_A$

$= \langle -400, -300\rangle\ \text{m} - \langle -400, 0\rangle\ \text{m} = \langle 0, -300\rangle\ \text{m}$

$= 300$ m south

b. $\Delta\mathbf{r}_3 = \mathbf{r}_R - \mathbf{0} = \mathbf{r}_R$ (A *zero vector* (**0**) is any vector with zero magnitude. The position vector of the origin, which is required when determining any displacement from the origin, is **0**.)

Determine the components of $\mathbf{r}_R$.

$\mathbf{r}_{R_{x,w}} = -300$ m (west)

$\mathbf{r}_{R_{y,s}} = -300$ m (south)

$|\mathbf{r}_R| = \sqrt{(-300\ \text{m})^2 + (-300\ \text{m})^2} = \sqrt{180\,000\ \text{m}^2}$

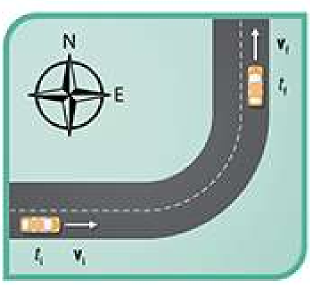
$= 424$ m

$$\alpha = \tan^{-1}\frac{|\mathbf{r}_{R_{y,s}}|}{|\mathbf{r}_{R_{x,w}}|} = \tan^{-1}\left(\frac{300\ \text{m}}{300\ \text{m}}\right) = 45°$$

The displacement is 424 m at 45° south of west.

c. $d_{total} = (400\ \text{m} + 300\ \text{m} + 100\ \text{m})$

$= 800$ m




## Velocity and Speed in Two Dimensions

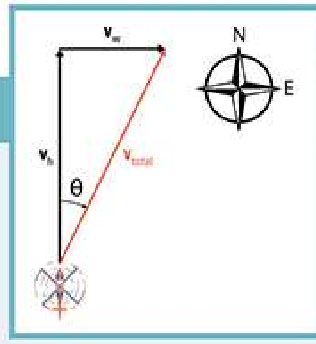
Average velocity and average speed between two positions in a Cartesian plane are determined as they are in one dimension. Use vector notation when describing average velocity in two dimensions.

average velocity: $\bar{\mathbf{v}} = \frac{\Delta\mathbf{r}}{\Delta t}$

average speed: $speed = \frac{distance}{\Delta t}$

The instantaneous velocity vector, which is the velocity of an object at any given moment, has a magnitude equal to the object's speed at that instant and points in the direction that the object is moving at that time. The diagram at left shows the instantaneous velocity of a car traveling around a curve. At time $t_i$ the vector points east, but at time $t_f$ the vector points north. In two- or three-dimensional motion we must include information about the direction of the motion.

The instantaneous speed is equal to the magnitude of the instantaneous velocity, $v = |\mathbf{v}|$. For instance, in the diagram on the previous page, if $|\mathbf{v}_i|$ equals $|\mathbf{v}_f|$ and $|\mathbf{v}|$ remains constant through the curve, the speed of the car is constant. Depending on the object's motion, the average speed and the magnitude of the average velocity may be quite different. These quantities are equal only if the distance equals the magnitude of the displacement, which can occur only in one-dimensional motion.




### *Example 4-2* Determining Two-Dimensional Velocity

A pilot flies a crop dusting helicopter above a field of sugar beets. She is flying 15.00 kph, aiming the copter due north ($\mathbf{v}_h$), but a 5.00 kph wind blowing due east ($\mathbf{v}_w$) also affects her copter. (a) What is the copter's resultant velocity vector? (b) How could she correct the copter's heading so that it is able to fly due north?

