

UNITS, PHYSICAL QUANTITIES, AND VECTORS

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? Being able to predict the path of a thunderstorm is essential for minimizing the damage it does to lives and property. If a thunderstorm is moving at 20 km/h in a direction 53° north of east, how far north does the thunderstorm move in 1 h?

Physics is one of the most fundamental of the sciences. Scientists of all disciplines use the ideas of physics, including chemists who study the structure of molecules, paleontologists who try to reconstruct how dinosaurs walked, and climatologists who study how human activities affect the atmosphere and oceans. Physics is also the foundation of all engineering and technology. No engineer could design a flat-screen TV, an interplanetary spacecraft, or even a better mousetrap without first understanding the basic laws of physics.

The study of physics is also an adventure. You will find it challenging, sometimes frustrating, occasionally painful, and often richly rewarding. If you've ever wondered why the sky is blue, how radio waves can travel through empty space, or how a satellite stays in orbit, you can find the answers by using fundamental physics. You will come to see physics as a towering achievement of the human intellect in its quest to understand our world and ourselves.

In this opening chapter, we'll go over some important preliminaries that we'll need throughout our study. We'll discuss the nature of physical theory and the use of idealized models to represent physical systems. We'll introduce the systems of units used to describe physical quantities and discuss ways to describe the accuracy of a number. We'll look at examples of problems for which we can't (or don't want to) find a precise answer, but for which rough estimates can be useful and interesting. Finally, we'll study several aspects of vectors and vector algebra. Vectors will be needed throughout our study of physics to describe and analyze physical quantities, such as velocity and force, that have direction as well as magnitude.

LEARNING GOALS

By studying this chapter, you will learn:

- Three fundamental quantities of physics and the units physicists use to measure them.
- How to keep track of significant figures in your calculations.
- The difference between scalars and vectors, and how to add and subtract vectors graphically.
- What the components of a vector are, and how to use them in calculations.
- What unit vectors are, and how to use them with components to describe vectors.
- Two ways of multiplying vectors.

1.1 The Nature of Physics

Physics is an *experimental* science. Physicists observe the phenomena of nature and try to find patterns that relate these phenomena. These patterns are called physical theories or, when they are very well established and widely used, physical laws or principles.

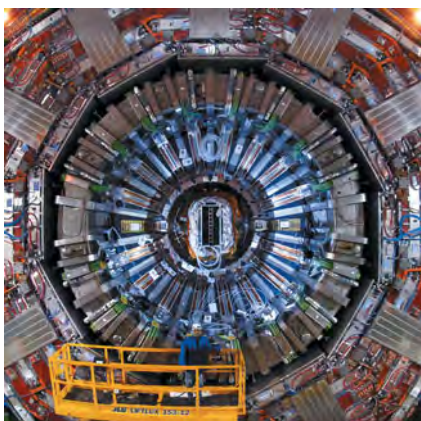
CAUTION The meaning of the word “theory” Calling an idea a theory does *not* mean that it’s just a random thought or an unproven concept. Rather, a theory is an explanation of natural phenomena based on observation and accepted fundamental principles. An example is the well-established theory of biological evolution, which is the result of extensive research and observation by generations of biologists. |

1.1 Two research laboratories. (a) According to legend, Galileo investigated falling bodies by dropping them from the Leaning Tower in Pisa, Italy, and he studied pendulum motion by observing the swinging of the chandelier in the adjacent cathedral. (b) The Large Hadron Collider (LHC) in Geneva, Switzerland, the world’s largest particle accelerator, is used to explore the smallest and most fundamental constituents of matter. This photo shows a portion of one of the LHC’s detectors (note the worker on the yellow platform).

(a)



(b)



To develop a physical theory, a physicist has to learn to ask appropriate questions, design experiments to try to answer the questions, and draw appropriate conclusions from the results. Figure 1.1 shows two famous facilities used for physics experiments.

Legend has it that Galileo Galilei (1564–1642) dropped light and heavy objects from the top of the Leaning Tower of Pisa (Fig. 1.1a) to find out whether their rates of fall were the same or different. From examining the results of his experiments (which were actually much more sophisticated than in the legend), he made the inductive leap to the principle, or theory, that the acceleration of a falling body is independent of its weight.

The development of physical theories such as Galileo’s often takes an indirect path, with blind alleys, wrong guesses, and the discarding of unsuccessful theories in favor of more promising ones. Physics is not simply a collection of facts and principles; it is also the *process* by which we arrive at general principles that describe how the physical universe behaves.

No theory is ever regarded as the final or ultimate truth. The possibility always exists that new observations will require that a theory be revised or discarded. It is in the nature of physical theory that we can disprove a theory by finding behavior that is inconsistent with it, but we can never prove that a theory is always correct.

Getting back to Galileo, suppose we drop a feather and a cannonball. They certainly do *not* fall at the same rate. This does not mean that Galileo was wrong; it means that his theory was incomplete. If we drop the feather and the cannonball *in a vacuum* to eliminate the effects of the air, then they do fall at the same rate. Galileo’s theory has a **range of validity**: It applies only to objects for which the force exerted by the air (due to air resistance and buoyancy) is much less than the weight. Objects like feathers or parachutes are clearly outside this range.

Often a new development in physics extends a principle’s range of validity. Galileo’s analysis of falling bodies was greatly extended half a century later by Newton’s laws of motion and law of gravitation.

1.2 Solving Physics Problems

At some point in their studies, almost all physics students find themselves thinking, “I understand the concepts, but I just can’t solve the problems.” But in physics, truly understanding a concept *means* being able to apply it to a variety of problems. Learning how to solve problems is absolutely essential; you don’t *know* physics unless you can *do* physics.

How do you learn to solve physics problems? In every chapter of this book you will find *Problem-Solving Strategies* that offer techniques for setting up and solving problems efficiently and accurately. Following each *Problem-Solving Strategy* are one or more worked *Examples* that show these techniques in action. (The *Problem-Solving Strategies* will also steer you away from some *incorrect* techniques that you may be tempted to use.) You’ll also find additional examples that aren’t associated with a particular *Problem-Solving Strategy*. In addition,

at the end of each chapter you'll find a *Bridging Problem* that uses more than one of the key ideas from the chapter. Study these strategies and problems carefully, and work through each example for yourself on a piece of paper.

Different techniques are useful for solving different kinds of physics problems, which is why this book offers dozens of *Problem-Solving Strategies*. No matter what kind of problem you're dealing with, however, there are certain key steps that you'll always follow. (These same steps are equally useful for problems in math, engineering, chemistry, and many other fields.) In this book we've organized these steps into four stages of solving a problem.

All of the *Problem-Solving Strategies* and *Examples* in this book will follow these four steps. (In some cases we will combine the first two or three steps.) We encourage you to follow these same steps when you solve problems yourself. You may find it useful to remember the acronym **I SEE**—short for *Identify*, *Set up*, *Execute*, and *Evaluate*.

Problem-Solving Strategy 1.1 Solving Physics Problems

IDENTIFY *the relevant concepts:* Use the physical conditions stated in the problem to help you decide which physics concepts are relevant. Identify the **target variables** of the problem—that is, the quantities whose values you're trying to find, such as the speed at which a projectile hits the ground, the intensity of a sound made by a siren, or the size of an image made by a lens. Identify the known quantities, as stated or implied in the problem. This step is essential whether the problem asks for an algebraic expression or a numerical answer.

SET UP *the problem:* Given the concepts you have identified and the known and target quantities, choose the equations that you'll use to solve the problem and decide how you'll use them. Make sure that the variables you have identified correlate exactly with those in the equations. If appropriate, draw a sketch of the situation described in the problem. (Graph paper, ruler, protractor, and compass will help you make clear, useful sketches.) As best you can,

estimate what your results will be and, as appropriate, predict what the physical behavior of a system will be. The worked examples in this book include tips on how to make these kinds of estimates and predictions. If this seems challenging, don't worry—you'll get better with practice!

EXECUTE *the solution:* This is where you “do the math.” Study the worked examples to see what's involved in this step.

EVALUATE *your answer:* Compare your answer with your estimates, and reconsider things if there's a discrepancy. If your answer includes an algebraic expression, assure yourself that it represents what would happen if the variables in it were taken to extremes. For future reference, make note of any answer that represents a quantity of particular significance. Ask yourself how you might answer a more general or more difficult version of the problem you have just solved.

Idealized Models

In everyday conversation we use the word “model” to mean either a small-scale replica, such as a model railroad, or a person who displays articles of clothing (or the absence thereof). In physics a **model** is a simplified version of a physical system that would be too complicated to analyze in full detail.

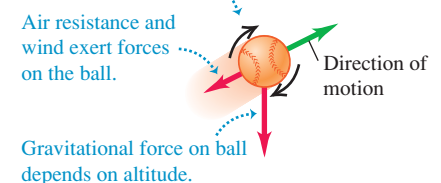
For example, suppose we want to analyze the motion of a thrown baseball (Fig. 1.2a). How complicated is this problem? The ball is not a perfect sphere (it has raised seams), and it spins as it moves through the air. Wind and air resistance influence its motion, the ball's weight varies a little as its distance from the center of the earth changes, and so on. If we try to include all these things, the analysis gets hopelessly complicated. Instead, we invent a simplified version of the problem. We neglect the size and shape of the ball by representing it as a point object, or **particle**. We neglect air resistance by making the ball move in a vacuum, and we make the weight constant. Now we have a problem that is simple enough to deal with (Fig. 1.2b). We will analyze this model in detail in Chapter 3.

We have to overlook quite a few minor effects to make an idealized model, but we must be careful not to neglect too much. If we ignore the effects of gravity completely, then our model predicts that when we throw the ball up, it will go in a straight line and disappear into space. A useful model is one that simplifies a problem enough to make it manageable, yet keeps its essential features.

1.2 To simplify the analysis of (a) a baseball in flight, we use (b) an idealized model.

(a) A real baseball in flight

Baseball spins and has a complex shape.



(b) An idealized model of the baseball

Baseball is treated as a point object (particle).



The validity of the predictions we make using a model is limited by the validity of the model. For example, Galileo's prediction about falling bodies (see Section 1.1) corresponds to an idealized model that does not include the effects of air resistance. This model works fairly well for a dropped cannonball, but not so well for a feather.

Idealized models play a crucial role throughout this book. Watch for them in discussions of physical theories and their applications to specific problems.

1.3 Standards and Units

As we learned in Section 1.1, physics is an experimental science. Experiments require measurements, and we generally use numbers to describe the results of measurements. Any number that is used to describe a physical phenomenon quantitatively is called a **physical quantity**. For example, two physical quantities that describe you are your weight and your height. Some physical quantities are so fundamental that we can define them only by describing how to measure them. Such a definition is called an **operational definition**. Two examples are measuring a distance by using a ruler and measuring a time interval by using a stopwatch. In other cases we define a physical quantity by describing how to calculate it from other quantities that we *can* measure. Thus we might define the average speed of a moving object as the distance traveled (measured with a ruler) divided by the time of travel (measured with a stopwatch).

When we measure a quantity, we always compare it with some reference standard. When we say that a Ferrari 458 Italia is 4.53 meters long, we mean that it is 4.53 times as long as a meter stick, which we define to be 1 meter long. Such a standard defines a **unit** of the quantity. The meter is a unit of distance, and the second is a unit of time. When we use a number to describe a physical quantity, we must always specify the unit that we are using; to describe a distance as simply "4.53" wouldn't mean anything.

To make accurate, reliable measurements, we need units of measurement that do not change and that can be duplicated by observers in various locations. The system of units used by scientists and engineers around the world is commonly called "the metric system," but since 1960 it has been known officially as the **International System**, or **SI** (the abbreviation for its French name, *Système International*). Appendix A gives a list of all SI units as well as definitions of the most fundamental units.

Time

From 1889 until 1967, the unit of time was defined as a certain fraction of the mean solar day, the average time between successive arrivals of the sun at its highest point in the sky. The present standard, adopted in 1967, is much more precise. It is based on an atomic clock, which uses the energy difference between the two lowest energy states of the cesium atom. When bombarded by microwaves of precisely the proper frequency, cesium atoms undergo a transition from one of these states to the other. One **second** (abbreviated s) is defined as the time required for 9,192,631,770 cycles of this microwave radiation (Fig. 1.3a).

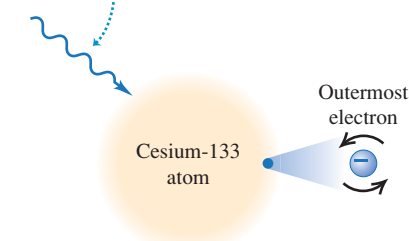
Length

In 1960 an atomic standard for the meter was also established, using the wavelength of the orange-red light emitted by atoms of krypton (^{86}Kr) in a glow discharge tube. Using this length standard, the speed of light in vacuum was measured to be 299,792,458 m/s. In November 1983, the length standard was changed again so that the speed of light in vacuum was *defined* to be precisely

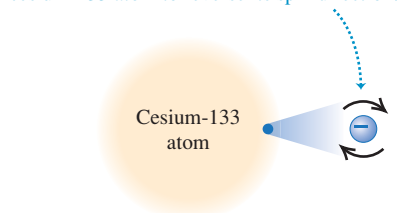
1.3 The measurements used to determine (a) the duration of a second and (b) the length of a meter. These measurements are useful for setting standards because they give the same results no matter where they are made.

(a) Measuring the second

Microwave radiation with a frequency of exactly 9,192,631,770 cycles per second ...

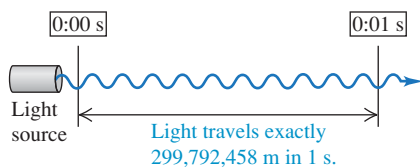


... causes the outermost electron of a cesium-133 atom to reverse its spin direction.



An atomic clock uses this phenomenon to tune microwaves to this exact frequency. It then counts 1 second for each 9,192,631,770 cycles.

(b) Measuring the meter



299,792,458 m/s. Hence the new definition of the **meter** (abbreviated m) is the distance that light travels in vacuum in $1/299,792,458$ second (Fig. 1.3b). This provides a much more precise standard of length than the one based on a wavelength of light.

Mass

The standard of mass, the **kilogram** (abbreviated kg), is defined to be the mass of a particular cylinder of platinum–iridium alloy kept at the International Bureau of Weights and Measures at Sèvres, near Paris (Fig. 1.4). An atomic standard of mass would be more fundamental, but at present we cannot measure masses on an atomic scale with as much accuracy as on a macroscopic scale. The *gram* (which is not a fundamental unit) is 0.001 kilogram.

Unit Prefixes

Once we have defined the fundamental units, it is easy to introduce larger and smaller units for the same physical quantities. In the metric system these other units are related to the fundamental units (or, in the case of mass, to the gram) by multiples of 10 or $\frac{1}{10}$. Thus one kilometer (1 km) is 1000 meters, and one centimeter (1 cm) is $\frac{1}{100}$ meter. We usually express multiples of 10 or $\frac{1}{10}$ in exponential notation: $1000 = 10^3$, $\frac{1}{1000} = 10^{-3}$, and so on. With this notation, $1 \text{ km} = 10^3 \text{ m}$ and $1 \text{ cm} = 10^{-2} \text{ m}$.

The names of the additional units are derived by adding a **prefix** to the name of the fundamental unit. For example, the prefix “kilo-,” abbreviated k, always means a unit larger by a factor of 1000; thus

$$\begin{aligned} 1 \text{ kilometer} &= 1 \text{ km} = 10^3 \text{ meters} = 10^3 \text{ m} \\ 1 \text{ kilogram} &= 1 \text{ kg} = 10^3 \text{ grams} = 10^3 \text{ g} \\ 1 \text{ kilowatt} &= 1 \text{ kW} = 10^3 \text{ watts} = 10^3 \text{ W} \end{aligned}$$

A table on the inside back cover of this book lists the standard SI prefixes, with their meanings and abbreviations.

Table 1.1 gives some examples of the use of multiples of 10 and their prefixes with the units of length, mass, and time. Figure 1.5 shows how these prefixes are used to describe both large and small distances.

The British System

Finally, we mention the British system of units. These units are used only in the United States and a few other countries, and in most of these they are being replaced by SI units. British units are now officially defined in terms of SI units, as follows:

$$\begin{aligned} \text{Length: } 1 \text{ inch} &= 2.54 \text{ cm (exactly)} \\ \text{Force: } 1 \text{ pound} &= 4.448221615260 \text{ newtons (exactly)} \end{aligned}$$

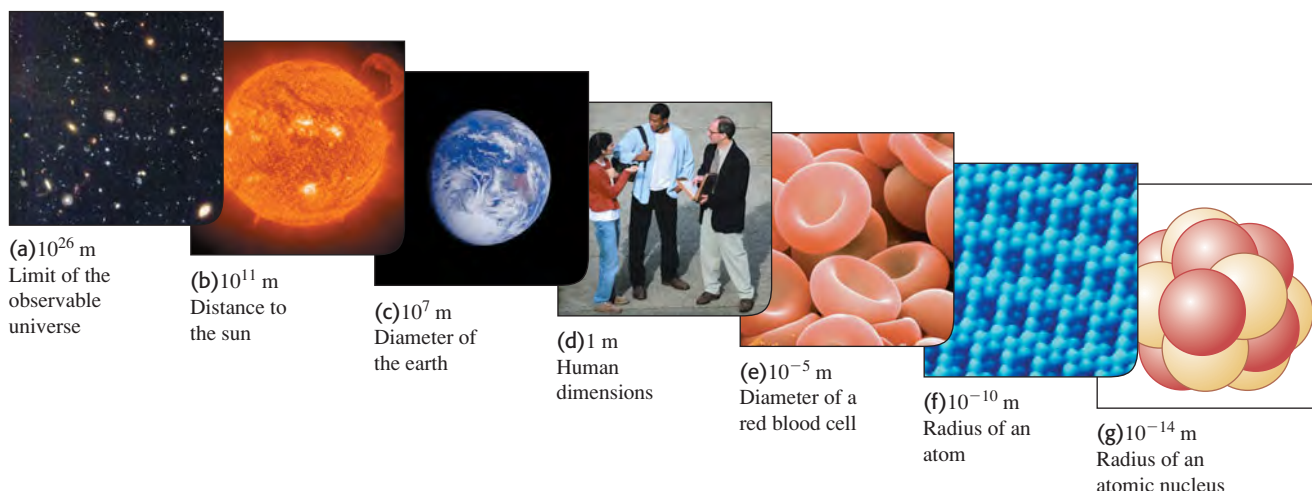
Table 1.1 Some Units of Length, Mass, and Time

Length	Mass	Time
1 nanometer = $1 \text{ nm} = 10^{-9} \text{ m}$ (a few times the size of the largest atom)	1 microgram = $1 \mu\text{g} = 10^{-6} \text{ g} = 10^{-9} \text{ kg}$ (mass of a very small dust particle)	1 nanosecond = $1 \text{ ns} = 10^{-9} \text{ s}$ (time for light to travel 0.3 m)
1 micrometer = $1 \mu\text{m} = 10^{-6} \text{ m}$ (size of some bacteria and living cells)	1 milligram = $1 \text{ mg} = 10^{-3} \text{ g} = 10^{-6} \text{ kg}$ (mass of a grain of salt)	1 microsecond = $1 \mu\text{s} = 10^{-6} \text{ s}$ (time for space station to move 8 mm)
1 millimeter = $1 \text{ mm} = 10^{-3} \text{ m}$ (diameter of the point of a ballpoint pen)	1 gram = $1 \text{ g} = 10^{-3} \text{ kg}$ (mass of a paper clip)	1 millisecond = $1 \text{ ms} = 10^{-3} \text{ s}$ (time for sound to travel 0.35 m)
1 centimeter = $1 \text{ cm} = 10^{-2} \text{ m}$ (diameter of your little finger)		
1 kilometer = $1 \text{ km} = 10^3 \text{ m}$ (a 10-minute walk)		

1.4 The international standard kilogram is the metal object carefully enclosed within these nested glass containers.



1.5 Some typical lengths in the universe. (f) is a scanning tunneling microscope image of atoms on a crystal surface; (g) is an artist's impression.



1.6 Many everyday items make use of both SI and British units. An example is this speedometer from a U.S.-built automobile, which shows the speed in both kilometers per hour (inner scale) and miles per hour (outer scale).



The newton, abbreviated N, is the SI unit of force. The British unit of time is the second, defined the same way as in SI. In physics, British units are used only in mechanics and thermodynamics; there is no British system of electrical units.

In this book we use SI units for all examples and problems, but we occasionally give approximate equivalents in British units. As you do problems using SI units, you may also wish to convert to the approximate British equivalents if they are more familiar to you (Fig. 1.6). But you should try to *think* in SI units as much as you can.

1.4 Unit Consistency and Conversions

We use equations to express relationships among physical quantities, represented by algebraic symbols. Each algebraic symbol always denotes both a number and a unit. For example, d might represent a distance of 10 m, t a time of 5 s, and v a speed of 2 m/s.

An equation must always be **dimensionally consistent**. You can't add apples and automobiles; two terms may be added or equated only if they have the same units. For example, if a body moving with constant speed v travels a distance d in a time t , these quantities are related by the equation

$$d = vt$$

If d is measured in meters, then the product vt must also be expressed in meters. Using the above numbers as an example, we may write

$$10 \text{ m} = \left(2 \frac{\text{m}}{\text{s}}\right)(5 \text{ s})$$

Because the unit 1/s on the right side of the equation cancels the unit s, the product has units of meters, as it must. In calculations, units are treated just like algebraic symbols with respect to multiplication and division.

CAUTION Always use units in calculations When a problem requires calculations using numbers with units, *always* write the numbers with the correct units and carry the units through the calculation as in the example above. This provides a very useful check. If at some stage in a calculation you find that an equation or an expression has inconsistent units, you know you have made an error somewhere. In this book we will *always* carry units through all calculations, and we strongly urge you to follow this practice when you solve problems. |

Problem-Solving Strategy 1.2 Solving Physics Problems



IDENTIFY *the relevant concepts:* In most cases, it's best to use the fundamental SI units (lengths in meters, masses in kilograms, and times in seconds) in every problem. If you need the answer to be in a different set of units (such as kilometers, grams, or hours), wait until the end of the problem to make the conversion.

SET UP *the problem* and **EXECUTE** *the solution:* Units are multiplied and divided just like ordinary algebraic symbols. This gives us an easy way to convert a quantity from one set of units to another: Express the same physical quantity in two different units and form an equality.

For example, when we say that $1 \text{ min} = 60 \text{ s}$, we don't mean that the number 1 is equal to the number 60; rather, we mean that 1 min represents the same physical time interval as 60 s. For this reason, the ratio $(1 \text{ min})/(60 \text{ s})$ equals 1, as does its reciprocal $(60 \text{ s})/(1 \text{ min})$. We may multiply a quantity by either of these

factors (which we call *unit multipliers*) without changing that quantity's physical meaning. For example, to find the number of seconds in 3 min, we write

$$3 \text{ min} = (3 \text{ min}) \left(\frac{60 \text{ s}}{1 \text{ min}} \right) = 180 \text{ s}$$

EVALUATE *your answer:* If you do your unit conversions correctly, unwanted units will cancel, as in the example above. If, instead, you had multiplied 3 min by $(1 \text{ min})/(60 \text{ s})$, your result would have been the nonsensical $\frac{1}{20} \text{ min}^2/\text{s}$. To be sure you convert units properly, you must write down the units at *all* stages of the calculation.

Finally, check whether your answer is reasonable. For example, the result $3 \text{ min} = 180 \text{ s}$ is reasonable because the second is a smaller unit than the minute, so there are more seconds than minutes in the same time interval.

Example 1.1 Converting speed units

The world land speed record is 763.0 mi/h, set on October 15, 1997, by Andy Green in the jet-engine car *Thrust SSC*. Express this speed in meters per second.

SOLUTION

IDENTIFY, SET UP, and EXECUTE: We need to convert the units of a speed from mi/h to m/s. We must therefore find unit multipliers that relate (i) miles to meters and (ii) hours to seconds. In Appendix E (or inside the front cover of this book) we find the equalities $1 \text{ mi} = 1.609 \text{ km}$, $1 \text{ km} = 1000 \text{ m}$, and $1 \text{ h} = 3600 \text{ s}$. We set up the conversion as follows, which ensures that all the desired cancellations by division take place:

$$\begin{aligned} 763.0 \text{ mi/h} &= \left(763.0 \frac{\text{mi}}{\text{h}} \right) \left(\frac{1.609 \text{ km}}{1 \text{ mi}} \right) \left(\frac{1000 \text{ m}}{1 \text{ km}} \right) \left(\frac{1 \text{ h}}{3600 \text{ s}} \right) \\ &= 341.0 \text{ m/s} \end{aligned}$$

Example 1.2 Converting volume units

The world's largest cut diamond is the First Star of Africa (mounted in the British Royal Sceptre and kept in the Tower of London). Its volume is 1.84 cubic inches. What is its volume in cubic centimeters? In cubic meters?

SOLUTION

IDENTIFY, SET UP, and EXECUTE: Here we are to convert the units of a volume from cubic inches (in.^3) to both cubic centimeters (cm^3) and cubic meters (m^3). Appendix E gives us the equality $1 \text{ in.} = 2.54 \text{ cm}$, from which we obtain $1 \text{ in.}^3 = (2.54 \text{ cm})^3$. We then have

$$\begin{aligned} 1.84 \text{ in.}^3 &= (1.84 \text{ in.}^3) \left(\frac{2.54 \text{ cm}}{1 \text{ in.}} \right)^3 \\ &= (1.84)(2.54)^3 \frac{\text{in.}^3 \text{ cm}^3}{\text{in.}^3} = 30.2 \text{ cm}^3 \end{aligned}$$

EVALUATE: Green's was the first supersonic land speed record (the speed of sound in air is about 340 m/s). This example shows a useful rule of thumb: A speed expressed in m/s is a bit less than half the value expressed in mi/h, and a bit less than one-third the value expressed in km/h. For example, a normal freeway speed is about $30 \text{ m/s} = 67 \text{ mi/h} = 108 \text{ km/h}$, and a typical walking speed is about $1.4 \text{ m/s} = 3.1 \text{ mi/h} = 5.0 \text{ km/h}$.

Appendix F also gives us $1 \text{ m} = 100 \text{ cm}$, so

$$\begin{aligned} 30.2 \text{ cm}^3 &= (30.2 \text{ cm}^3) \left(\frac{1 \text{ m}}{100 \text{ cm}} \right)^3 \\ &= (30.2) \left(\frac{1}{100} \right)^3 \frac{\text{cm}^3 \text{ m}^3}{\text{cm}^3} = 30.2 \times 10^{-6} \text{ m}^3 \\ &= 3.02 \times 10^{-5} \text{ m}^3 \end{aligned}$$

EVALUATE: Following the pattern of these conversions, you can show that $1 \text{ in.}^3 \approx 16 \text{ cm}^3$ and that $1 \text{ m}^3 \approx 60,000 \text{ in.}^3$. These approximate unit conversions may be useful for future reference.

1.5 Uncertainty and Significant Figures

1.7 This spectacular mishap was the result of a very small percent error—traveling a few meters too far at the end of a journey of hundreds of thousands of meters.



Table 1.2 Using Significant Figures

Multiplication or division:

Result may have no more significant figures than the starting number with the fewest significant figures:

$$\frac{0.745 \times 2.2}{3.885} = 0.42$$

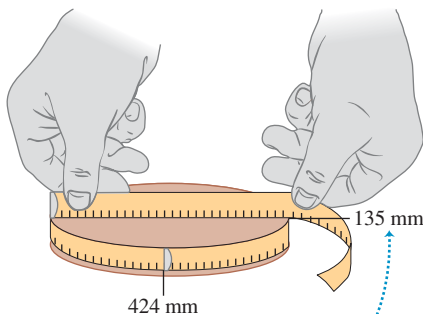
$$1.32578 \times 10^7 \times 4.11 \times 10^{-3} = 5.45 \times 10^4$$

Addition or subtraction:

Number of significant figures is determined by the starting number with the largest uncertainty (i.e., fewest digits to the right of the decimal point):

$$27.153 + 138.2 - 11.74 = 153.6$$

1.8 Determining the value of π from the circumference and diameter of a circle.



The measured values have only three significant figures, so their calculated ratio (π) also has only three significant figures.

Measurements always have uncertainties. If you measure the thickness of the cover of a hardbound version of this book using an ordinary ruler, your measurement is reliable only to the nearest millimeter, and your result will be 3 mm. It would be *wrong* to state this result as 3.00 mm; given the limitations of the measuring device, you can't tell whether the actual thickness is 3.00 mm, 2.85 mm, or 3.11 mm. But if you use a micrometer caliper, a device that measures distances reliably to the nearest 0.01 mm, the result will be 2.91 mm. The distinction between these two measurements is in their **uncertainty**. The measurement using the micrometer caliper has a smaller uncertainty; it's a more accurate measurement. The uncertainty is also called the **error** because it indicates the maximum difference there is likely to be between the measured value and the true value. The uncertainty or error of a measured value depends on the measurement technique used.

We often indicate the **accuracy** of a measured value—that is, how close it is likely to be to the true value—by writing the number, the symbol \pm , and a second number indicating the uncertainty of the measurement. If the diameter of a steel rod is given as 56.47 ± 0.02 mm, this means that the true value is unlikely to be less than 56.45 mm or greater than 56.49 mm. In a commonly used shorthand notation, the number 1.6454(21) means 1.6454 ± 0.0021 . The numbers in parentheses show the uncertainty in the final digits of the main number.

We can also express accuracy in terms of the maximum likely **fractional error** or **percent error** (also called *fractional uncertainty* and *percent uncertainty*). A resistor labeled “47 ohms \pm 10%” probably has a true resistance that differs from 47 ohms by no more than 10% of 47 ohms—that is, by about 5 ohms. The resistance is probably between 42 and 52 ohms. For the diameter of the steel rod given above, the fractional error is $(0.02 \text{ mm})/(56.47 \text{ mm})$, or about 0.0004; the percent error is $(0.0004)(100\%)$, or about 0.04%. Even small percent errors can sometimes be very significant (Fig. 1.7).

In many cases the uncertainty of a number is not stated explicitly. Instead, the uncertainty is indicated by the number of meaningful digits, or **significant figures**, in the measured value. We gave the thickness of the cover of this book as 2.91 mm, which has three significant figures. By this we mean that the first two digits are known to be correct, while the third digit is uncertain. The last digit is in the hundredths place, so the uncertainty is about 0.01 mm. Two values with the *same* number of significant figures may have *different* uncertainties; a distance given as 137 km also has three significant figures, but the uncertainty is about 1 km.

When you use numbers that have uncertainties to compute other numbers, the computed numbers are also uncertain. When numbers are multiplied or divided, the number of significant figures in the result can be no greater than in the factor with the fewest significant figures. For example, $3.1416 \times 2.34 \times 0.58 = 4.3$. When we add and subtract numbers, it's the location of the decimal point that matters, not the number of significant figures. For example, $123.62 + 8.9 = 132.5$. Although 123.62 has an uncertainty of about 0.01, 8.9 has an uncertainty of about 0.1. So their sum has an uncertainty of about 0.1 and should be written as 132.5, not 132.52. Table 1.2 summarizes these rules for significant figures.

As an application of these ideas, suppose you want to verify the value of π , the ratio of the circumference of a circle to its diameter. The true value of this ratio to ten digits is 3.141592654. To test this, you draw a large circle and measure its circumference and diameter to the nearest millimeter, obtaining the values 424 mm and 135 mm (Fig. 1.8). You punch these into your calculator and obtain the quotient $(424 \text{ mm})/(135 \text{ mm}) = 3.140740741$. This may seem to disagree with the true value of π , but keep in mind that each of your measurements has three significant figures, so your measured value of π can have only three significant figures. It should be stated simply as 3.14. Within the limit of three significant figures, your value does agree with the true value.

In the examples and problems in this book we usually give numerical values with three significant figures, so your answers should usually have no more than three significant figures. (Many numbers in the real world have even less accuracy. An automobile speedometer, for example, usually gives only two significant figures.) Even if you do the arithmetic with a calculator that displays ten digits, it would be wrong to give a ten-digit answer because it misrepresents the accuracy of the results. Always round your final answer to keep only the correct number of significant figures or, in doubtful cases, one more at most. In Example 1.1 it would have been wrong to state the answer as 341.01861 m/s. Note that when you reduce such an answer to the appropriate number of significant figures, you must *round*, not *truncate*. Your calculator will tell you that the ratio of 525 m to 311 m is 1.688102894; to three significant figures, this is 1.69, not 1.68.

When we calculate with very large or very small numbers, we can show significant figures much more easily by using **scientific notation**, sometimes called **powers-of-10 notation**. The distance from the earth to the moon is about 384,000,000 m, but writing the number in this form doesn't indicate the number of significant figures. Instead, we move the decimal point eight places to the left (corresponding to dividing by 10^8) and multiply by 10^8 ; that is,

$$384,000,000 \text{ m} = 3.84 \times 10^8 \text{ m}$$

In this form, it is clear that we have three significant figures. The number 4.00×10^{-7} also has three significant figures, even though two of them are zeros. Note that in scientific notation the usual practice is to express the quantity as a number between 1 and 10 multiplied by the appropriate power of 10.

When an integer or a fraction occurs in a general equation, we treat that number as having no uncertainty at all. For example, in the equation $v_x^2 = v_{0x}^2 + 2a_x(x - x_0)$, which is Eq. (2.13) in Chapter 2, the coefficient 2 is *exactly* 2. We can consider this coefficient as having an infinite number of significant figures (2.000000...). The same is true of the exponent 2 in v_x^2 and v_{0x}^2 .

Finally, let's note that **precision** is not the same as *accuracy*. A cheap digital watch that gives the time as 10:35:17 A.M. is very *precise* (the time is given to the second), but if the watch runs several minutes slow, then this value isn't very *accurate*. On the other hand, a grandfather clock might be very accurate (that is, display the correct time), but if the clock has no second hand, it isn't very precise. A high-quality measurement is both precise *and* accurate.

Example 1.3 Significant figures in multiplication

The rest energy E of an object with rest mass m is given by Einstein's famous equation $E = mc^2$, where c is the speed of light in vacuum. Find E for an electron for which (to three significant figures) $m = 9.11 \times 10^{-31}$ kg. The SI unit for E is the joule (J); $1 \text{ J} = 1 \text{ kg} \cdot \text{m}^2/\text{s}^2$.

SOLUTION

IDENTIFY and SET UP: Our target variable is the energy E . We are given the value of the mass m ; from Section 1.3 (or Appendix F) the speed of light is $c = 2.99792458 \times 10^8$ m/s.


EXECUTE: Substituting the values of m and c into Einstein's equation, we find

$$\begin{aligned} E &= (9.11 \times 10^{-31} \text{ kg})(2.99792458 \times 10^8 \text{ m/s})^2 \\ &= (9.11)(2.99792458)^2(10^{-31})(10^8)^2 \text{ kg} \cdot \text{m}^2/\text{s}^2 \\ &= (81.87659678)(10^{[-31+(2 \times 8)]}) \text{ kg} \cdot \text{m}^2/\text{s}^2 \\ &= 8.187659678 \times 10^{-14} \text{ kg} \cdot \text{m}^2/\text{s}^2 \end{aligned}$$

Since the value of m was given to only three significant figures, we must round this to

$$E = 8.19 \times 10^{-14} \text{ kg} \cdot \text{m}^2/\text{s}^2 = 8.19 \times 10^{-14} \text{ J}$$

EVALUATE: While the rest energy contained in an electron may seem ridiculously small, on the atomic scale it is tremendous. Compare our answer to 10^{-19} J, the energy gained or lost by a single atom during a typical chemical reaction. The rest energy of an electron is about 1,000,000 times larger! (We'll discuss the significance of rest energy in Chapter 37.)

Test Your Understanding of Section 1.5 The density of a material is equal to its mass divided by its volume. What is the density (in kg/m^3) of a rock of mass 1.80 kg and volume $6.0 \times 10^{-4} \text{ m}^3$? (i) $3 \times 10^3 \text{ kg}/\text{m}^3$; (ii) $3.0 \times 10^3 \text{ kg}/\text{m}^3$; (iii) $3.00 \times 10^3 \text{ kg}/\text{m}^3$; (iv) $3.000 \times 10^3 \text{ kg}/\text{m}^3$; (v) any of these—all of these answers are mathematically equivalent. 

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PhET: Estimation

1.6 Estimates and Orders of Magnitude

We have stressed the importance of knowing the accuracy of numbers that represent physical quantities. But even a very crude estimate of a quantity often gives us useful information. Sometimes we know how to calculate a certain quantity, but we have to guess at the data we need for the calculation. Or the calculation might be too complicated to carry out exactly, so we make some rough approximations. In either case our result is also a guess, but such a guess can be useful even if it is uncertain by a factor of two, ten, or more. Such calculations are often called **order-of-magnitude estimates**. The great Italian-American nuclear physicist Enrico Fermi (1901–1954) called them “back-of-the-envelope calculations.”

Exercises 1.16 through 1.25 at the end of this chapter are of the estimating, or order-of-magnitude, variety. Most require guesswork for the needed input data. Don't try to look up a lot of data; make the best guesses you can. Even when they are off by a factor of ten, the results can be useful and interesting.

Example 1.4 An order-of-magnitude estimate

You are writing an adventure novel in which the hero escapes across the border with a billion dollars' worth of gold in his suitcase. Could anyone carry that much gold? Would it fit in a suitcase?

SOLUTION

IDENTIFY, SET UP, and EXECUTE: Gold sells for around \$400 an ounce. (The price has varied between \$200 and \$1000 over the past decade or so.) An ounce is about 30 grams; that's worth remembering. So ten dollars' worth of gold has a mass of $\frac{1}{40}$ ounce, or around one gram. A billion (10^9) dollars' worth of gold

is a hundred million (10^8) grams, or a hundred thousand (10^5) kilograms. This corresponds to a weight in British units of around 200,000 lb, or 100 tons. No human hero could lift that weight!

Roughly what is the *volume* of this gold? The density of gold is much greater than that of water ($1 \text{ g}/\text{cm}^3$), or $1000 \text{ kg}/\text{m}^3$; if its density is 10 times that of water, this much gold will have a volume of 10 m^3 , many times the volume of a suitcase.

EVALUATE: Clearly your novel needs rewriting. Try the calculation again with a suitcase full of five-carat (1-gram) diamonds, each worth \$100,000. Would this work?

Application Scalar Temperature, Vector Wind

This weather station measures temperature, a scalar quantity that can be positive or negative (say, $+20^\circ\text{C}$ or -5°C) but has no direction. It also measures wind velocity, which is a vector quantity with both magnitude and direction (for example, $15 \text{ km}/\text{h}$ from the west).

Test Your Understanding of Section 1.6 Can you estimate the total number of teeth in all the mouths of everyone (students, staff, and faculty) on your campus? (*Hint:* How many teeth are in your mouth? Count them!)

1.7 Vectors and Vector Addition

Some physical quantities, such as time, temperature, mass, and density, can be described completely by a single number with a unit. But many other important quantities in physics have a *direction* associated with them and cannot be described by a single number. A simple example is describing the motion of an airplane: We must say not only how fast the plane is moving but also in what direction. The speed of the airplane combined with its direction of motion together constitute a quantity called *velocity*. Another example is *force*, which in physics means a push or pull exerted on a body. Giving a complete description of a force means describing both how hard the force pushes or pulls on the body and the direction of the push or pull.



When a physical quantity is described by a single number, we call it a **scalar quantity**. In contrast, a **vector quantity** has both a **magnitude** (the “how much” or “how big” part) and a direction in space. Calculations that combine scalar quantities use the operations of ordinary arithmetic. For example, $6 \text{ kg} + 3 \text{ kg} = 9 \text{ kg}$, or $4 \times 2 \text{ s} = 8 \text{ s}$. However, combining vectors requires a different set of operations.

To understand more about vectors and how they combine, we start with the simplest vector quantity, **displacement**. Displacement is simply a change in the position of an object. Displacement is a vector quantity because we must state not only how far the object moves but also in what direction. Walking 3 km north from your front door doesn’t get you to the same place as walking 3 km southeast; these two displacements have the same magnitude but different directions.

We usually represent a vector quantity such as displacement by a single letter, such as \vec{A} in Fig. 1.9a. In this book we always print vector symbols in **boldface italic type with an arrow above them**. We do this to remind you that vector quantities have different properties from scalar quantities; the arrow is a reminder that vectors have direction. When you handwrite a symbol for a vector, *always* write it with an arrow on top. If you don’t distinguish between scalar and vector quantities in your notation, you probably won’t make the distinction in your thinking either, and hopeless confusion will result.

We always *draw* a vector as a line with an arrowhead at its tip. The length of the line shows the vector’s magnitude, and the direction of the line shows the vector’s direction. Displacement is always a straight-line segment directed from the starting point to the ending point, even though the object’s actual path may be curved (Fig. 1.9b). Note that displacement is not related directly to the total *distance* traveled. If the object were to continue on past P_2 and then return to P_1 , the displacement for the entire trip would be *zero* (Fig. 1.9c).