***Write what you know.***

$\mathbf{v}_w$ = 5.00 km/h east = <5.00, 0> km/h

$\mathbf{v}_h$ = 15.00 km/h north = <0,15.00> km/h

***Write the formula and solve for the unknown.***

$$\mathbf{v}_{total} = \mathbf{v}_w + \mathbf{v}_h$$

***Plug in known values and evaluate.***

a. $\mathbf{v}_{total}$ = <5.00, 0> km/h + <0, 15.00> km/h

= <5.00, 15.00> km/h

total speed:

$$|\mathbf{v}_{total}| = \sqrt{(\mathbf{v}_x)^2 + (\mathbf{v}_y)^2}$$

$$= \sqrt{(5.00\ \text{km/h})^2 + (15.00\ \text{km/h})^2}$$

$$= \sqrt{25.0\ \text{km}^2/\text{h}^2 + 225.0\ \text{km}^2/\text{h}^2}$$

$$= 15.8\ \text{km/h}$$

copter's direction:

$$\theta = \tan^{-1}\left(\frac{v_x}{v_y}\right)$$

$$= \tan^{-1}\left(\frac{|5.00\ \cancel{\text{km/h}}|}{|15.00\ \cancel{\text{km/h}}|}\right)$$

$$= 18.4°$$

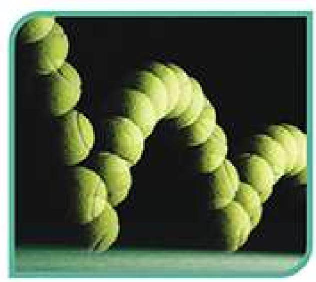
The vector $\mathbf{v}_{total}$ is 15.8 kph at 18.4° east of north.

b. She will have to fly her copter at 15.8 kph and pointed to 18.4° to the west of north to fly due north.

## Acceleration in Two Dimensions

A vector can change in any of three ways: magnitude only, direction only, or both magnitude and direction. Most real motion involves the third kind. Recall from Chapter 2 that acceleration is the rate of change of the velocity vector. The average acceleration vector ($\bar{\mathbf{a}}$) is equal to the change in velocity divided by the time interval.

$$\bar{\mathbf{a}} = \frac{\Delta \mathbf{v}}{\Delta t} = \frac{\mathbf{v}_f - \mathbf{v}_i}{\Delta t} \qquad (4.1)$$

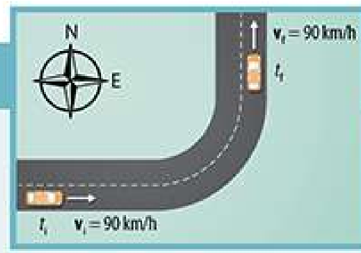


▲ Acceleration in two dimensions. The velocity of the ball changes as it bounces up and down and slows down while moving left to right.

The direction of the average acceleration is always the same direction as the velocity difference vector, regardless of the direction of motion. For example, as a car slows to a stop at a traffic light, the magnitude of its final velocity is less than the magnitude of its initial velocity, so $\Delta\mathbf{v}$ points in the direction opposite the car's motion. Therefore, as the car slows, $\bar{\mathbf{a}}$ points in the opposite direction from **v**. But when a moving object changes *direction*, its acceleration vector is always at an angle to its path. As with velocity, acceleration direction is indicated by a vector angle.

The instantaneous acceleration of an object is its acceleration at a particular moment. Its vector also points in the direction of the instantaneous velocity difference vector. In two-dimensional motion, determining the instantaneous change in velocity can be fairly complicated without the use of calculus. We will limit the discussion of acceleration to problems where either direction or speed vary but not both. As with one-dimensional acceleration, if the acceleration is uniform, then the average and instantaneous accelerations are the same.

### *Example 4-3* Determining Two-Dimensional Acceleration




A car heading due east at 90.0 kph enters a curve in the road. The curve ends with the car heading due north at 90.0 kph. Determine the car's average acceleration if the turn took 5.0 s.

***Write what you know.***

A diagram of the car on the curve is given at right. Note the orientation of the initial and final velocity vectors.

$\mathbf{v}_i = 90.0$ km/h east $= <90.0, 0.0>$ km/h

$\mathbf{v}_f = 90.0$ km/h north $= <0.0, 90.0>$ km/h

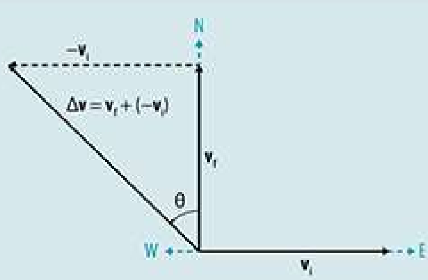
$\Delta t = 5.0$ s

$\bar{\mathbf{a}} = ?$

***Write the formula and solve for the unknown.***

$$\Delta \mathbf{v} = \mathbf{v}_f - \mathbf{v}_i = \mathbf{v}_f + (-\mathbf{v}_i)$$