If two vectors have the same direction, they are **parallel**. If they have the same magnitude *and* the same direction, they are **equal**, no matter where they are located in space. The vector \vec{A}' from point P_3 to point P_4 in Fig. 1.10 has the same length and direction as the vector \vec{A} from P_1 to P_2 . These two displacements are equal, even though they start at different points. We write this as $\vec{A}' = \vec{A}$ in Fig. 1.10; the boldface equals sign emphasizes that equality of two vector quantities is not the same relationship as equality of two scalar quantities. Two vector quantities are equal only when they have the same magnitude *and* the same direction.

The vector \vec{B} in Fig. 1.10, however, is not equal to \vec{A} because its direction is *opposite* to that of \vec{A} . We define the **negative of a vector** as a vector having the same magnitude as the original vector but the *opposite* direction. The negative of vector quantity \vec{A} is denoted as $-\vec{A}$, and we use a boldface minus sign to emphasize the vector nature of the quantities. If \vec{A} is 87 m south, then $-\vec{A}$ is 87 m north. Thus we can write the relationship between \vec{A} and \vec{B} in Fig. 1.10 as $\vec{A} = -\vec{B}$ or $\vec{B} = -\vec{A}$. When two vectors \vec{A} and \vec{B} have opposite directions, whether their magnitudes are the same or not, we say that they are **antiparallel**.

We usually represent the *magnitude* of a vector quantity (in the case of a displacement vector, its length) by the same letter used for the vector, but in *light italic type with no arrow on top*. An alternative notation is the vector symbol with vertical bars on both sides:

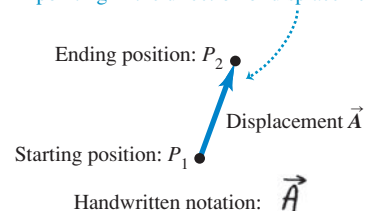
$$(\text{Magnitude of } \vec{A}) = A = |\vec{A}| \quad (1.1)$$

The magnitude of a vector quantity is a scalar quantity (a number) and is *always positive*. Note that a vector can never be equal to a scalar because they are different kinds of quantities. The expression “ $\vec{A} = 6 \text{ m}$ ” is just as wrong as “2 oranges = 3 apples”!

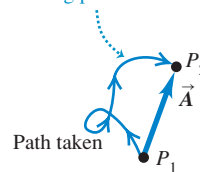
When drawing diagrams with vectors, it’s best to use a scale similar to those used for maps. For example, a displacement of 5 km might be represented in a diagram by a vector 1 cm long, and a displacement of 10 km by a vector 2 cm long. In a diagram for velocity vectors, a vector that is 1 cm long might represent

1.9 Displacement as a vector quantity. A displacement is always a straight-line segment directed from the starting point to the ending point, even if the path is curved.

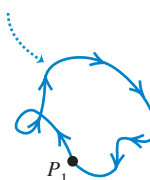
(a) We represent a displacement by an arrow pointing in the direction of displacement.



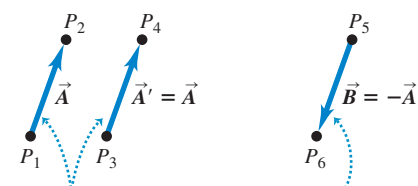
(b) Displacement depends only on the starting and ending positions—not on the path taken.



(c) Total displacement for a round trip is 0, regardless of the distance traveled.



1.10 The meaning of vectors that have the same magnitude and the same or opposite direction.

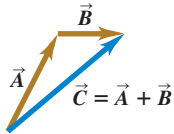


Displacements \vec{A} and \vec{A}' are equal because they have the same length and direction.

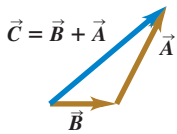
Displacement \vec{B} has the same magnitude as \vec{A} but opposite direction; \vec{B} is the negative of \vec{A} .

1.11 Three ways to add two vectors. As shown in (b), the order in vector addition doesn't matter; vector addition is commutative.

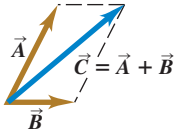
(a) We can add two vectors by placing them head to tail.



(b) Adding them in reverse order gives the same result.

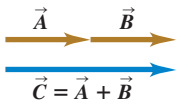


(c) We can also add them by constructing a parallelogram.

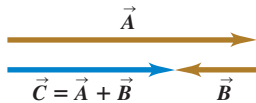


1.12 (a) Only when two vectors \vec{A} and \vec{B} are parallel does the magnitude of their sum equal the sum of their magnitudes: $C = A + B$. (b) When \vec{A} and \vec{B} are antiparallel, the magnitude of their sum equals the *difference* of their magnitudes: $C = |A - B|$.

(a) The sum of two parallel vectors



(b) The sum of two antiparallel vectors



a velocity of magnitude 5 m/s. A velocity of 20 m/s would then be represented by a vector 4 cm long.

Vector Addition and Subtraction

Suppose a particle undergoes a displacement \vec{A} followed by a second displacement \vec{B} . The final result is the same as if the particle had started at the same initial point and undergone a single displacement \vec{C} (Fig. 1.11a). We call displacement \vec{C} the **vector sum**, or **resultant**, of displacements \vec{A} and \vec{B} . We express this relationship symbolically as

$$\vec{C} = \vec{A} + \vec{B} \quad (1.2)$$

The boldface plus sign emphasizes that adding two vector quantities requires a geometrical process and is not the same operation as adding two scalar quantities such as $2 + 3 = 5$. In vector addition we usually place the *tail* of the *second* vector at the *head*, or tip, of the *first* vector (Fig. 1.11a).

If we make the displacements \vec{A} and \vec{B} in reverse order, with \vec{B} first and \vec{A} second, the result is the same (Fig. 1.11b). Thus

$$\vec{C} = \vec{B} + \vec{A} \quad \text{and} \quad \vec{A} + \vec{B} = \vec{B} + \vec{A} \quad (1.3)$$

This shows that the order of terms in a vector sum doesn't matter. In other words, vector addition obeys the commutative law.

Figure 1.11c shows another way to represent the vector sum: If vectors \vec{A} and \vec{B} are both drawn with their tails at the same point, vector \vec{C} is the diagonal of a parallelogram constructed with \vec{A} and \vec{B} as two adjacent sides.

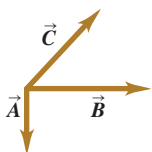
CAUTION **Magnitudes in vector addition** It's a common error to conclude that if $\vec{C} = \vec{A} + \vec{B}$, then the magnitude C should equal the magnitude A plus the magnitude B . In general, this conclusion is *wrong*; for the vectors shown in Fig. 1.11, you can see that $C < A + B$. The magnitude of $\vec{A} + \vec{B}$ depends on the magnitudes of \vec{A} and \vec{B} and on the angle between \vec{A} and \vec{B} (see Problem 1.90). Only in the special case in which \vec{A} and \vec{B} are *parallel* is the magnitude of $\vec{C} = \vec{A} + \vec{B}$ equal to the sum of the magnitudes of \vec{A} and \vec{B} (Fig. 1.12a). When the vectors are *antiparallel* (Fig. 1.12b), the magnitude of \vec{C} equals the *difference* of the magnitudes of \vec{A} and \vec{B} . Be careful about distinguishing between scalar and vector quantities, and you'll avoid making errors about the magnitude of a vector sum. **|**

When we need to add more than two vectors, we may first find the vector sum of any two, add this vectorially to the third, and so on. Figure 1.13a shows three vectors \vec{A} , \vec{B} , and \vec{C} . In Fig. 1.13b we first add \vec{A} and \vec{B} to give a vector sum \vec{D} ; we then add vectors \vec{C} and \vec{D} by the same process to obtain the vector sum \vec{R} :

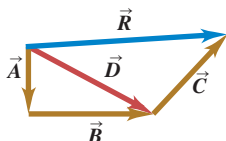
$$\vec{R} = (\vec{A} + \vec{B}) + \vec{C} = \vec{D} + \vec{C}$$

1.13 Several constructions for finding the vector sum $\vec{A} + \vec{B} + \vec{C}$.

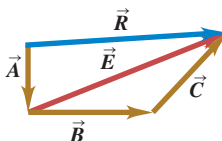
(a) To find the sum of these three vectors ...



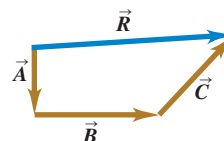
(b) we could add \vec{A} and \vec{B} to get \vec{D} and then add \vec{C} to \vec{D} to get the final sum (resultant) \vec{R} , ...



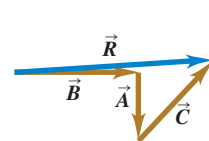
(c) or we could add \vec{B} and \vec{C} to get \vec{E} and then add \vec{A} to \vec{E} to get \vec{R} , ...



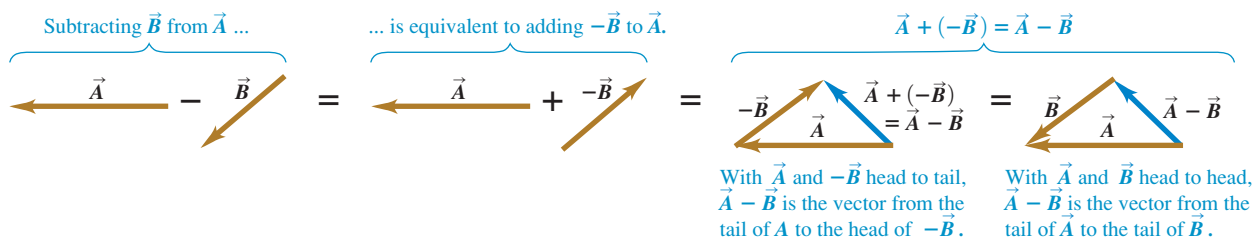
(d) or we could add \vec{A} , \vec{B} , and \vec{C} to get \vec{R} directly, ...



(e) or we could add \vec{A} , \vec{B} , and \vec{C} in any other order and still get \vec{R} .



1.14 To construct the vector difference $\vec{A} - \vec{B}$, you can either place the tail of $-\vec{B}$ at the head of \vec{A} or place the two vectors \vec{A} and \vec{B} head to head.



Alternatively, we can first add \vec{B} and \vec{C} to obtain vector \vec{E} (Fig. 1.13c), and then add \vec{A} and \vec{E} to obtain \vec{R} :

$$\vec{R} = \vec{A} + (\vec{B} + \vec{C}) = \vec{A} + \vec{E}$$

We don't even need to draw vectors \vec{D} and \vec{E} ; all we need to do is draw \vec{A} , \vec{B} , and \vec{C} in succession, with the tail of each at the head of the one preceding it. The sum vector \vec{R} extends from the tail of the first vector to the head of the last vector (Fig. 1.13d). The order makes no difference; Fig. 1.13e shows a different order, and we invite you to try others. We see that vector addition obeys the associative law.

We can *subtract* vectors as well as add them. To see how, recall that vector $-\vec{A}$ has the same magnitude as \vec{A} but the opposite direction. We define the difference $\vec{A} - \vec{B}$ of two vectors \vec{A} and \vec{B} to be the vector sum of \vec{A} and $-\vec{B}$:

$$\vec{A} - \vec{B} = \vec{A} + (-\vec{B}) \quad (1.4)$$

Figure 1.14 shows an example of vector subtraction.

A vector quantity such as a displacement can be multiplied by a scalar quantity (an ordinary number). The displacement $2\vec{A}$ is a displacement (vector quantity) in the same direction as the vector \vec{A} but twice as long; this is the same as adding \vec{A} to itself (Fig. 1.15a). In general, when a vector \vec{A} is multiplied by a scalar c , the result $c\vec{A}$ has magnitude $|c|A$ (the absolute value of c multiplied by the magnitude of the vector \vec{A}). If c is positive, $c\vec{A}$ is in the same direction as \vec{A} ; if c is negative, $c\vec{A}$ is in the direction opposite to \vec{A} . Thus $3\vec{A}$ is parallel to \vec{A} , while $-3\vec{A}$ is antiparallel to \vec{A} (Fig. 1.15b).

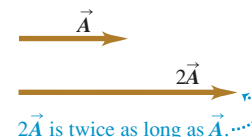
A scalar used to multiply a vector may also be a physical quantity. For example, you may be familiar with the relationship $\vec{F} = m\vec{a}$; the net force \vec{F} (a vector quantity) that acts on a body is equal to the product of the body's mass m (a scalar quantity) and its acceleration \vec{a} (a vector quantity). The direction of \vec{F} is the same as that of \vec{a} because m is positive, and the magnitude of \vec{F} is equal to the mass m (which is positive) multiplied by the magnitude of \vec{a} . The unit of force is the unit of mass multiplied by the unit of acceleration.

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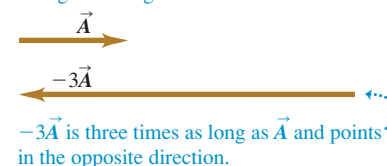
PhET: Vector Addition

1.15 Multiplying a vector (a) by a positive scalar and (b) by a negative scalar.

(a) Multiplying a vector by a positive scalar changes the magnitude (length) of the vector, but not its direction.



(b) Multiplying a vector by a negative scalar changes its magnitude and reverses its direction.



Example 1.5 Addition of two vectors at right angles

A cross-country skier skis 1.00 km north and then 2.00 km east on a horizontal snowfield. How far and in what direction is she from the starting point?

SOLUTION

IDENTIFY and SET UP: The problem involves combining two displacements at right angles to each other. In this case, vector addition amounts to solving a right triangle, which we can do using the Pythagorean theorem and simple trigonometry. The target variables are the skier's straight-line distance and direction from her

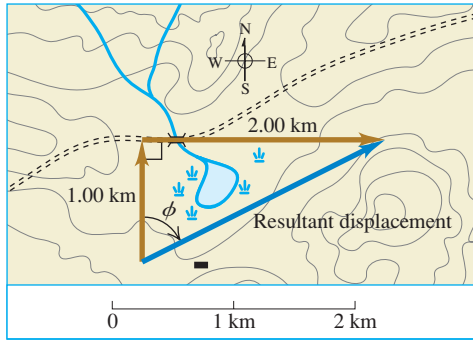
starting point. Figure 1.16 is a scale diagram of the two displacements and the resultant net displacement. We denote the direction from the starting point by the angle ϕ (the Greek letter phi). The displacement appears to be about 2.4 km. Measurement with a protractor indicates that ϕ is about 63° .

EXECUTE: The distance from the starting point to the ending point is equal to the length of the hypotenuse:

$$\sqrt{(1.00 \text{ km})^2 + (2.00 \text{ km})^2} = 2.24 \text{ km}$$

Continued

1.16 The vector diagram, drawn to scale, for a ski trip.



A little trigonometry (from Appendix B) allows us to find angle ϕ :

$$\tan \phi = \frac{\text{Opposite side}}{\text{Adjacent side}} = \frac{2.00 \text{ km}}{1.00 \text{ km}}$$

$$\phi = 63.4^\circ$$

We can describe the direction as 63.4° east of north or $90^\circ - 63.4^\circ = 26.6^\circ$ north of east.

EVALUATE: Our answers (2.24 km and $\phi = 63.4^\circ$) are close to our predictions. In the more general case in which you have to add two vectors *not* at right angles to each other, you can use the law of cosines in place of the Pythagorean theorem and use the law of sines to find an angle corresponding to ϕ in this example. (You'll find these trigonometric rules in Appendix B.) We'll see more techniques for vector addition in Section 1.8.

Test Your Understanding of Section 1.7 Two displacement vectors, \vec{S} and \vec{T} , have magnitudes $S = 3 \text{ m}$ and $T = 4 \text{ m}$. Which of the following could be the magnitude of the difference vector $\vec{S} - \vec{T}$? (There may be more than one correct answer.) (i) 9 m; (ii) 7 m; (iii) 5 m; (iv) 1 m; (v) 0 m; (vi) -1 m .



1.8 Components of Vectors

In Section 1.7 we added vectors by using a scale diagram and by using properties of right triangles. Measuring a diagram offers only very limited accuracy, and calculations with right triangles work only when the two vectors are perpendicular. So we need a simple but general method for adding vectors. This is called the method of *components*.

To define what we mean by the components of a vector \vec{A} , we begin with a rectangular (Cartesian) coordinate system of axes (Fig. 1.17a). We then draw the vector with its tail at O , the origin of the coordinate system. We can represent any vector lying in the xy -plane as the sum of a vector parallel to the x -axis and a vector parallel to the y -axis. These two vectors are labeled \vec{A}_x and \vec{A}_y in Fig. 1.17a; they are called the **component vectors** of vector \vec{A} , and their vector sum is equal to \vec{A} . In symbols,

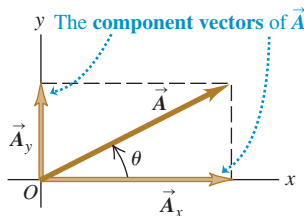
$$\vec{A} = \vec{A}_x + \vec{A}_y \quad (1.5)$$

Since each component vector lies along a coordinate-axis direction, we need only a single number to describe each one. When \vec{A}_x points in the positive x -direction, we define the number A_x to be equal to the magnitude of \vec{A}_x . When \vec{A}_x points in the negative x -direction, we define the number A_x to be equal to the negative of that magnitude (the magnitude of a vector quantity is itself never negative). We define the number A_y in the same way. The two numbers A_x and A_y are called the **components** of \vec{A} (Fig. 1.17b).

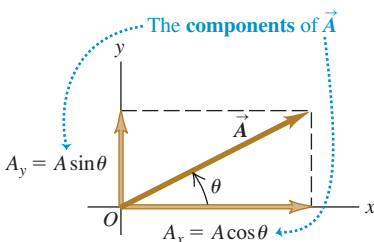
CAUTION **Components are not vectors** The components A_x and A_y of a vector \vec{A} are just numbers; they are *not* vectors themselves. This is why we print the symbols for components in light italic type with *no* arrow on top instead of in boldface italic with an arrow, which is reserved for vectors. |

1.17 Representing a vector \vec{A} in terms of (a) component vectors \vec{A}_x and \vec{A}_y and (b) components A_x and A_y (which in this case are both positive).

(a)



(b)



We can calculate the components of the vector \vec{A} if we know its magnitude A and its direction. We'll describe the direction of a vector by its angle θ relative to some reference direction. In Fig. 1.17b this reference direction is the positive x -axis, and the angle between vector \vec{A} and the positive x -axis

is θ (the Greek letter theta). Imagine that the vector \vec{A} originally lies along the $+x$ -axis and that you then rotate it to its correct direction, as indicated by the arrow in Fig. 1.17b on the angle θ . If this rotation is from the $+x$ -axis toward the $+y$ -axis, as shown in Fig. 1.17b, then θ is *positive*; if the rotation is from the $+x$ -axis toward the $-y$ -axis, θ is *negative*. Thus the $+y$ -axis is at an angle of 90° , the $-x$ -axis at 180° , and the $-y$ -axis at 270° (or -90°). If θ is measured in this way, then from the definition of the trigonometric functions,

$$\frac{A_x}{A} = \cos \theta \quad \text{and} \quad \frac{A_y}{A} = \sin \theta$$

$$A_x = A \cos \theta \quad \text{and} \quad A_y = A \sin \theta \quad (1.6)$$

(θ measured from the $+x$ -axis, rotating toward the $+y$ -axis)

In Fig. 1.17b A_x and A_y are positive. This is consistent with Eqs. (1.6); θ is in the first quadrant (between 0° and 90°), and both the cosine and the sine of an angle in this quadrant are positive. But in Fig. 1.18a the component B_x is negative. Again, this agrees with Eqs. (1.6); the cosine of an angle in the second quadrant is negative. The component B_y is positive ($\sin \theta$ is positive in the second quadrant). In Fig. 1.18b both C_x and C_y are negative (both $\cos \theta$ and $\sin \theta$ are negative in the third quadrant).

CAUTION Relating a vector's magnitude and direction to its components Equations (1.6) are correct *only* when the angle θ is measured from the positive x -axis as described above. If the angle of the vector is given from a different reference direction or using a different sense of rotation, the relationships are different. Be careful! Example 1.6 illustrates this point. ■

Example 1.6 Finding components

(a) What are the x - and y -components of vector \vec{D} in Fig. 1.19a? The magnitude of the vector is $D = 3.00$ m, and the angle $\alpha = 45^\circ$. (b) What are the x - and y -components of vector \vec{E} in Fig. 1.19b? The magnitude of the vector is $E = 4.50$ m, and the angle $\beta = 37.0^\circ$.

SOLUTION

IDENTIFY and SET UP: We can use Eqs. (1.6) to find the components of these vectors, but we have to be careful: Neither of the angles α or β in Fig. 1.19 is measured from the $+x$ -axis toward the $+y$ -axis. We estimate from the figure that the lengths of the com-

ponents in part (a) are both roughly 2 m, and that those in part (b) are 3 m and 4 m. We've indicated the signs of the components in the figure.

EXECUTE: (a) The angle α (the Greek letter alpha) between the positive x -axis and \vec{D} is measured toward the *negative* y -axis. The angle we must use in Eqs. (1.6) is $\theta = -\alpha = -45^\circ$. We then find

$$D_x = D \cos \theta = (3.00 \text{ m})(\cos(-45^\circ)) = +2.1 \text{ m}$$

$$D_y = D \sin \theta = (3.00 \text{ m})(\sin(-45^\circ)) = -2.1 \text{ m}$$

Had you been careless and substituted $+45^\circ$ for θ in Eqs. (1.6), your result for D_y would have had the wrong sign.

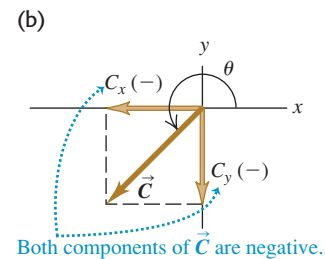
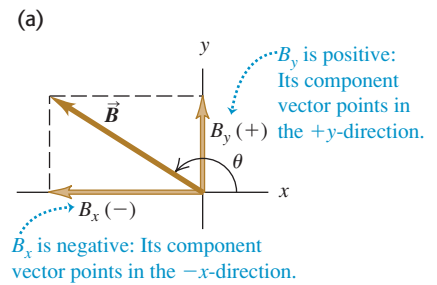
(b) The x - and y -axes in Fig. 1.19b are at right angles, so it doesn't matter that they aren't horizontal and vertical, respectively. But to use Eqs. (1.6), we must use the angle $\theta = 90.0^\circ - \beta = 90.0^\circ - 37.0^\circ = 53.0^\circ$. Then we find

$$E_x = E \cos 53.0^\circ = (4.50 \text{ m})(\cos 53.0^\circ) = +2.71 \text{ m}$$

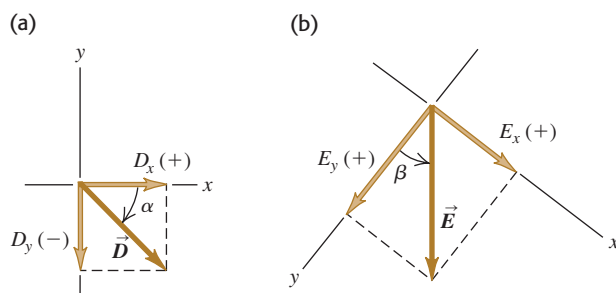
$$E_y = E \sin 53.0^\circ = (4.50 \text{ m})(\sin 53.0^\circ) = +3.59 \text{ m}$$

EVALUATE: Our answers to both parts are close to our predictions. But ask yourself this: Why do the answers in part (a) correctly have only two significant figures?

1.18 The components of a vector may be positive or negative numbers.



1.19 Calculating the x - and y -components of vectors.



Doing Vector Calculations Using Components

Using components makes it relatively easy to do various calculations involving vectors. Let's look at three important examples.

1. Finding a vector's magnitude and direction from its components. We can describe a vector completely by giving either its magnitude and direction or its x - and y -components. Equations (1.6) show how to find the components if we know the magnitude and direction. We can also reverse the process: We can find the magnitude and direction if we know the components. By applying the Pythagorean theorem to Fig. 1.17b, we find that the magnitude of vector \vec{A} is

$$A = \sqrt{A_x^2 + A_y^2} \quad (1.7)$$

(We always take the positive root.) Equation (1.7) is valid for any choice of x -axis and y -axis, as long as they are mutually perpendicular. The expression for the vector direction comes from the definition of the tangent of an angle. If θ is measured from the positive x -axis, and a positive angle is measured toward the positive y -axis (as in Fig. 1.17b), then

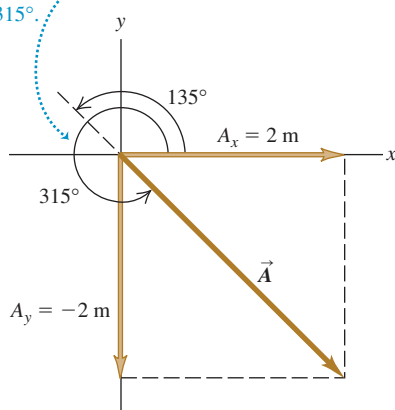
$$\tan \theta = \frac{A_y}{A_x} \quad \text{and} \quad \theta = \arctan \frac{A_y}{A_x} \quad (1.8)$$

We will always use the notation \arctan for the inverse tangent function. The notation \tan^{-1} is also commonly used, and your calculator may have an INV or 2ND button to be used with the TAN button.

1.20 Drawing a sketch of a vector reveals the signs of its x - and y -components.

Suppose that $\tan \theta = \frac{A_y}{A_x} = -1$. What is θ ?

Two angles have tangents of -1 : 135° and 315° . Inspection of the diagram shows that θ must be 315° .



CAUTION Finding the direction of a vector from its components There's one slight complication in using Eqs. (1.8) to find θ : Any two angles that differ by 180° have the same tangent. Suppose $A_x = 2$ m and $A_y = -2$ m as in Fig. 1.20; then $\tan \theta = -1$. But both 135° and 315° (or -45°) have tangents of -1 . To decide which is correct, we have to look at the individual components. Because A_x is positive and A_y is negative, the angle must be in the fourth quadrant; thus $\theta = 315^\circ$ (or -45°) is the correct value. Most pocket calculators give $\arctan(-1) = -45^\circ$. In this case that is correct; but if instead we have $A_x = -2$ m and $A_y = 2$ m, then the correct angle is 135° . Similarly, when A_x and A_y are both negative, the tangent is positive, but the angle is in the third quadrant. You should *always* draw a sketch like Fig. 1.20 to check which of the two possibilities is the correct one. **|**

2. Multiplying a vector by a scalar. If we multiply a vector \vec{A} by a scalar c , each component of the product $\vec{D} = c\vec{A}$ is the product of c and the corresponding component of \vec{A} :

$$D_x = cA_x \quad D_y = cA_y \quad (\text{components of } \vec{D} = c\vec{A}) \quad (1.9)$$

For example, Eq. (1.9) says that each component of the vector $2\vec{A}$ is twice as great as the corresponding component of the vector \vec{A} , so $2\vec{A}$ is in the same direction as \vec{A} but has twice the magnitude. Each component of the vector $-3\vec{A}$ is three times as great as the corresponding component of the vector \vec{A} but has the opposite sign, so $-3\vec{A}$ is in the opposite direction from \vec{A} and has three times the magnitude. Hence Eqs. (1.9) are consistent with our discussion in Section 1.7 of multiplying a vector by a scalar (see Fig. 1.15).

3. Using components to calculate the vector sum (resultant) of two or more vectors. Figure 1.21 shows two vectors \vec{A} and \vec{B} and their vector sum \vec{R} , along with the x - and y -components of all three vectors. You can see from the diagram that the x -component R_x of the vector sum is simply the sum ($A_x + B_x$)

of the x -components of the vectors being added. The same is true for the y -components. In symbols,

$$R_x = A_x + B_x \quad R_y = A_y + B_y \quad (\text{components of } \vec{R} = \vec{A} + \vec{B}) \quad (1.10)$$

Figure 1.21 shows this result for the case in which the components A_x , A_y , B_x , and B_y are all positive. You should draw additional diagrams to verify for yourself that Eqs. (1.10) are valid for *any* signs of the components of \vec{A} and \vec{B} .

If we know the components of any two vectors \vec{A} and \vec{B} , perhaps by using Eqs. (1.6), we can compute the components of the vector sum \vec{R} . Then if we need the magnitude and direction of \vec{R} , we can obtain them from Eqs. (1.7) and (1.8) with the A 's replaced by R 's.

We can extend this procedure to find the sum of any number of vectors. If \vec{R} is the vector sum of \vec{A} , \vec{B} , \vec{C} , \vec{D} , \vec{E} , \dots , the components of \vec{R} are

$$\begin{aligned} R_x &= A_x + B_x + C_x + D_x + E_x + \dots \\ R_y &= A_y + B_y + C_y + D_y + E_y + \dots \end{aligned} \quad (1.11)$$

We have talked only about vectors that lie in the xy -plane, but the component method works just as well for vectors having any direction in space. We can introduce a z -axis perpendicular to the xy -plane; then in general a vector \vec{A} has components A_x , A_y , and A_z in the three coordinate directions. Its magnitude A is

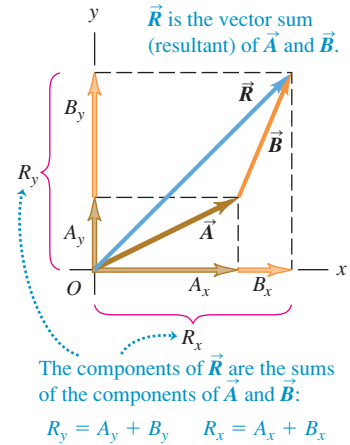
$$A = \sqrt{A_x^2 + A_y^2 + A_z^2} \quad (1.12)$$

Again, we always take the positive root. Also, Eqs. (1.11) for the components of the vector sum \vec{R} have an additional member:

$$R_z = A_z + B_z + C_z + D_z + E_z + \dots$$

We've focused on adding *displacement* vectors, but the method is applicable to all vector quantities. When we study the concept of force in Chapter 4, we'll find that forces are vectors that obey the same rules of vector addition that we've used with displacement.

1.21 Finding the vector sum (resultant) of \vec{A} and \vec{B} using components.



Problem-Solving Strategy 1.3 Vector Addition

IDENTIFY *the relevant concepts:* Decide what the target variable is. It may be the magnitude of the vector sum, the direction, or both.

SET UP *the problem:* Sketch the vectors being added, along with suitable coordinate axes. Place the tail of the first vector at the origin of the coordinates, place the tail of the second vector at the head of the first vector, and so on. Draw the vector sum \vec{R} from the tail of the first vector (at the origin) to the head of the last vector. Use your sketch to estimate the magnitude and direction of \vec{R} . Select the mathematical tools you'll use for the full calculation: Eqs. (1.6) to obtain the components of the vectors given, if necessary, Eqs. (1.11) to obtain the components of the vector sum, Eq. (1.12) to obtain its magnitude, and Eqs. (1.8) to obtain its direction.

EXECUTE *the solution* as follows:

1. Find the x - and y -components of each individual vector and record your results in a table, as in Example 1.7 below. If a vector is described by a magnitude A and an angle θ , measured

from the $+x$ -axis toward the $+y$ -axis, then its components are given by Eqs. 1.6:

$$A_x = A \cos \theta \quad A_y = A \sin \theta$$

If the angles of the vectors are given in some other way, perhaps using a different reference direction, convert them to angles measured from the $+x$ -axis as in Example 1.6 above.

2. Add the individual x -components algebraically (including signs) to find R_x , the x -component of the vector sum. Do the same for the y -components to find R_y . See Example 1.7 below.
3. Calculate the magnitude R and direction θ of the vector sum using Eqs. (1.7) and (1.8):

$$R = \sqrt{R_x^2 + R_y^2} \quad \theta = \arctan \frac{R_y}{R_x}$$

EVALUATE *your answer:* Confirm that your results for the magnitude and direction of the vector sum agree with the estimates you made from your sketch. The value of θ that you find with a calculator may be off by 180° ; your drawing will indicate the correct value.

Example 1.7 Adding vectors using their components

Three players on a reality TV show are brought to the center of a large, flat field. Each is given a meter stick, a compass, a calculator, a shovel, and (in a different order for each contestant) the following three displacements:

$$\vec{A}: 72.4 \text{ m}, 32.0^\circ \text{ east of north}$$

$$\vec{B}: 57.3 \text{ m}, 36.0^\circ \text{ south of west}$$

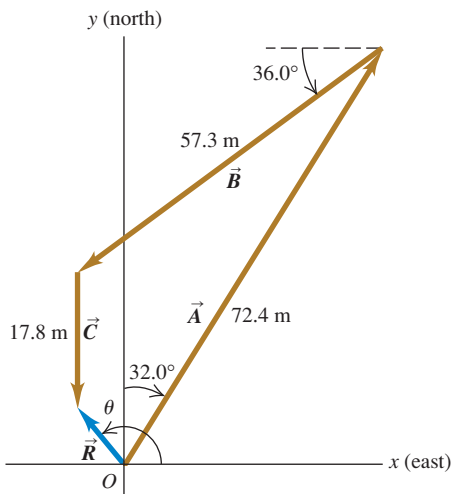
$$\vec{C}: 17.8 \text{ m due south}$$

The three displacements lead to the point in the field where the keys to a new Porsche are buried. Two players start measuring immediately, but the winner first *calculates* where to go. What does she calculate?

SOLUTION

IDENTIFY and SET UP: The goal is to find the sum (resultant) of the three displacements, so this is a problem in vector addition. Figure 1.22 shows the situation. We have chosen the $+x$ -axis as

1.22 Three successive displacements \vec{A} , \vec{B} , and \vec{C} and the resultant (vector sum) displacement $\vec{R} = \vec{A} + \vec{B} + \vec{C}$.



east and the $+y$ -axis as north. We estimate from the diagram that the vector sum \vec{R} is about 10 m, 40° west of north (which corresponds to $\theta \approx 130^\circ$).

EXECUTE: The angles of the vectors, measured from the $+x$ -axis toward the $+y$ -axis, are $(90.0^\circ - 32.0^\circ) = 58.0^\circ$, $(180.0^\circ + 36.0^\circ) = 216.0^\circ$, and 270.0° , respectively. We may now use Eqs. (1.6) to find the components of \vec{A} :

$$A_x = A \cos \theta_A = (72.4 \text{ m})(\cos 58.0^\circ) = 38.37 \text{ m}$$

$$A_y = A \sin \theta_A = (72.4 \text{ m})(\sin 58.0^\circ) = 61.40 \text{ m}$$

We've kept an extra significant figure in the components; we'll round to the correct number of significant figures at the end of our calculation. The table below shows the components of all the displacements, the addition of the components, and the other calculations.

Distance	Angle	x -component	y -component
$A = 72.4 \text{ m}$	58.0°	38.37 m	61.40 m
$B = 57.3 \text{ m}$	216.0°	-46.36 m	-33.68 m
$C = 17.8 \text{ m}$	270.0°	0.00 m	-17.80 m
		$R_x = -7.99 \text{ m}$	$R_y = 9.92 \text{ m}$

$$R = \sqrt{(-7.99 \text{ m})^2 + (9.92 \text{ m})^2} = 12.7 \text{ m}$$

$$\theta = \arctan \frac{9.92 \text{ m}}{-7.99 \text{ m}} = -51^\circ$$

Comparing to Fig. 1.22 shows that the calculated angle is clearly off by 180° . The correct value is $\theta = 180^\circ - 51^\circ = 129^\circ$, or 39° west of north.

EVALUATE: Our calculated answers for R and θ agree with our estimates. Notice how drawing the diagram in Fig. 1.22 made it easy to avoid a 180° error in the direction of the vector sum.

Example 1.8 A simple vector addition in three dimensions

After an airplane takes off, it travels 10.4 km west, 8.7 km north, and 2.1 km up. How far is it from the takeoff point?

SOLUTION

Let the $+x$ -axis be east, the $+y$ -axis north, and the $+z$ -axis up. Then the components of the airplane's displacement are $A_x = -10.4 \text{ km}$, $A_y = 8.7 \text{ km}$, and $A_z = 2.1 \text{ km}$. From Eq. (1.12), the magnitude of the displacement is

$$A = \sqrt{(-10.4 \text{ km})^2 + (8.7 \text{ km})^2 + (2.1 \text{ km})^2} = 13.7 \text{ km}$$

Test Your Understanding of Section 1.8 Two vectors \vec{A} and \vec{B} both lie in the xy -plane. (a) Is it possible for \vec{A} to have the same magnitude as \vec{B} but different components? (b) Is it possible for \vec{A} to have the same components as \vec{B} but a different magnitude?

1.9 Unit Vectors

A **unit vector** is a vector that has a magnitude of 1, with no units. Its only purpose is to *point*—that is, to describe a direction in space. Unit vectors provide a convenient notation for many expressions involving components of vectors. We will always include a caret or “hat” (^) in the symbol for a unit vector to distinguish it from ordinary vectors whose magnitude may or may not be equal to 1.

In an x - y coordinate system we can define a unit vector \hat{i} that points in the direction of the positive x -axis and a unit vector \hat{j} that points in the direction of the positive y -axis (Fig. 1.23a). Then we can express the relationship between component vectors and components, described at the beginning of Section 1.8, as follows:

$$\begin{aligned}\vec{A}_x &= A_x \hat{i} \\ \vec{A}_y &= A_y \hat{j}\end{aligned}\quad (1.13)$$

Similarly, we can write a vector \vec{A} in terms of its components as

$$\vec{A} = A_x \hat{i} + A_y \hat{j}\quad (1.14)$$

Equations (1.13) and (1.14) are vector equations; each term, such as $A_x \hat{i}$, is a vector quantity (Fig. 1.23b).

Using unit vectors, we can express the vector sum \vec{R} of two vectors \vec{A} and \vec{B} as follows:

$$\begin{aligned}\vec{A} &= A_x \hat{i} + A_y \hat{j} \\ \vec{B} &= B_x \hat{i} + B_y \hat{j} \\ \vec{R} &= \vec{A} + \vec{B} \\ &= (A_x \hat{i} + A_y \hat{j}) + (B_x \hat{i} + B_y \hat{j}) \\ &= (A_x + B_x) \hat{i} + (A_y + B_y) \hat{j} \\ &= R_x \hat{i} + R_y \hat{j}\end{aligned}\quad (1.15)$$

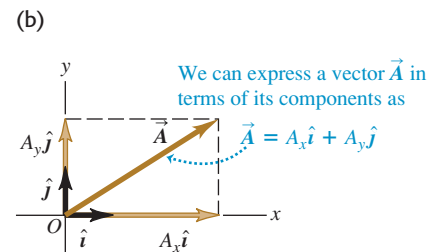
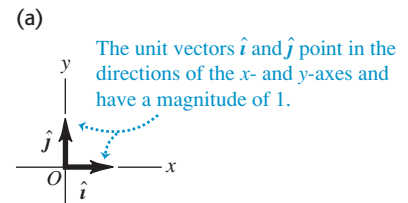
Equation (1.15) restates the content of Eqs. (1.10) in the form of a single vector equation rather than two component equations.

If the vectors do not all lie in the xy -plane, then we need a third component. We introduce a third unit vector \hat{k} that points in the direction of the positive z -axis (Fig. 1.24). Then Eqs. (1.14) and (1.15) become

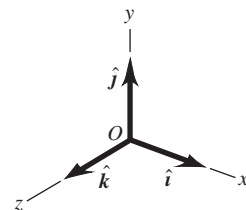
$$\begin{aligned}\vec{A} &= A_x \hat{i} + A_y \hat{j} + A_z \hat{k} \\ \vec{B} &= B_x \hat{i} + B_y \hat{j} + B_z \hat{k}\end{aligned}\quad (1.16)$$

$$\begin{aligned}\vec{R} &= (A_x + B_x) \hat{i} + (A_y + B_y) \hat{j} + (A_z + B_z) \hat{k} \\ &= R_x \hat{i} + R_y \hat{j} + R_z \hat{k}\end{aligned}\quad (1.17)$$

1.23 (a) The unit vectors \hat{i} and \hat{j} .
(b) Expressing a vector \vec{A} in terms of its components.



1.24 The unit vectors \hat{i} , \hat{j} , and \hat{k} .



Example 1.9 Using unit vectors

Given the two displacements

$$\vec{D} = (6.00\hat{i} + 3.00\hat{j} - 1.00\hat{k}) \text{ m} \quad \text{and}$$

$$\vec{E} = (4.00\hat{i} - 5.00\hat{j} + 8.00\hat{k}) \text{ m}$$

find the magnitude of the displacement $2\vec{D} - \vec{E}$.

SOLUTION

IDENTIFY and SET UP: We are to multiply the vector \vec{D} by 2 (a scalar) and subtract the vector \vec{E} from the result, so as to obtain the vector $\vec{F} = 2\vec{D} - \vec{E}$. Equation (1.9) says that to multiply \vec{D} by 2, we multiply each of its components by 2. We can use Eq. (1.17) to do the subtraction; recall from Section 1.7 that subtracting a vector is the same as adding the negative of that vector.

EXECUTE: We have

$$\begin{aligned} \vec{F} &= 2(6.00\hat{i} + 3.00\hat{j} - 1.00\hat{k}) \text{ m} - (4.00\hat{i} - 5.00\hat{j} + 8.00\hat{k}) \text{ m} \\ &= [(12.00 - 4.00)\hat{i} + (6.00 + 5.00)\hat{j} + (-2.00 - 8.00)\hat{k}] \text{ m} \\ &= (8.00\hat{i} + 11.00\hat{j} - 10.00\hat{k}) \text{ m} \end{aligned}$$

From Eq. (1.12) the magnitude of \vec{F} is

$$\begin{aligned} F &= \sqrt{F_x^2 + F_y^2 + F_z^2} \\ &= \sqrt{(8.00 \text{ m})^2 + (11.00 \text{ m})^2 + (-10.00 \text{ m})^2} \\ &= 16.9 \text{ m} \end{aligned}$$

EVALUATE: Our answer is of the same order of magnitude as the larger components that appear in the sum. We wouldn't expect our answer to be much larger than this, but it could be much smaller.