$$\bar{\mathbf{a}} = \frac{\Delta \mathbf{v}}{\Delta t}$$




***Plug in known values and evaluate.***

$$-\mathbf{v}_i = <-90.0, 0.0> \text{ km/h}$$

$$\Delta \mathbf{v} = <0.0, 90.0> \text{ km/h} + <-90.0, 0.0> \text{ km/h} = <-90.0, 90.0> \text{ km/h}$$

$$\Delta v = \sqrt{(\Delta \mathbf{v}_x)^2 + (\Delta \mathbf{v}_y)^2} = \sqrt{(-90.0 \text{ km/h})^2 + (90.0 \text{ km/h})^2} = 127.\underline{2}7 \text{ km/h}$$

***Determine the direction of Δv.***

$$\theta = \tan^{-1}\left(\frac{\Delta v_x}{\Delta v_y}\right) = \tan^{-1}\left(\frac{90.0 \text{ km/h}}{90.0 \text{ km/h}}\right) = 45.0°$$

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{127.\underline{2}7 \frac{\text{km}}{\text{h}}\left(\frac{1000 \text{ m}}{1 \text{ km}}\right)\left(\frac{1 \text{ h}}{3600 \text{ s}}\right)}{5.0 \text{ s}} = 7.1 \text{ m/s}^2$$

The average acceleration of the car 7.1 m/s² at 45° west of north.

## 4.1 SECTION REVIEW

1. In physics, a location in two dimensions is most efficiently represented by what quantity?
2. Describe how displacement is calculated in two-dimensional motion. In your answer include the formula that you would use.
3. How is the direction of the average acceleration vector determined if you are given the initial and final velocities?
4. A visitor walks directly from the White House 1.83 km in the direction 20° south of east. Then he turns left and walks due east for an additional 0.67 km. He turns and walks 0.25 km due south to the US Capitol Building. What is his displacement from the White House?
5. A quarterback is attempting to run toward his goal line at 4.6 m/s. A linebacker hits him and their combined final velocity is 3.7 m/s at an angle of 120° back and to the left of the quarterback's original direction. The time to change direction was 0.20 s. Calculate the average acceleration of the quarterback during the tackle.
6. An athlete sprints a circular 400.0 m track in 50.0 s. Assume that he runs at a constant speed.
   a. What is his speed over the entire course?
   b. What is the magnitude of his instantaneous velocity at any point along the circuit?
   c. If he starts facing west, what is his instantaneous velocity halfway around the circle?
   d. What is the average acceleration for one-half lap of the track?

**Use the careers box below to answer Questions 7–8.**

7. Describe a challenge that a humanitarian engineer working with a remote people group might face that would not be an issue for an engineer working in an urban environment.
8. Why might a Christian consider a career as a humanitarian engineer?

## careers

### SERVING AS A HUMANITARIAN ENGINEER: HELPING WHERE IT IS MOST NEEDED

In 2000 engineering professor Dr. Bernard Amadei visited a Mayan village in Belize that lacked a clean water supply. In fact, the village children could not attend school because their time was devoted to collecting water from sources located miles away. After consulting with his colleagues on possible solutions, Dr. Amadei and a team of students from the University of Colorado Boulder returned to the village. The team built a new water supply system powered by energy from a nearby waterfall. Soon afterward Dr. Amadei founded Engineers Without Borders, an aid organization dedicated to providing engineered solutions to problems faced by people in need around the world.

Helping people in need can provide a great deal of personal satisfaction. Today you can get a college degree in humanitarian engineering. Engineers like the one shown at right, specialize in applying their knowledge and training to meeting the needs of people whose lives have been adversely affected by war, poverty, or disaster. As a humanitarian engineer, you might work on a drinking water project like the one in Belize, or perhaps you'll find ways to use diminishing natural resources more efficiently and sustainably. One key to providing workable long-term solutions to such problems is to find answers that are affordable, self-sustaining, and designed to make good use of local resources—including the skills and labor of local people. If you enjoy physics, like to find answers to real-life problems, and have a heart to serve others, humanitarian engineering may be the right career path for you.