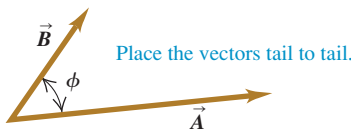
Test Your Understanding of Section 1.9 Arrange the following vectors in order of their magnitude, with the vector of largest magnitude first. (i) $\vec{A} = (3\hat{i} + 5\hat{j} - 2\hat{k}) \text{ m}$; (ii) $\vec{B} = (-3\hat{i} + 5\hat{j} - 2\hat{k}) \text{ m}$; (iii) $\vec{C} = (3\hat{i} - 5\hat{j} - 2\hat{k}) \text{ m}$; (iv) $\vec{D} = (3\hat{i} + 5\hat{j} + 2\hat{k}) \text{ m}$.



1.10 Products of Vectors

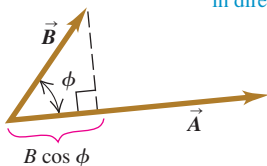
1.25 Calculating the scalar product of two vectors, $\vec{A} \cdot \vec{B} = AB \cos \phi$.

(a)



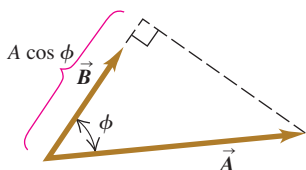
(b) $\vec{A} \cdot \vec{B}$ equals $A(B \cos \phi)$.

(Magnitude of \vec{A}) times (Component of \vec{B} in direction of \vec{A})



(c) $\vec{A} \cdot \vec{B}$ also equals $B(A \cos \phi)$

(Magnitude of \vec{B}) times (Component of \vec{A} in direction of \vec{B})



Vector addition develops naturally from the problem of combining displacements and will prove useful for calculating many other vector quantities. We can also express many physical relationships by using *products* of vectors. Vectors are not ordinary numbers, so ordinary multiplication is not directly applicable to vectors. We will define two different kinds of products of vectors. The first, called the *scalar product*, yields a result that is a scalar quantity. The second, the *vector product*, yields another vector.

Scalar Product

The **scalar product** of two vectors \vec{A} and \vec{B} is denoted by $\vec{A} \cdot \vec{B}$. Because of this notation, the scalar product is also called the **dot product**. Although \vec{A} and \vec{B} are vectors, the quantity $\vec{A} \cdot \vec{B}$ is a scalar.

To define the scalar product $\vec{A} \cdot \vec{B}$ we draw the two vectors \vec{A} and \vec{B} with their tails at the same point (Fig. 1.25a). The angle ϕ (the Greek letter phi) between their directions ranges from 0° to 180° . Figure 1.25b shows the projection of the vector \vec{B} onto the direction of \vec{A} ; this projection is the component of \vec{B} in the direction of \vec{A} and is equal to $B \cos \phi$. (We can take components along any direction that's convenient, not just the x - and y -axes.) We define $\vec{A} \cdot \vec{B}$ to be the magnitude of \vec{A} multiplied by the component of \vec{B} in the direction of \vec{A} . Expressed as an equation,

$$\vec{A} \cdot \vec{B} = AB \cos \phi = |\vec{A}||\vec{B}| \cos \phi \quad \text{(definition of the scalar (dot) product)} \quad (1.18)$$

Alternatively, we can define $\vec{A} \cdot \vec{B}$ to be the magnitude of \vec{B} multiplied by the component of \vec{A} in the direction of \vec{B} , as in Fig. 1.25c. Hence $\vec{A} \cdot \vec{B} = B(A \cos \phi) = AB \cos \phi$, which is the same as Eq. (1.18).

The scalar product is a scalar quantity, not a vector, and it may be positive, negative, or zero. When ϕ is between 0° and 90° , $\cos \phi > 0$ and the scalar product is

positive (Fig. 1.26a). When ϕ is between 90° and 180° so that $\cos \phi < 0$, the component of \vec{B} in the direction of \vec{A} is negative, and $\vec{A} \cdot \vec{B}$ is negative (Fig. 1.26b). Finally, when $\phi = 90^\circ$, $\vec{A} \cdot \vec{B} = 0$ (Fig. 1.26c). *The scalar product of two perpendicular vectors is always zero.*

For any two vectors \vec{A} and \vec{B} , $AB \cos \phi = BA \cos \phi$. This means that $\vec{A} \cdot \vec{B} = \vec{B} \cdot \vec{A}$. The scalar product obeys the commutative law of multiplication; the order of the two vectors does not matter.

We will use the scalar product in Chapter 6 to describe work done by a force. When a constant force \vec{F} is applied to a body that undergoes a displacement \vec{s} , the work W (a scalar quantity) done by the force is given by

$$W = \vec{F} \cdot \vec{s}$$

The work done by the force is positive if the angle between \vec{F} and \vec{s} is between 0° and 90° , negative if this angle is between 90° and 180° , and zero if \vec{F} and \vec{s} are perpendicular. (This is another example of a term that has a special meaning in physics; in everyday language, “work” isn’t something that can be positive or negative.) In later chapters we’ll use the scalar product for a variety of purposes, from calculating electric potential to determining the effects that varying magnetic fields have on electric circuits.

Calculating the Scalar Product Using Components

We can calculate the scalar product $\vec{A} \cdot \vec{B}$ directly if we know the x -, y -, and z -components of \vec{A} and \vec{B} . To see how this is done, let’s first work out the scalar products of the unit vectors. This is easy, since \hat{i} , \hat{j} , and \hat{k} all have magnitude 1 and are perpendicular to each other. Using Eq. (1.18), we find

$$\begin{aligned} \hat{i} \cdot \hat{i} = \hat{j} \cdot \hat{j} = \hat{k} \cdot \hat{k} &= (1)(1) \cos 0^\circ = 1 \\ \hat{i} \cdot \hat{j} = \hat{i} \cdot \hat{k} = \hat{j} \cdot \hat{k} &= (1)(1) \cos 90^\circ = 0 \end{aligned} \tag{1.19}$$

Now we express \vec{A} and \vec{B} in terms of their components, expand the product, and use these products of unit vectors:

$$\begin{aligned} \vec{A} \cdot \vec{B} &= (A_x \hat{i} + A_y \hat{j} + A_z \hat{k}) \cdot (B_x \hat{i} + B_y \hat{j} + B_z \hat{k}) \\ &= A_x \hat{i} \cdot B_x \hat{i} + A_x \hat{i} \cdot B_y \hat{j} + A_x \hat{i} \cdot B_z \hat{k} \\ &\quad + A_y \hat{j} \cdot B_x \hat{i} + A_y \hat{j} \cdot B_y \hat{j} + A_y \hat{j} \cdot B_z \hat{k} \\ &\quad + A_z \hat{k} \cdot B_x \hat{i} + A_z \hat{k} \cdot B_y \hat{j} + A_z \hat{k} \cdot B_z \hat{k} \\ &= A_x B_x \hat{i} \cdot \hat{i} + A_x B_y \hat{i} \cdot \hat{j} + A_x B_z \hat{i} \cdot \hat{k} \\ &\quad + A_y B_x \hat{j} \cdot \hat{i} + A_y B_y \hat{j} \cdot \hat{j} + A_y B_z \hat{j} \cdot \hat{k} \\ &\quad + A_z B_x \hat{k} \cdot \hat{i} + A_z B_y \hat{k} \cdot \hat{j} + A_z B_z \hat{k} \cdot \hat{k} \end{aligned} \tag{1.20}$$

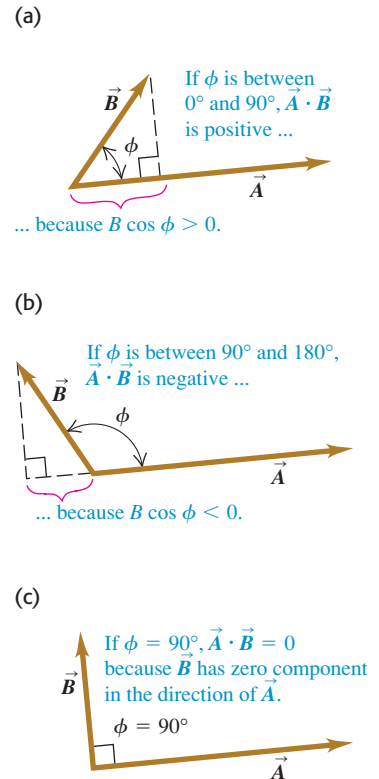
From Eqs. (1.19) we see that six of these nine terms are zero, and the three that survive give simply

$$\vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z \quad \text{(scalar (dot) product in terms of components)} \tag{1.21}$$

Thus *the scalar product of two vectors is the sum of the products of their respective components.*

The scalar product gives a straightforward way to find the angle ϕ between any two vectors \vec{A} and \vec{B} whose components are known. In this case we can use Eq. (1.21) to find the scalar product of \vec{A} and \vec{B} . Example 1.11 on the next page shows how to do this.

1.26 The scalar product $\vec{A} \cdot \vec{B} = AB \cos \phi$ can be positive, negative, or zero, depending on the angle between \vec{A} and \vec{B} .



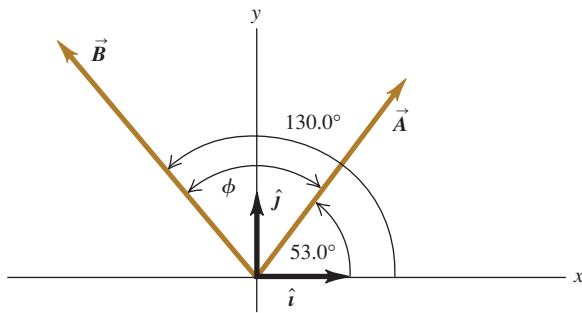
Example 1.10 Calculating a scalar product

Find the scalar product $\vec{A} \cdot \vec{B}$ of the two vectors in Fig. 1.27. The magnitudes of the vectors are $A = 4.00$ and $B = 5.00$.

SOLUTION

IDENTIFY and SET UP: We can calculate the scalar product in two ways: using the magnitudes of the vectors and the angle between them (Eq. 1.18), and using the components of the vectors (Eq. 1.21). We'll do it both ways, and the results will check each other.

1.27 Two vectors in two dimensions.



EXECUTE: The angle between the two vectors is $\phi = 130.0^\circ - 53.0^\circ = 77.0^\circ$, so Eq. (1.18) gives us

$$\vec{A} \cdot \vec{B} = AB \cos \phi = (4.00)(5.00) \cos 77.0^\circ = 4.50$$

To use Eq. (1.21), we must first find the components of the vectors. The angles of \vec{A} and \vec{B} are given with respect to the $+x$ -axis and are measured in the sense from the $+x$ -axis to the $+y$ -axis, so we can use Eqs. (1.6):

$$A_x = (4.00) \cos 53.0^\circ = 2.407$$

$$A_y = (4.00) \sin 53.0^\circ = 3.195$$

$$B_x = (5.00) \cos 130.0^\circ = -3.214$$

$$B_y = (5.00) \sin 130.0^\circ = 3.830$$

As in Example 1.7, we keep an extra significant figure in the components and round at the end. Equation (1.21) now gives us

$$\begin{aligned} \vec{A} \cdot \vec{B} &= A_x B_x + A_y B_y + A_z B_z \\ &= (2.407)(-3.214) + (3.195)(3.830) + (0)(0) = 4.50 \end{aligned}$$

EVALUATE: Both methods give the same result, as they should.

Example 1.11 Finding an angle with the scalar product

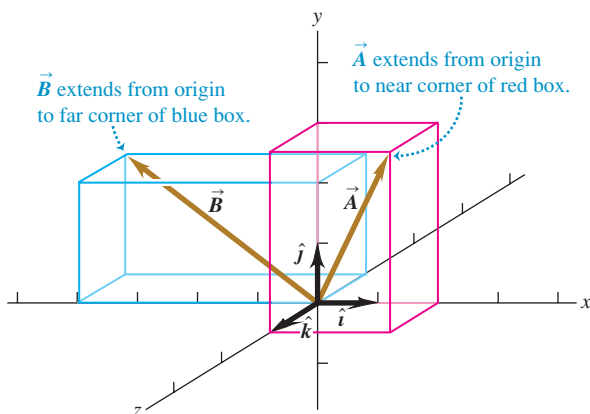
Find the angle between the vectors

$$\begin{aligned} \vec{A} &= 2.00\hat{i} + 3.00\hat{j} + 1.00\hat{k} \quad \text{and} \\ \vec{B} &= -4.00\hat{i} + 2.00\hat{j} - 1.00\hat{k} \end{aligned}$$

SOLUTION

IDENTIFY and SET UP: We're given the x -, y -, and z -components of two vectors. Our target variable is the angle ϕ between them (Fig. 1.28). To find this, we'll solve Eq. (1.18), $\vec{A} \cdot \vec{B} = AB \cos \phi$, for ϕ in terms of the scalar product $\vec{A} \cdot \vec{B}$ and the magnitudes A and B . We can evaluate the scalar product using Eq. (1.21),

1.28 Two vectors in three dimensions.



$\vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z$, and we can find A and B using Eq. (1.7).

EXECUTE: We solve Eq. (1.18) for $\cos \phi$ and write $\vec{A} \cdot \vec{B}$ using Eq. (1.21). Our result is

$$\cos \phi = \frac{\vec{A} \cdot \vec{B}}{AB} = \frac{A_x B_x + A_y B_y + A_z B_z}{AB}$$

We can use this formula to find the angle between *any* two vectors \vec{A} and \vec{B} . Here we have $A_x = 2.00$, $A_y = 3.00$, and $A_z = 1.00$, and $B_x = -4.00$, $B_y = 2.00$, and $B_z = -1.00$. Thus

$$\begin{aligned} \vec{A} \cdot \vec{B} &= A_x B_x + A_y B_y + A_z B_z \\ &= (2.00)(-4.00) + (3.00)(2.00) + (1.00)(-1.00) \\ &= -3.00 \\ A &= \sqrt{A_x^2 + A_y^2 + A_z^2} = \sqrt{(2.00)^2 + (3.00)^2 + (1.00)^2} \\ &= \sqrt{14.00} \\ B &= \sqrt{B_x^2 + B_y^2 + B_z^2} = \sqrt{(-4.00)^2 + (2.00)^2 + (-1.00)^2} \\ &= \sqrt{21.00} \\ \cos \phi &= \frac{A_x B_x + A_y B_y + A_z B_z}{AB} = \frac{-3.00}{\sqrt{14.00} \sqrt{21.00}} = -0.175 \\ \phi &= 100^\circ \end{aligned}$$

EVALUATE: As a check on this result, note that the scalar product $\vec{A} \cdot \vec{B}$ is negative. This means that ϕ is between 90° and 180° (see Fig. 1.26), which agrees with our answer.

Vector Product

The **vector product** of two vectors \vec{A} and \vec{B} , also called the **cross product**, is denoted by $\vec{A} \times \vec{B}$. As the name suggests, the vector product is itself a vector. We'll use this product in Chapter 10 to describe torque and angular momentum; in Chapters 27 and 28 we'll use it to describe magnetic fields and forces.

To define the vector product $\vec{A} \times \vec{B}$, we again draw the two vectors \vec{A} and \vec{B} with their tails at the same point (Fig. 1.29a). The two vectors then lie in a plane. We define the vector product to be a vector quantity with a direction perpendicular to this plane (that is, perpendicular to both \vec{A} and \vec{B}) and a magnitude equal to $AB \sin \phi$. That is, if $\vec{C} = \vec{A} \times \vec{B}$, then

$$C = AB \sin \phi \quad (\text{magnitude of the vector (cross) product of } \vec{A} \text{ and } \vec{B}) \quad (1.22)$$

We measure the angle ϕ from \vec{A} toward \vec{B} and take it to be the smaller of the two possible angles, so ϕ ranges from 0° to 180° . Then $\sin \phi \geq 0$ and C in Eq. (1.22) is never negative, as must be the case for a vector magnitude. Note also that when \vec{A} and \vec{B} are parallel or antiparallel, $\phi = 0$ or 180° and $C = 0$. That is, *the vector product of two parallel or antiparallel vectors is always zero*. In particular, *the vector product of any vector with itself is zero*.

CAUTION **Vector product vs. scalar product** Be careful not to confuse the expression $AB \sin \phi$ for the magnitude of the vector product $\vec{A} \times \vec{B}$ with the similar expression $AB \cos \phi$ for the scalar product $\vec{A} \cdot \vec{B}$. To see the difference between these two expressions, imagine that we vary the angle between \vec{A} and \vec{B} while keeping their magnitudes constant. When \vec{A} and \vec{B} are parallel, the magnitude of the vector product will be zero and the scalar product will be maximum. When \vec{A} and \vec{B} are perpendicular, the magnitude of the vector product will be maximum and the scalar product will be zero. ■

There are always *two* directions perpendicular to a given plane, one on each side of the plane. We choose which of these is the direction of $\vec{A} \times \vec{B}$ as follows. Imagine rotating vector \vec{A} about the perpendicular line until it is aligned with \vec{B} , choosing the smaller of the two possible angles between \vec{A} and \vec{B} . Curl the fingers of your right hand around the perpendicular line so that the fingertips point in the direction of rotation; your thumb will then point in the direction of $\vec{A} \times \vec{B}$. Figure 1.29a shows this **right-hand rule** and describes a second way to think about this rule.

Similarly, we determine the direction of $\vec{B} \times \vec{A}$ by rotating \vec{B} into \vec{A} as in Fig. 1.29b. The result is a vector that is *opposite* to the vector $\vec{A} \times \vec{B}$. The vector product is *not* commutative! In fact, for any two vectors \vec{A} and \vec{B} ,

$$\vec{A} \times \vec{B} = -\vec{B} \times \vec{A} \quad (1.23)$$

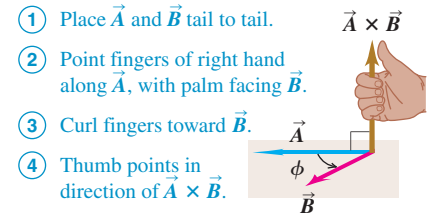
Just as we did for the scalar product, we can give a geometrical interpretation of the magnitude of the vector product. In Fig. 1.30a, $B \sin \phi$ is the component of vector \vec{B} that is *perpendicular* to the direction of vector \vec{A} . From Eq. (1.22) the magnitude of $\vec{A} \times \vec{B}$ equals the magnitude of \vec{A} multiplied by the component of \vec{B} perpendicular to \vec{A} . Figure 1.30b shows that the magnitude of $\vec{A} \times \vec{B}$ also equals the magnitude of \vec{B} multiplied by the component of \vec{A} perpendicular to \vec{B} . Note that Fig. 1.30 shows the case in which ϕ is between 0° and 90° ; you should draw a similar diagram for ϕ between 90° and 180° to show that the same geometrical interpretation of the magnitude of $\vec{A} \times \vec{B}$ still applies.

Calculating the Vector Product Using Components

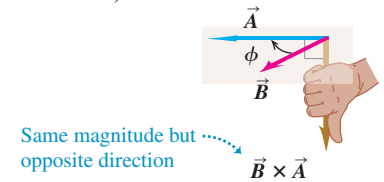
If we know the components of \vec{A} and \vec{B} , we can calculate the components of the vector product using a procedure similar to that for the scalar product. First we work out the multiplication table for the unit vectors \hat{i} , \hat{j} , and \hat{k} , all three of which

1.29 (a) The vector product $\vec{A} \times \vec{B}$ determined by the right-hand rule. (b) $\vec{B} \times \vec{A} = -\vec{A} \times \vec{B}$; the vector product is anticommutative.

(a) Using the right-hand rule to find the direction of $\vec{A} \times \vec{B}$

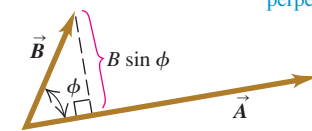


(b) $\vec{B} \times \vec{A} = -\vec{A} \times \vec{B}$ (the vector product is anticommutative)

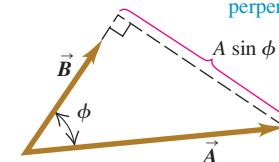


1.30 Calculating the magnitude $AB \sin \phi$ of the vector product of two vectors, $\vec{A} \times \vec{B}$.

(a) (Magnitude of $\vec{A} \times \vec{B}$) equals $A(B \sin \phi)$. (Magnitude of \vec{A}) times (Component of \vec{B} perpendicular to \vec{A})

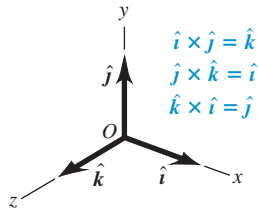


(b) (Magnitude of $\vec{A} \times \vec{B}$) also equals $B(A \sin \phi)$. (Magnitude of \vec{B}) times (Component of \vec{A} perpendicular to \vec{B})

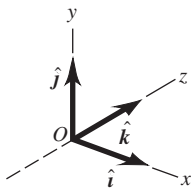


1.31 (a) We will always use a right-handed coordinate system, like this one. (b) We will never use a left-handed coordinate system (in which $\hat{i} \times \hat{j} = -\hat{k}$, and so on).

(a) A right-handed coordinate system



(b) A left-handed coordinate system; we will not use these.



are perpendicular to each other (Fig. 1.31a). The vector product of any vector with itself is zero, so

$$\hat{i} \times \hat{i} = \hat{j} \times \hat{j} = \hat{k} \times \hat{k} = \mathbf{0}$$

The boldface zero is a reminder that each product is a zero *vector*—that is, one with all components equal to zero and an undefined direction. Using Eqs. (1.22) and (1.23) and the right-hand rule, we find

$$\begin{aligned} \hat{i} \times \hat{j} &= -\hat{j} \times \hat{i} = \hat{k} \\ \hat{j} \times \hat{k} &= -\hat{k} \times \hat{j} = \hat{i} \\ \hat{k} \times \hat{i} &= -\hat{i} \times \hat{k} = \hat{j} \end{aligned} \tag{1.24}$$

You can verify these equations by referring to Fig. 1.31a.

Next we express \vec{A} and \vec{B} in terms of their components and the corresponding unit vectors, and we expand the expression for the vector product:

$$\begin{aligned} \vec{A} \times \vec{B} &= (A_x \hat{i} + A_y \hat{j} + A_z \hat{k}) \times (B_x \hat{i} + B_y \hat{j} + B_z \hat{k}) \\ &= A_x \hat{i} \times B_x \hat{i} + A_x \hat{i} \times B_y \hat{j} + A_x \hat{i} \times B_z \hat{k} \\ &\quad + A_y \hat{j} \times B_x \hat{i} + A_y \hat{j} \times B_y \hat{j} + A_y \hat{j} \times B_z \hat{k} \\ &\quad + A_z \hat{k} \times B_x \hat{i} + A_z \hat{k} \times B_y \hat{j} + A_z \hat{k} \times B_z \hat{k} \end{aligned} \tag{1.25}$$

We can also rewrite the individual terms in Eq. (1.25) as $A_x \hat{i} \times B_y \hat{j} = (A_x B_y) \hat{i} \times \hat{j}$, and so on. Evaluating these by using the multiplication table for the unit vectors in Eqs. (1.24) and then grouping the terms, we get

$$\vec{A} \times \vec{B} = (A_y B_z - A_z B_y) \hat{i} + (A_z B_x - A_x B_z) \hat{j} + (A_x B_y - A_y B_x) \hat{k} \tag{1.26}$$

Thus the components of $\vec{C} = \vec{A} \times \vec{B}$ are given by

$$\begin{aligned} C_x &= A_y B_z - A_z B_y & C_y &= A_z B_x - A_x B_z & C_z &= A_x B_y - A_y B_x \\ &\text{(components of } \vec{C} = \vec{A} \times \vec{B}) \end{aligned} \tag{1.27}$$

The vector product can also be expressed in determinant form as

$$\vec{A} \times \vec{B} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$

If you aren't familiar with determinants, don't worry about this form.

With the axis system of Fig. 1.31a, if we reverse the direction of the z -axis, we get the system shown in Fig. 1.31b. Then, as you may verify, the definition of the vector product gives $\hat{i} \times \hat{j} = -\hat{k}$ instead of $\hat{i} \times \hat{j} = \hat{k}$. In fact, all vector products of the unit vectors \hat{i} , \hat{j} , and \hat{k} would have signs opposite to those in Eqs. (1.24). We see that there are two kinds of coordinate systems, differing in the signs of the vector products of unit vectors. An axis system in which $\hat{i} \times \hat{j} = \hat{k}$, as in Fig. 1.31a, is called a **right-handed system**. The usual practice is to use *only* right-handed systems, and we will follow that practice throughout this book.

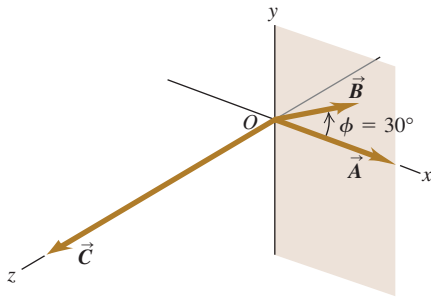
Example 1.12 Calculating a vector product

Vector \vec{A} has magnitude 6 units and is in the direction of the $+x$ -axis. Vector \vec{B} has magnitude 4 units and lies in the xy -plane, making an angle of 30° with the $+x$ -axis (Fig. 1.32). Find the vector product $\vec{C} = \vec{A} \times \vec{B}$.

SOLUTION

IDENTIFY and SET UP: We'll find the vector product in two ways, which will provide a check of our calculations. First we'll use Eq. (1.22) and the right-hand rule; then we'll use Eqs. (1.27) to find the vector product using components.

1.32 Vectors \vec{A} and \vec{B} and their vector product $\vec{C} = \vec{A} \times \vec{B}$. The vector \vec{B} lies in the xy -plane.



EXECUTE: From Eq. (1.22) the magnitude of the vector product is

$$AB \sin \phi = (6)(4)(\sin 30^\circ) = 12$$

By the right-hand rule, the direction of $\vec{A} \times \vec{B}$ is along the $+z$ -axis (the direction of the unit vector \hat{k}), so we have $\vec{C} = \vec{A} \times \vec{B} = 12\hat{k}$.

To use Eqs. (1.27), we first determine the components of \vec{A} and \vec{B} :

$$\begin{array}{lll} A_x = 6 & A_y = 0 & A_z = 0 \\ B_x = 4 \cos 30^\circ = 2\sqrt{3} & B_y = 4 \sin 30^\circ = 2 & B_z = 0 \end{array}$$

Then Eqs. (1.27) yield

$$\begin{aligned} C_x &= (0)(0) - (0)(2) = 0 \\ C_y &= (0)(2\sqrt{3}) - (6)(0) = 0 \\ C_z &= (6)(2) - (0)(2\sqrt{3}) = 12 \end{aligned}$$

Thus again we have $\vec{C} = 12\hat{k}$.

EVALUATE: Both methods give the same result. Depending on the situation, one or the other of the two approaches may be the more convenient one to use.

Test Your Understanding of Section 1.10 Vector \vec{A} has magnitude 2 and vector \vec{B} has magnitude 3. The angle ϕ between \vec{A} and \vec{B} is known to be 0° , 90° , or 180° . For each of the following situations, state what the value of ϕ must be. (In each situation there may be more than one correct answer.) (a) $\vec{A} \cdot \vec{B} = 0$; (b) $\vec{A} \times \vec{B} = \mathbf{0}$; (c) $\vec{A} \cdot \vec{B} = 6$; (d) $\vec{A} \cdot \vec{B} = -6$; (e) (Magnitude of $\vec{A} \times \vec{B}$) = 6. |

Physical quantities and units: Three fundamental physical quantities are mass, length, and time. The corresponding basic SI units are the kilogram, the meter, and the second. Derived units for other physical quantities are products or quotients of the basic units. Equations must be dimensionally consistent; two terms can be added only when they have the same units. (See Examples 1.1 and 1.2.)

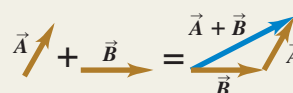
Significant figures: The accuracy of a measurement can be indicated by the number of significant figures or by a stated uncertainty. The result of a calculation usually has no more significant figures than the input data. When only crude estimates are available for input data, we can often make useful order-of-magnitude estimates. (See Examples 1.3 and 1.4.)

Significant figures in magenta

$$\pi = \frac{C}{2r} = \frac{0.424 \text{ m}}{2(0.06750 \text{ m})} = 3.14$$

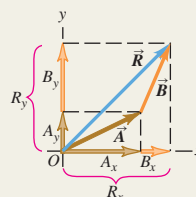
$$123.62 + 8.9 = 132.5$$

Scalars, vectors, and vector addition: Scalar quantities are numbers and combine with the usual rules of arithmetic. Vector quantities have direction as well as magnitude and combine according to the rules of vector addition. The negative of a vector has the same magnitude but points in the opposite direction. (See Example 1.5.)



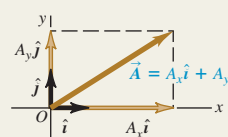
Vector components and vector addition: Vector addition can be carried out using components of vectors. The x -component of $\vec{R} = \vec{A} + \vec{B}$ is the sum of the x -components of \vec{A} and \vec{B} , and likewise for the y - and z -components. (See Examples 1.6–1.8.)

$$\begin{aligned} R_x &= A_x + B_x \\ R_y &= A_y + B_y \\ R_z &= A_z + B_z \end{aligned} \quad (1.10)$$



Unit vectors: Unit vectors describe directions in space. A unit vector has a magnitude of 1, with no units. The unit vectors \hat{i} , \hat{j} , and \hat{k} , aligned with the x -, y -, and z -axes of a rectangular coordinate system, are especially useful. (See Example 1.9.)

$$\vec{A} = A_x \hat{i} + A_y \hat{j} + A_z \hat{k} \quad (1.16)$$

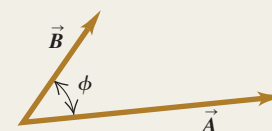


Scalar product: The scalar product $C = \vec{A} \cdot \vec{B}$ of two vectors \vec{A} and \vec{B} is a scalar quantity. It can be expressed in terms of the magnitudes of \vec{A} and \vec{B} and the angle ϕ between the two vectors, or in terms of the components of \vec{A} and \vec{B} . The scalar product is commutative; $\vec{A} \cdot \vec{B} = \vec{B} \cdot \vec{A}$. The scalar product of two perpendicular vectors is zero. (See Examples 1.10 and 1.11.)

$$\vec{A} \cdot \vec{B} = AB \cos \phi = |\vec{A}| |\vec{B}| \cos \phi \quad (1.18)$$

$$\vec{A} \cdot \vec{B} = A_x B_x + A_y B_y + A_z B_z \quad (1.21)$$

Scalar product $\vec{A} \cdot \vec{B} = AB \cos \phi$



Vector product: The vector product $\vec{C} = \vec{A} \times \vec{B}$ of two vectors \vec{A} and \vec{B} is another vector \vec{C} . The magnitude of $\vec{A} \times \vec{B}$ depends on the magnitudes of \vec{A} and \vec{B} and the angle ϕ between the two vectors. The direction of $\vec{A} \times \vec{B}$ is perpendicular to the plane of the two vectors being multiplied, as given by the right-hand rule. The components of $\vec{C} = \vec{A} \times \vec{B}$ can be expressed in terms of the components of \vec{A} and \vec{B} . The vector product is not commutative; $\vec{A} \times \vec{B} = -\vec{B} \times \vec{A}$. The vector product of two parallel or antiparallel vectors is zero. (See Example 1.12.)

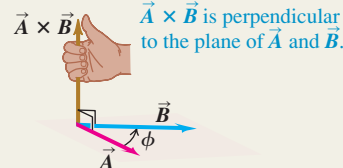
$$C = AB \sin \phi \quad (1.22)$$

$$C_x = A_y B_z - A_z B_y$$

$$C_y = A_z B_x - A_x B_z \quad (1.27)$$

$$C_z = A_x B_y - A_y B_x$$

$\vec{A} \times \vec{B}$ is perpendicular to the plane of \vec{A} and \vec{B} .



(Magnitude of $\vec{A} \times \vec{B}$) = $AB \sin \phi$

BRIDGING PROBLEM

Vectors on the Roof

An air-conditioning unit is fastened to a roof that slopes at an angle of 35° above the horizontal (Fig. 1.33). Its weight is a force on the air conditioner that is directed vertically downward. In order that the unit not crush the roof tiles, the component of the unit's weight perpendicular to the roof cannot exceed 425 N. (One newton, or 1 N, is the SI unit of force. It is equal to 0.2248 lb.) (a) What is the maximum allowed weight of the unit? (b) If the fasteners fail, the unit slides 1.50 m along the roof before it comes to a halt against a ledge. How much work does the weight force do on the unit during its slide if the unit has the weight calculated in part (a)? As we described in Section 1.10, the work done by a force \vec{F} on an object that undergoes a displacement \vec{s} is $W = \vec{F} \cdot \vec{s}$.

SOLUTION GUIDE

See MasteringPhysics® study area for a Video Tutor solution.



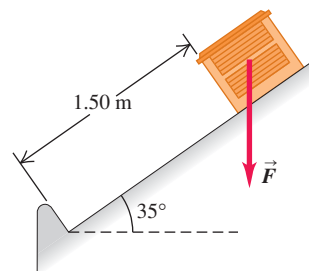
IDENTIFY and SET UP

1. This problem involves vectors and components. What are the known quantities? Which aspect(s) of the weight vector (magnitude, direction, and/or particular components) represent the target variable for part (a)? Which aspect(s) must you know to solve part (b)?
2. Make a sketch based on Fig. 1.33. Add x - and y -axes, choosing the positive direction for each. Your axes don't have to be horizontal and vertical, but they do have to be mutually perpendicular. Make the most convenient choice.
3. Choose the equations you'll use to determine the target variables.

EXECUTE

4. Use the relationship between the magnitude and direction of a vector and its components to solve for the target variable in

1.33 An air-conditioning unit on a slanted roof.



part (a). Be careful: Is 35° the correct angle to use in the equation? (*Hint*: Check your sketch.)

5. Make sure your answer has the correct number of significant figures.
6. Use the definition of the scalar product to solve for the target variable in part (b). Again, make sure to use the correct number of significant figures.

EVALUATE

7. Did your answer to part (a) include a vector component whose absolute value is greater than the magnitude of the vector? Is that possible?
8. There are two ways to find the scalar product of two vectors, one of which you used to solve part (b). Check your answer by repeating the calculation using the other way. Do you get the same answer?

Problems

For instructor-assigned homework, go to www.masteringphysics.com



•, ••, •••: Problems of increasing difficulty. **CP**: Cumulative problems incorporating material from earlier chapters. **CALC**: Problems requiring calculus. **BIO**: Biosciences problems.

DISCUSSION QUESTIONS

- Q1.1** How many correct experiments do we need to disprove a theory? How many do we need to prove a theory? Explain.
- Q1.2** A guidebook describes the rate of climb of a mountain trail as 120 meters per kilometer. How can you express this as a number with no units?
- Q1.3** Suppose you are asked to compute the tangent of 5.00 meters. Is this possible? Why or why not?
- Q1.4** A highway contractor stated that in building a bridge deck he poured 250 yards of concrete. What do you think he meant?
- Q1.5** What is your height in centimeters? What is your weight in newtons?
- Q1.6** The U.S. National Institute of Standards and Technology (NIST) maintains several accurate copies of the international standard kilogram. Even after careful cleaning, these national standard

kilograms are gaining mass at an average rate of about $1 \mu\text{g}/\text{y}$ ($\text{y} = \text{year}$) when compared every 10 years or so to the standard international kilogram. Does this apparent change have any importance? Explain.

- Q1.7** What physical phenomena (other than a pendulum or cesium clock) could you use to define a time standard?
- Q1.8** Describe how you could measure the thickness of a sheet of paper with an ordinary ruler.
- Q1.9** The quantity $\pi = 3.14159\dots$ is a number with no dimensions, since it is a ratio of two lengths. Describe two or three other geometrical or physical quantities that are dimensionless.
- Q1.10** What are the units of volume? Suppose another student tells you that a cylinder of radius r and height h has volume given by $\pi r^3 h$. Explain why this cannot be right.

Q1.11 Three archers each fire four arrows at a target. Joe's four arrows hit at points 10 cm above, 10 cm below, 10 cm to the left, and 10 cm to the right of the center of the target. All four of Moe's arrows hit within 1 cm of a point 20 cm from the center, and Flo's four arrows all hit within 1 cm of the center. The contest judge says that one of the archers is precise but not accurate, another archer is accurate but not precise, and the third archer is both accurate and precise. Which description goes with which archer? Explain your reasoning.

Q1.12 A circular racetrack has a radius of 500 m. What is the displacement of a bicyclist when she travels around the track from the north side to the south side? When she makes one complete circle around the track? Explain your reasoning.

Q1.13 Can you find two vectors with different lengths that have a vector sum of zero? What length restrictions are required for three vectors to have a vector sum of zero? Explain your reasoning.

Q1.14 One sometimes speaks of the "direction of time," evolving from past to future. Does this mean that time is a vector quantity? Explain your reasoning.

Q1.15 Air traffic controllers give instructions to airline pilots telling them in which direction they are to fly. These instructions are called "vectors." If these are the only instructions given, is the name "vector" used correctly? Why or why not?

Q1.16 Can you find a vector quantity that has a magnitude of zero but components that are different from zero? Explain. Can the magnitude of a vector be less than the magnitude of any of its components? Explain.

Q1.17 (a) Does it make sense to say that a vector is *negative*? Why? (b) Does it make sense to say that one vector is the negative of another? Why? Does your answer here contradict what you said in part (a)?

Q1.18 If \vec{C} is the vector sum of \vec{A} and \vec{B} , $\vec{C} = \vec{A} + \vec{B}$, what must be true about the directions and magnitudes of \vec{A} and \vec{B} if $C = A + B$? What must be true about the directions and magnitudes of \vec{A} and \vec{B} if $C = 0$?

Q1.19 If \vec{A} and \vec{B} are nonzero vectors, is it possible for $\vec{A} \cdot \vec{B}$ and $\vec{A} \times \vec{B}$ both to be zero? Explain.

Q1.20 What does $\vec{A} \cdot \vec{A}$, the scalar product of a vector with itself, give? What about $\vec{A} \times \vec{A}$, the vector product of a vector with itself?

Q1.21 Let \vec{A} represent any nonzero vector. Why is \vec{A}/A a unit vector, and what is its direction? If θ is the angle that \vec{A} makes with the $+x$ -axis, explain why $(\vec{A}/A) \cdot \hat{i}$ is called the *direction cosine* for that axis.

Q1.22 Which of the following are legitimate mathematical operations: (a) $\vec{A} \cdot (\vec{B} - \vec{C})$; (b) $(\vec{A} - \vec{B}) \times \vec{C}$; (c) $\vec{A} \cdot (\vec{B} \times \vec{C})$; (d) $\vec{A} \times (\vec{B} \times \vec{C})$; (e) $\vec{A} \times (\vec{B} \cdot \vec{C})$? In each case, give the reason for your answer.

Q1.23 Consider the two repeated vector products $\vec{A} \times (\vec{B} \times \vec{C})$ and $(\vec{A} \times \vec{B}) \times \vec{C}$. Give an example that illustrates the general rule that these two vector products do not have the same magnitude or direction. Can you choose the vectors \vec{A} , \vec{B} , and \vec{C} such that these two vector products *are* equal? If so, give an example.

Q1.24 Show that, no matter what \vec{A} and \vec{B} are, $\vec{A} \cdot (\vec{A} \times \vec{B}) = 0$. (*Hint:* Do not look for an elaborate mathematical proof. Rather look at the definition of the direction of the cross product.)

Q1.25 (a) If $\vec{A} \cdot \vec{B} = 0$, does it necessarily follow that $A = 0$ or $B = 0$? Explain. (b) If $\vec{A} \times \vec{B} = \mathbf{0}$, does it necessarily follow that $A = 0$ or $B = 0$? Explain.

Q1.26 If $\vec{A} = \mathbf{0}$ for a vector in the xy -plane, does it follow that $A_x = -A_y$? What *can* you say about A_x and A_y ?

EXERCISES

Section 1.3 Standards and Units

Section 1.4 Unit Consistency and Conversions

1.1 • Starting with the definition 1 in. = 2.54 cm, find the number of (a) kilometers in 1.00 mile and (b) feet in 1.00 km.

1.2 •• According to the label on a bottle of salad dressing, the volume of the contents is 0.473 liter (L). Using only the conversions 1 L = 1000 cm³ and 1 in. = 2.54 cm, express this volume in cubic inches.

1.3 •• How many nanoseconds does it take light to travel 1.00 ft in vacuum? (This result is a useful quantity to remember.)

1.4 •• The density of gold is 19.3 g/cm³. What is this value in kilograms per cubic meter?

1.5 • The most powerful engine available for the classic 1963 Chevrolet Corvette Sting Ray developed 360 horsepower and had a displacement of 327 cubic inches. Express this displacement in liters (L) by using only the conversions 1 L = 1000 cm³ and 1 in. = 2.54 cm.

1.6 •• A square field measuring 100.0 m by 100.0 m has an area of 1.00 hectare. An acre has an area of 43,600 ft². If a country lot has an area of 12.0 acres, what is the area in hectares?

1.7 • How many years older will you be 1.00 gigasecond from now? (Assume a 365-day year.)

1.8 • While driving in an exotic foreign land you see a speed limit sign on a highway that reads 180,000 furlongs per fortnight. How many miles per hour is this? (One furlong is $\frac{1}{8}$ mile, and a fortnight is 14 days. A furlong originally referred to the length of a plowed furrow.)

1.9 • A certain fuel-efficient hybrid car gets gasoline mileage of 55.0 mpg (miles per gallon). (a) If you are driving this car in Europe and want to compare its mileage with that of other European cars, express this mileage in km/L (L = liter). Use the conversion factors in Appendix E. (b) If this car's gas tank holds 45 L, how many tanks of gas will you use to drive 1500 km?

1.10 • The following conversions occur frequently in physics and are very useful. (a) Use 1 mi = 5280 ft and 1 h = 3600 s to convert 60 mph to units of ft/s. (b) The acceleration of a freely falling object is 32 ft/s². Use 1 ft = 30.48 cm to express this acceleration in units of m/s². (c) The density of water is 1.0 g/cm³. Convert this density to units of kg/m³.

1.11 •• **Neptunium.** In the fall of 2002, a group of scientists at Los Alamos National Laboratory determined that the critical mass of neptunium-237 is about 60 kg. The critical mass of a fissionable material is the minimum amount that must be brought together to start a chain reaction. This element has a density of 19.5 g/cm³. What would be the radius of a sphere of this material that has a critical mass?

1.12 • **BIO** (a) The recommended daily allowance (RDA) of the trace metal magnesium is 410 mg/day for males. Express this quantity in $\mu\text{g/day}$. (b) For adults, the RDA of the amino acid lysine is 12 mg per kg of body weight. How many grams per day should a 75-kg adult receive? (c) A typical multivitamin tablet can contain 2.0 mg of vitamin B₂ (riboflavin), and the RDA is 0.0030 g/day. How many such tablets should a person take each day to get the proper amount of this vitamin, assuming that he gets none from any other sources? (d) The RDA for the trace element selenium is 0.000070 g/day. Express this dose in mg/day.

Section 1.5 Uncertainty and Significant Figures

1.13 •• Figure 1.7 shows the result of unacceptable error in the stopping position of a train. (a) If a train travels 890 km from Berlin

to Paris and then overshoots the end of the track by 10 m, what is the percent error in the total distance covered? (b) Is it correct to write the total distance covered by the train as 890,010 m? Explain.

1.14 • With a wooden ruler you measure the length of a rectangular piece of sheet metal to be 12 mm. You use micrometer calipers to measure the width of the rectangle and obtain the value 5.98 mm. Give your answers to the following questions to the correct number of significant figures. (a) What is the area of the rectangle? (b) What is the ratio of the rectangle's width to its length? (c) What is the perimeter of the rectangle? (d) What is the difference between the length and width? (e) What is the ratio of the length to the width?

1.15 •• A useful and easy-to-remember approximate value for the number of seconds in a year is $\pi \times 10^7$. Determine the percent error in this approximate value. (There are 365.24 days in one year.)

Section 1.6 Estimates and Orders of Magnitude

1.16 • How many gallons of gasoline are used in the United States in one day? Assume that there are two cars for every three people, that each car is driven an average of 10,000 mi per year, and that the average car gets 20 miles per gallon.

1.17 •• BIO A rather ordinary middle-aged man is in the hospital for a routine check-up. The nurse writes the quantity 200 on his medical chart but forgets to include the units. Which of the following quantities could the 200 plausibly represent? (a) his mass in kilograms; (b) his height in meters; (c) his height in centimeters; (d) his height in millimeters; (e) his age in months.

1.18 • How many kernels of corn does it take to fill a 2-L soft drink bottle?

1.19 • How many words are there in this book?

1.20 • BIO Four astronauts are in a spherical space station. (a) If, as is typical, each of them breathes about 500 cm³ of air with each breath, approximately what volume of air (in cubic meters) do these astronauts breathe in a year? (b) What would the diameter (in meters) of the space station have to be to contain all this air?

1.21 • BIO How many times does a typical person blink her eyes in a lifetime?

1.22 • BIO How many times does a human heart beat during a lifetime? How many gallons of blood does it pump? (Estimate that the heart pumps 50 cm³ of blood with each beat.)

1.23 • In Wagner's opera *Das Rheingold*, the goddess Freia is ransomed for a pile of gold just tall enough and wide enough to hide her from sight. Estimate the monetary value of this pile. The density of gold is 19.3 g/cm³, and its value is about \$10 per gram (although this varies).

1.24 • You are using water to dilute small amounts of chemicals in the laboratory, drop by drop. How many drops of water are in a 1.0-L bottle? (*Hint:* Start by estimating the diameter of a drop of water.)

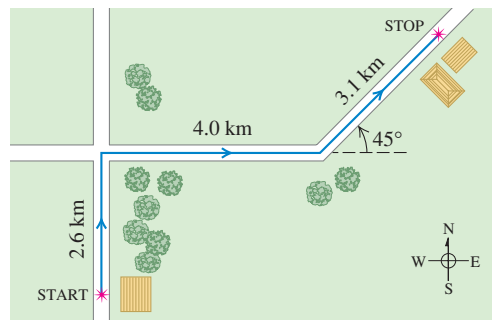
1.25 • How many pizzas are consumed each academic year by students at your school?

Section 1.7 Vectors and Vector Addition

1.26 •• Hearing rattles from a snake, you make two rapid displacements of magnitude 1.8 m and 2.4 m. In sketches (roughly to scale), show how your two displacements might add up to give a resultant of magnitude (a) 4.2 m; (b) 0.6 m; (c) 3.0 m.

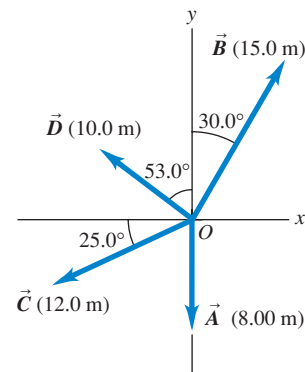
1.27 •• A postal employee drives a delivery truck along the route shown in Fig. E1.27. Determine the magnitude and direction of the resultant displacement by drawing a scale diagram. (See also Exercise 1.34 for a different approach to this same problem.)

Figure E1.27



1.28 •• For the vectors \vec{A} and \vec{B} in Fig. E1.28, use a scale drawing to find the magnitude and direction of (a) the vector sum $\vec{A} + \vec{B}$ and (b) the vector difference $\vec{A} - \vec{B}$. Use your answers to find the magnitude and direction of (c) $-\vec{A} - \vec{B}$ and (d) $\vec{B} - \vec{A}$. (See also Exercise 1.35 for a different approach to this problem.)

Figure E1.28



1.29 •• A spelunker is surveying a cave. She follows a passage 180 m straight west, then 210 m in a direction 45° east of south, and then 280 m at 30° east of north. After a fourth unmeasured displacement, she finds herself back where she started. Use a scale drawing to determine the magnitude and direction of the fourth displacement. (See also Problem 1.69 for a different approach to this problem.)

Section 1.8 Components of Vectors

1.30 •• Let the angle θ be the angle that the vector \vec{A} makes with the $+x$ -axis, measured counterclockwise from that axis. Find the angle θ for a vector that has the following components: (a) $A_x = 2.00$ m, $A_y = -1.00$ m; (b) $A_x = 2.00$ m, $A_y = 1.00$ m; (c) $A_x = -2.00$ m, $A_y = 1.00$ m; (d) $A_x = -2.00$ m, $A_y = -1.00$ m.

1.31 • Compute the x - and y -components of the vectors \vec{A} , \vec{B} , \vec{C} , and \vec{D} in Fig. E1.28.

1.32 • Vector \vec{A} is in the direction 34.0° clockwise from the $-y$ -axis. The x -component of \vec{A} is $A_x = -16.0$ m. (a) What is the y -component of \vec{A} ? (b) What is the magnitude of \vec{A} ?

1.33 • Vector \vec{A} has y -component $A_y = +13.0$ m. \vec{A} makes an angle of 32.0° counterclockwise from the $+y$ -axis. (a) What is the x -component of \vec{A} ? (b) What is the magnitude of \vec{A} ?

1.34 •• A postal employee drives a delivery truck over the route shown in Fig. E1.27. Use the method of components to determine the magnitude and direction of her resultant displacement. In a vector-addition diagram (roughly to scale), show that the resultant displacement found from your diagram is in qualitative agreement with the result you obtained using the method of components.

1.35 • For the vectors \vec{A} and \vec{B} in Fig. E1.28, use the method of components to find the magnitude and direction of (a) the vector sum $\vec{A} + \vec{B}$; (b) the vector sum $\vec{B} + \vec{A}$; (c) the vector difference $\vec{A} - \vec{B}$; (d) the vector difference $\vec{B} - \vec{A}$.

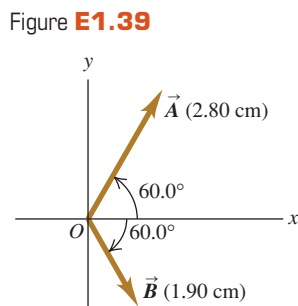
1.36 • Find the magnitude and direction of the vector represented by the following pairs of components: (a) $A_x = -8.60$ cm,

$A_y = 5.20$ cm; (b) $A_x = -9.70$ m, $A_y = -2.45$ m; (c) $A_x = 7.75$ km, $A_y = -2.70$ km.

1.37 • A disoriented physics professor drives 3.25 km north, then 2.90 km west, and then 1.50 km south. Find the magnitude and direction of the resultant displacement, using the method of components. In a vector-addition diagram (roughly to scale), show that the resultant displacement found from your diagram is in qualitative agreement with the result you obtained using the method of components.

1.38 • Two ropes in a vertical plane exert equal-magnitude forces on a hanging weight but pull with an angle of 86.0° between them. What pull does each one exert if their resultant pull is 372 N directly upward?

1.39 • Vector \vec{A} is 2.80 cm long and is 60.0° above the x -axis in the first quadrant. Vector \vec{B} is 1.90 cm long and is 60.0° below the x -axis in the fourth quadrant (Fig. E1.39). Use components to find the magnitude and direction of (a) $\vec{A} + \vec{B}$; (b) $\vec{A} - \vec{B}$; (c) $\vec{B} - \vec{A}$. In each case, sketch the vector addition or subtraction and show that your numerical answers are in qualitative agreement with your sketch.



Section 1.9 Unit Vectors

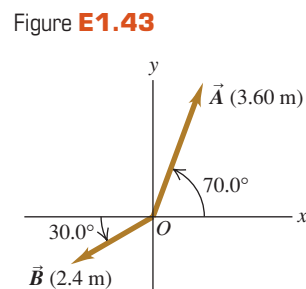
1.40 • In each case, find the x - and y -components of vector \vec{A} : (a) $\vec{A} = 5.0\hat{i} - 6.3\hat{j}$; (b) $\vec{A} = 11.2\hat{j} - 9.91\hat{i}$; (c) $\vec{A} = -15.0\hat{i} + 22.4\hat{j}$; (d) $\vec{A} = 5.0\vec{B}$, where $\vec{B} = 4\hat{i} - 6\hat{j}$.

1.41 • Write each vector in Fig. E1.28 in terms of the unit vectors \hat{i} and \hat{j} .

1.42 • Given two vectors $\vec{A} = 4.00\hat{i} + 7.00\hat{j}$ and $\vec{B} = 5.00\hat{i} - 2.00\hat{j}$, (a) find the magnitude of each vector; (b) write an expression for the vector difference $\vec{A} - \vec{B}$ using unit vectors; (c) find the magnitude and direction of the vector difference $\vec{A} - \vec{B}$. (d) In a vector diagram show \vec{A} , \vec{B} , and $\vec{A} - \vec{B}$, and also show that your diagram agrees qualitatively with your answer in part (c).

1.43 • (a) Write each vector in Fig. E1.43 in terms of the unit vectors \hat{i} and \hat{j} . (b) Use unit vectors to express the vector \vec{C} , where $\vec{C} = 3.00\vec{A} - 4.00\vec{B}$. (c) Find the magnitude and direction of \vec{C} .

1.44 • (a) Is the vector $(\hat{i} + \hat{j} + \hat{k})$ a unit vector? Justify your answer. (b) Can a unit vector have any components with magnitude greater than unity? Can it have any negative components? In each case justify your answer. (c) If $\vec{A} = a(3.0\hat{i} + 4.0\hat{j})$, where a is a constant, determine the value of a that makes \vec{A} a unit vector.



Section 1.10 Products of Vectors

1.45 • For the vectors \vec{A} , \vec{B} , and \vec{C} in Fig. E1.28, find the scalar products (a) $\vec{A} \cdot \vec{B}$; (b) $\vec{B} \cdot \vec{C}$; (c) $\vec{A} \cdot \vec{C}$.

1.46 • (a) Find the scalar product of the two vectors \vec{A} and \vec{B} given in Exercise 1.42. (b) Find the angle between these two vectors.

1.47 • Find the angle between each of the following pairs of vectors:

(a) $\vec{A} = -2.00\hat{i} + 6.00\hat{j}$ and $\vec{B} = 2.00\hat{i} - 3.00\hat{j}$

(b) $\vec{A} = 3.00\hat{i} + 5.00\hat{j}$ and $\vec{B} = 10.00\hat{i} + 6.00\hat{j}$

(c) $\vec{A} = -4.00\hat{i} + 2.00\hat{j}$ and $\vec{B} = 7.00\hat{i} + 14.00\hat{j}$

1.48 • Find the vector product $\vec{A} \times \vec{B}$ (expressed in unit vectors) of the two vectors given in Exercise 1.42. What is the magnitude of the vector product?

1.49 • For the vectors \vec{A} and \vec{D} in Fig. E1.28, (a) find the magnitude and direction of the vector product $\vec{A} \times \vec{D}$; (b) find the magnitude and direction of $\vec{D} \times \vec{A}$.

1.50 • For the two vectors in Fig. E1.39, (a) find the magnitude and direction of the vector product $\vec{A} \times \vec{B}$; (b) find the magnitude and direction of $\vec{B} \times \vec{A}$.

1.51 • For the two vectors \vec{A} and \vec{B} in Fig. E1.43, (a) find the scalar product $\vec{A} \cdot \vec{B}$; (b) find the magnitude and direction of the vector product $\vec{A} \times \vec{B}$.

1.52 • The vector \vec{A} is 3.50 cm long and is directed into this page. Vector \vec{B} points from the lower right corner of this page to the upper left corner of this page. Define an appropriate right-handed coordinate system, and find the three components of the vector product $\vec{A} \times \vec{B}$, measured in cm^2 . In a diagram, show your coordinate system and the vectors \vec{A} , \vec{B} , and $\vec{A} \times \vec{B}$.

1.53 • Given two vectors $\vec{A} = -2.00\hat{i} + 3.00\hat{j} + 4.00\hat{k}$ and $\vec{B} = 3.00\hat{i} + 1.00\hat{j} - 3.00\hat{k}$, do the following. (a) Find the magnitude of each vector. (b) Write an expression for the vector difference $\vec{A} - \vec{B}$ using unit vectors. (c) Find the magnitude of the vector difference $\vec{A} - \vec{B}$. Is this the same as the magnitude of $\vec{B} - \vec{A}$? Explain.

PROBLEMS

1.54 • An acre, a unit of land measurement still in wide use, has a length of one furlong ($\frac{1}{8}$ mi) and a width one-tenth of its length. (a) How many acres are in a square mile? (b) How many square feet are in an acre? See Appendix E. (c) An acre-foot is the volume of water that would cover 1 acre of flat land to a depth of 1 foot. How many gallons are in 1 acre-foot?

1.55 • **An Earthlike Planet.** In January 2006 astronomers reported the discovery of a planet comparable in size to the earth orbiting another star and having a mass about 5.5 times the earth's mass. It is believed to consist of a mixture of rock and ice, similar to Neptune. If this planet has the same density as Neptune (1.76 g/cm^3), what is its radius expressed (a) in kilometers and (b) as a multiple of earth's radius? Consult Appendix F for astronomical data.

1.56 • **The Hydrogen Maser.** You can use the radio waves generated by a hydrogen maser as a standard of frequency. The frequency of these waves is 1,420,405,751.786 hertz. (A hertz is another name for one cycle per second.) A clock controlled by a hydrogen maser is off by only 1 s in 100,000 years. For the following questions, use only three significant figures. (The large number of significant figures given for the frequency simply illustrates the remarkable accuracy to which it has been measured.) (a) What is the time for one cycle of the radio wave? (b) How many cycles occur in 1 h? (c) How many cycles would have occurred during the age of the earth, which is estimated to be 4.6×10^9 years? (d) By how many seconds would a hydrogen maser clock be off after a time interval equal to the age of the earth?

1.57 • **BIO Breathing Oxygen.** The density of air under standard laboratory conditions is 1.29 kg/m^3 , and about 20% of that air consists of oxygen. Typically, people breathe about $\frac{1}{2}$ L of air per breath. (a) How many grams of oxygen does a person breathe

in a day? (b) If this air is stored uncompressed in a cubical tank, how long is each side of the tank?

1.58 ••• A rectangular piece of aluminum is 7.60 ± 0.01 cm long and 1.90 ± 0.01 cm wide. (a) Find the area of the rectangle and the uncertainty in the area. (b) Verify that the fractional uncertainty in the area is equal to the sum of the fractional uncertainties in the length and in the width. (This is a general result; see Challenge Problem 1.98.)

1.59 ••• As you eat your way through a bag of chocolate chip cookies, you observe that each cookie is a circular disk with a diameter of 8.50 ± 0.02 cm and a thickness of 0.050 ± 0.005 cm. (a) Find the average volume of a cookie and the uncertainty in the volume. (b) Find the ratio of the diameter to the thickness and the uncertainty in this ratio.

1.60 • BIO Biological tissues are typically made up of 98% water. Given that the density of water is 1.0×10^3 kg/m³, estimate the mass of (a) the heart of an adult human; (b) a cell with a diameter of $0.5 \mu\text{m}$; (c) a honey bee.

1.61 • BIO Estimate the number of atoms in your body. (*Hint:* Based on what you know about biology and chemistry, what are the most common types of atom in your body? What is the mass of each type of atom? Appendix D gives the atomic masses for different elements, measured in atomic mass units; you can find the value of an atomic mass unit, or 1 u, in Appendix E.)

1.62 ••• How many dollar bills would you have to stack to reach the moon? Would that be cheaper than building and launching a spacecraft? (*Hint:* Start by folding a dollar bill to see how many thicknesses make 1.0 mm.)

1.63 ••• How much would it cost to paper the entire United States (including Alaska and Hawaii) with dollar bills? What would be the cost to each person in the United States?

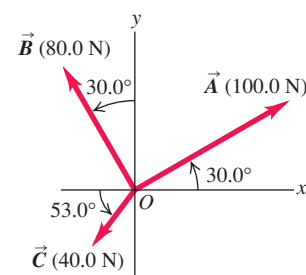
1.64 • Stars in the Universe. Astronomers frequently say that there are more stars in the universe than there are grains of sand on all the beaches on the earth. (a) Given that a typical grain of sand is about 0.2 mm in diameter, estimate the number of grains of sand on all the earth's beaches, and hence the approximate number of stars in the universe. It would be helpful to consult an atlas and do some measuring. (b) Given that a typical galaxy contains about 100 billion stars and there are more than 100 billion galaxies in the known universe, estimate the number of stars in the universe and compare this number with your result from part (a).

1.65 ••• Two workers pull horizontally on a heavy box, but one pulls twice as hard as the other. The larger pull is directed at 25.0° west of north, and the resultant of these two pulls is 460.0 N directly northward. Use vector components to find the magnitude of each of these pulls and the direction of the smaller pull.

1.66 •• Three horizontal ropes pull on a large stone stuck in the ground, producing the vector forces \vec{A} , \vec{B} , and \vec{C} shown in Fig. P1.66. Find the magnitude and direction of a fourth force on the stone that will make the vector sum of the four forces zero.

1.67 •• You are to program a robotic arm on an assembly line to move in the xy -plane. Its first displacement is \vec{A} ; its second displacement is \vec{B} , of magnitude 6.40 cm and direction 63.0° measured in the sense from the $+x$ -axis toward the $-y$ -axis. The resultant $\vec{C} = \vec{A} + \vec{B}$ of the two displacements should also have a magnitude of 6.40 cm, but a direction 22.0° measured in the sense

Figure P1.66



from the $+x$ -axis toward the $+y$ -axis. (a) Draw the vector-addition diagram for these vectors, roughly to scale. (b) Find the components of \vec{A} . (c) Find the magnitude and direction of \vec{A} .

1.68 ••• Emergency Landing. A plane leaves the airport in Galisteo and flies 170 km at 68° east of north and then changes direction to fly 230 km at 48° south of east, after which it makes an immediate emergency landing in a pasture. When the airport sends out a rescue crew, in which direction and how far should this crew fly to go directly to this plane?

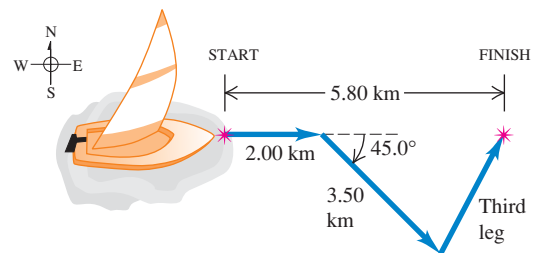
1.69 ••• As noted in Exercise 1.29, a spelunker is surveying a cave. She follows a passage 180 m straight west, then 210 m in a direction 45° east of south, and then 280 m at 30° east of north. After a fourth unmeasured displacement she finds herself back where she started. Use the method of components to determine the magnitude and direction of the fourth displacement. Draw the vector-addition diagram and show that it is in qualitative agreement with your numerical solution.

1.70 •• (a) Find the magnitude and direction of the vector \vec{R} that is the sum of the three vectors \vec{A} , \vec{B} , and \vec{C} in Fig. E1.28. In a diagram, show how \vec{R} is formed from these three vectors. (b) Find the magnitude and direction of the vector $\vec{S} = \vec{C} - \vec{A} - \vec{B}$. In a diagram, show how \vec{S} is formed from these three vectors.

1.71 •• A rocket fires two engines simultaneously. One produces a thrust of 480 N directly forward, while the other gives a 513-N thrust at 32.4° above the forward direction. Find the magnitude and direction (relative to the forward direction) of the resultant force that these engines exert on the rocket.

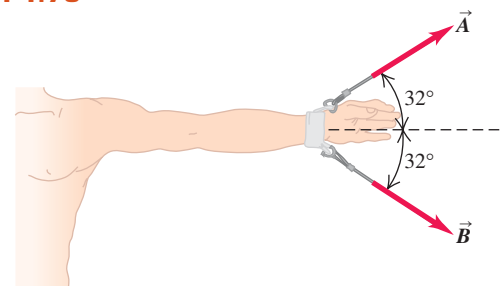
1.72 •• A sailor in a small sailboat encounters shifting winds. She sails 2.00 km east, then 3.50 km southeast, and then an additional distance in an unknown direction. Her final position is 5.80 km directly east of the starting point (Fig. P1.72). Find the magnitude and direction of the third leg of the journey. Draw the vector-addition diagram and show that it is in qualitative agreement with your numerical solution.

Figure P1.72



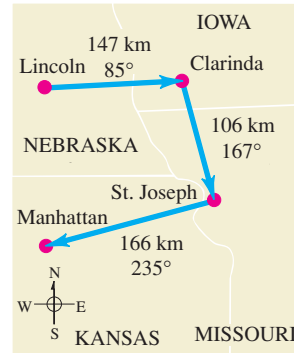
1.73 ••• BIO Dislocated Shoulder. A patient with a dislocated shoulder is put into a traction apparatus as shown in Fig. P1.73. The pulls \vec{A} and \vec{B} have equal magnitudes and must combine to produce an outward traction force of 5.60 N on the patient's arm. How large should these pulls be?

Figure P1.73



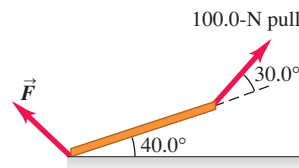
1.74 ••• On a training flight, a student pilot flies from Lincoln, Nebraska, to Clarinda, Iowa, then to St. Joseph, Missouri, and then to Manhattan, Kansas (Fig. P1.74). The directions are shown relative to north: 0° is north, 90° is east, 180° is south, and 270° is west. Use the method of components to find (a) the distance she has to fly from Manhattan to get back to Lincoln, and (b) the direction (relative to north) she must fly to get there. Illustrate your solutions with a vector diagram.

Figure P1.74



1.75 •• Equilibrium. We say an object is in *equilibrium* if all the forces on it balance (add up to zero). Figure P1.75 shows a beam weighing 124 N that is supported in equilibrium by a 100.0-N pull and a force \vec{F} at the floor. The third force on the beam is the 124-N weight that acts vertically downward. (a) Use vector components to find the magnitude and direction of \vec{F} . (b) Check the reasonableness of your answer in part (a) by doing a graphical solution approximately to scale.

Figure P1.75



1.76 ••• Getting Back. An explorer in the dense jungles of equatorial Africa leaves his hut. He takes 40 steps northeast, then 80 steps 60° north of west, then 50 steps due south. Assume his steps all have equal length. (a) Sketch, roughly to scale, the three vectors and their resultant. (b) Save the explorer from becoming hopelessly lost in the jungle by giving him the displacement, calculated using the method of components, that will return him to his hut.

1.77 ••• A graphic artist is creating a new logo for her company's website. In the graphics program she is using, each pixel in an image file has coordinates (x, y) , where the origin $(0, 0)$ is at the upper left corner of the image, the $+x$ -axis points to the right, and the $+y$ -axis points down. Distances are measured in pixels. (a) The artist draws a line from the pixel location $(10, 20)$ to the location $(210, 200)$. She wishes to draw a second line that starts at $(10, 20)$, is 250 pixels long, and is at an angle of 30° measured clockwise from the first line. At which pixel location should this second line end? Give your answer to the nearest pixel. (b) The artist now draws an arrow that connects the lower right end of the first line to the lower right end of the second line. Find the length and direction of this arrow. Draw a diagram showing all three lines.

1.78 ••• A ship leaves the island of Guam and sails 285 km at 40.0° north of west. In which direction must it now head and how far must it sail so that its resultant displacement will be 115 km directly east of Guam?

1.79 •• BIO Bones and Muscles. A patient in therapy has a forearm that weighs 20.5 N and that lifts a 112.0-N weight. These two forces have direction vertically downward. The only other significant forces on his forearm come from the biceps muscle (which acts perpendicularly to the forearm) and the force at the elbow. If the biceps produces a pull of 232 N when the forearm is raised 43° above the horizontal, find the magnitude and direction of the force that the elbow exerts on the forearm. (The sum of the elbow force and the biceps force must balance the weight of the

arm and the weight it is carrying, so their vector sum must be 132.5 N, upward.)

1.80 ••• You are hungry and decide to go to your favorite neighborhood fast-food restaurant. You leave your apartment and take the elevator 10 flights down (each flight is 3.0 m) and then go 15 m south to the apartment exit. You then proceed 0.2 km east, turn north, and go 0.1 km to the entrance of the restaurant. (a) Determine the displacement from your apartment to the restaurant. Use unit vector notation for your answer, being sure to make clear your choice of coordinates. (b) How far did you travel along the path you took from your apartment to the restaurant, and what is the magnitude of the displacement you calculated in part (a)?

1.81 •• While following a treasure map, you start at an old oak tree. You first walk 825 m directly south, then turn and walk 1.25 km at 30.0° west of north, and finally walk 1.00 km at 40.0° north of east, where you find the treasure: a biography of Isaac Newton! (a) To return to the old oak tree, in what direction should you head and how far will you walk? Use components to solve this problem. (b) To see whether your calculation in part (a) is reasonable, check it with a graphical solution drawn roughly to scale.

1.82 •• A fence post is 52.0 m from where you are standing, in a direction 37.0° north of east. A second fence post is due south from you. What is the distance of the second post from you, if the distance between the two posts is 80.0 m?

1.83 •• A dog in an open field runs 12.0 m east and then 28.0 m in a direction 50.0° west of north. In what direction and how far must the dog then run to end up 10.0 m south of her original starting point?

1.84 ••• Ricardo and Jane are standing under a tree in the middle of a pasture. An argument ensues, and they walk away in different directions. Ricardo walks 26.0 m in a direction 60.0° west of north. Jane walks 16.0 m in a direction 30.0° south of west. They then stop and turn to face each other. (a) What is the distance between them? (b) In what direction should Ricardo walk to go directly toward Jane?

1.85 ••• John, Paul, and George are standing in a strawberry field. Paul is 14.0 m due west of John. George is 36.0 m from Paul, in a direction 37.0° south of east from Paul's location. How far is George from John? What is the direction of George's location from that of John?

1.86 ••• You are camping with two friends, Joe and Karl. Since all three of you like your privacy, you don't pitch your tents close together. Joe's tent is 21.0 m from yours, in the direction 23.0° south of east. Karl's tent is 32.0 m from yours, in the direction 37.0° north of east. What is the distance between Karl's tent and Joe's tent?

1.87 •• Vectors \vec{A} and \vec{B} have scalar product -6.00 and their vector product has magnitude $+9.00$. What is the angle between these two vectors?

1.88 •• Bond Angle in Methane. In the methane molecule, CH_4 , each hydrogen atom is at a corner of a regular tetrahedron with the carbon atom at the center. In coordinates where one of the C-H bonds is in the direction of $\hat{i} + \hat{j} + \hat{k}$, an adjacent C-H bond is in the $\hat{i} - \hat{j} - \hat{k}$ direction. Calculate the angle between these two bonds.

1.89 •• Vector \vec{A} has magnitude 12.0 m and vector \vec{B} has magnitude 16.0 m. The scalar product $\vec{A} \cdot \vec{B}$ is 90.0 m^2 . What is the magnitude of the vector product between these two vectors?

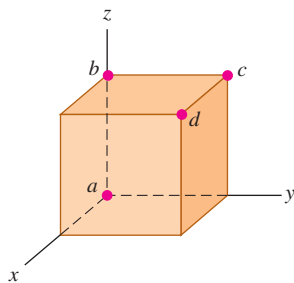
1.90 •• When two vectors \vec{A} and \vec{B} are drawn from a common point, the angle between them is ϕ . (a) Using vector techniques, show that the magnitude of their vector sum is given by

$$\sqrt{A^2 + B^2 + 2AB \cos \phi}$$

(b) If \vec{A} and \vec{B} have the same magnitude, for which value of ϕ will their vector sum have the same magnitude as \vec{A} or \vec{B} ?

1.91 •• A cube is placed so that one corner is at the origin and three edges are along the x -, y -, and z -axes of a coordinate system (Fig. P1.91). Use vectors to compute (a) the angle between the edge along the z -axis (line ab) and the diagonal from the origin to the opposite corner (line ad), and (b) the angle between line ac (the diagonal of a face) and line ad .

Figure P1.91



1.92 •• Vector \vec{A} has magnitude 6.00 m and vector \vec{B} has magnitude 3.00 m. The vector product between these two vectors has magnitude 12.0 m^2 . What are the two possible values for the scalar product of these two vectors? For each value of $\vec{A} \cdot \vec{B}$, draw a sketch that shows \vec{A} and \vec{B} and explain why the vector products in the two sketches are the same but the scalar products differ.

1.93 •• The scalar product of vectors \vec{A} and \vec{B} is $+48.0 \text{ m}^2$. Vector \vec{A} has magnitude 9.00 m and direction 28.0° west of south. If vector \vec{B} has direction 39.0° south of east, what is the magnitude of \vec{B} ?

1.94 ••• Obtain a *unit vector* perpendicular to the two vectors given in Exercise 1.53.

1.95 •• You are given vectors $\vec{A} = 5.0\hat{i} - 6.5\hat{j}$ and $\vec{B} = -3.5\hat{i} + 7.0\hat{j}$. A third vector \vec{C} lies in the xy -plane. Vector \vec{C} is perpendicular to vector \vec{A} , and the scalar product of \vec{C} with \vec{B} is 15.0. From this information, find the components of vector \vec{C} .

1.96 •• Two vectors \vec{A} and \vec{B} have magnitudes $A = 3.00$ and $B = 3.00$. Their vector product is $\vec{A} \times \vec{B} = -5.00\hat{k} + 2.00\hat{i}$. What is the angle between \vec{A} and \vec{B} ?

1.97 •• Later in our study of physics we will encounter quantities represented by $(\vec{A} \times \vec{B}) \cdot \vec{C}$. (a) Prove that for any three vectors \vec{A} , \vec{B} , and \vec{C} , $\vec{A} \cdot (\vec{B} \times \vec{C}) = (\vec{A} \times \vec{B}) \cdot \vec{C}$. (b) Calculate $(\vec{A} \times \vec{B}) \cdot \vec{C}$ for the three vectors \vec{A} with magnitude $A = 5.00$ and angle $\theta_A = 26.0^\circ$ measured in the sense from the $+x$ -axis toward the $+y$ -axis, \vec{B} with $B = 4.00$ and $\theta_B = 63.0^\circ$, and \vec{C} with magnitude 6.00 and in the $+z$ -direction. Vectors \vec{A} and \vec{B} are in the xy -plane.

CHALLENGE PROBLEMS

1.98 ••• The length of a rectangle is given as $L \pm l$ and its width as $W \pm w$. (a) Show that the uncertainty in its area A is $a = Lw + lW$. Assume that the uncertainties l and w are small, so that the product lw is very small and you can ignore it. (b) Show that the fractional uncertainty in the area is equal to the sum of the fractional uncertainty in length and the fractional uncertainty in width. (c) A rectangular solid has dimensions $L \pm l$, $W \pm w$, and $H \pm h$. Find the fractional uncertainty in the volume, and show that it equals the sum of the fractional uncertainties in the length, width, and height.

1.99 ••• **Completed Pass.** At Enormous State University (ESU), the football team records its plays using vector displacements, with the origin taken to be the position of the ball before the play starts. In a certain pass play, the receiver starts at $+1.0\hat{i} - 5.0\hat{j}$, where the units are yards, \hat{i} is to the right, and

\hat{j} is downfield. Subsequent displacements of the receiver are $+9.0\hat{i}$ (in motion before the snap), $+11.0\hat{j}$ (breaks downfield), $-6.0\hat{i} + 4.0\hat{j}$ (zigs), and $+12.0\hat{i} + 18.0\hat{j}$ (zags). Meanwhile, the quarterback has dropped straight back to a position $-7.0\hat{j}$. How far and in which direction must the quarterback throw the ball? (Like the coach, you will be well advised to diagram the situation before solving it numerically.)

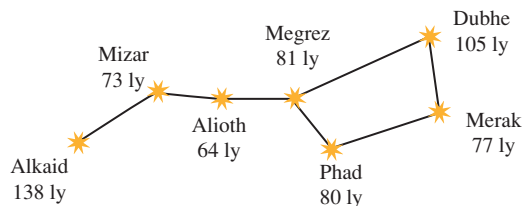
1.100 ••• **Navigating in the Solar System.** The *Mars Polar Lander* spacecraft was launched on January 3, 1999. On December 3, 1999, the day *Mars Polar Lander* touched down on the Martian surface, the positions of the earth and Mars were given by these coordinates:

	x	y	z
Earth	0.3182 AU	0.9329 AU	0.0000 AU
Mars	1.3087 AU	-0.4423 AU	-0.0414 AU

In these coordinates, the sun is at the origin and the plane of the earth's orbit is the xy -plane. The earth passes through the $+x$ -axis once a year on the autumnal equinox, the first day of autumn in the northern hemisphere (on or about September 22). One AU, or *astronomical unit*, is equal to $1.496 \times 10^8 \text{ km}$, the average distance from the earth to the sun. (a) In a diagram, show the positions of the sun, the earth, and Mars on December 3, 1999. (b) Find the following distances in AU on December 3, 1999: (i) from the sun to the earth; (ii) from the sun to Mars; (iii) from the earth to Mars. (c) As seen from the earth, what was the angle between the direction to the sun and the direction to Mars on December 3, 1999? (d) Explain whether Mars was visible from your location at midnight on December 3, 1999. (When it is midnight at your location, the sun is on the opposite side of the earth from you.)

1.101 ••• **Navigating in the Big Dipper.** All the stars of the Big Dipper (part of the constellation Ursa Major) may appear to be the same distance from the earth, but in fact they are very far from each other. Figure P1.101 shows the distances from the earth to each of these stars. The distances are given in light-years (ly), the distance that light travels in one year. One light-year equals $9.461 \times 10^{15} \text{ m}$. (a) Alkaid and Merak are 25.6° apart in the earth's sky. In a diagram, show the relative positions of Alkaid, Merak, and our sun. Find the distance in light-years from Alkaid to Merak. (b) To an inhabitant of a planet orbiting Merak, how many degrees apart in the sky would Alkaid and our sun be?

Figure P1.101



1.102 ••• The vector $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$, called the *position vector*, points from the origin $(0, 0, 0)$ to an arbitrary point in space with coordinates (x, y, z) . Use what you know about vectors to prove the following: All points (x, y, z) that satisfy the equation $Ax + By + Cz = 0$, where A , B , and C are constants, lie in a plane that passes through the origin and that is perpendicular to the vector $A\hat{i} + B\hat{j} + C\hat{k}$. Sketch this vector and the plane.

Answers

Chapter Opening Question ?

Take the $+x$ -axis to point east and the $+y$ -axis to point north. Then what we are trying to find is the y -component of the velocity vector, which has magnitude $v = 20$ km/h and is at an angle $\theta = 53^\circ$ measured from the $+x$ -axis toward the $+y$ -axis. From Eqs. (1.6) we have $v_y = v \sin \theta = (20 \text{ km/h}) \sin 53^\circ = 16$ km/h. So the thunderstorm moves 16 km north in 1 h.

Test Your Understanding Questions

1.5 Answer: (ii) Density = $(1.80 \text{ kg}) / (6.0 \times 10^{-4} \text{ m}^3) = 3.0 \times 10^3 \text{ kg/m}^3$. When we multiply or divide, the number with the fewest significant figures controls the number of significant figures in the result.

1.6 The answer depends on how many students are enrolled at your campus.

1.7 Answers: (ii), (iii), and (iv) The vector $-\vec{T}$ has the same magnitude as the vector \vec{T} , so $\vec{S} - \vec{T} = \vec{S} + (-\vec{T})$ is the *sum* of one vector of magnitude 3 m and one of magnitude 4 m. This sum has magnitude 7 m if \vec{S} and $-\vec{T}$ are parallel and magnitude 1 m if \vec{S} and $-\vec{T}$ are antiparallel. The magnitude of $\vec{S} - \vec{T}$ is 5 m if \vec{S} and $-\vec{T}$ are perpendicular, so that the vectors \vec{S} , \vec{T} , and $\vec{S} - \vec{T}$ form a 3–4–5 right triangle. Answer (i) is impossible because the magnitude of the sum of two vectors cannot be greater than the sum of the magnitudes; answer (v) is impossible because the sum of two vectors can be zero only if the two vectors are antiparallel and have the same magnitude; and answer (vi) is impossible because the magnitude of a vector cannot be negative.

1.8 Answers: (a) yes, (b) no Vectors \vec{A} and \vec{B} can have the same magnitude but different components if they point in different directions. If they have the same components, however, they are the same vector ($\vec{A} = \vec{B}$) and so must have the same magnitude.

1.9 Answer: all have the same magnitude The four vectors \vec{A} , \vec{B} , \vec{C} , and \vec{D} all point in different directions, but all have the same magnitude:

$$\begin{aligned} A = B = C = D &= \sqrt{(\pm 3 \text{ m})^2 + (\pm 5 \text{ m})^2 + (\pm 2 \text{ m})^2} \\ &= \sqrt{9 \text{ m}^2 + 25 \text{ m}^2 + 4 \text{ m}^2} = \sqrt{38 \text{ m}^2} = 6.2 \text{ m} \end{aligned}$$

1.10 Answers: (a) $\phi = 90^\circ$, (b) $\phi = 0^\circ$ or $\phi = 180^\circ$, (c) $\phi = 0^\circ$, (d) $\phi = 180^\circ$, (e) $\phi = 90^\circ$ (a) The scalar product is zero only if \vec{A} and \vec{B} are perpendicular. (b) The vector product is zero only if \vec{A} and \vec{B} are either parallel or antiparallel. (c) The scalar product is equal to the product of the magnitudes ($\vec{A} \cdot \vec{B} = AB$) only if \vec{A} and \vec{B} are parallel. (d) The scalar product is equal to the negative of the product of the magnitudes ($\vec{A} \cdot \vec{B} = -AB$) only if \vec{A} and \vec{B} are antiparallel. (e) The magnitude of the vector product is equal to the product of the magnitudes [(magnitude of $\vec{A} \times \vec{B}$) = AB] only if \vec{A} and \vec{B} are perpendicular.

Bridging Problem

**Answers: (a) $5.2 \times 10^2 \text{ N}$
(b) $4.5 \times 10^2 \text{ N} \cdot \text{m}$**