Appendix A: Units of Measurement

The units of measurement primarily used in this book are those used by scientists throughout the world—the International System of Units, or SI (after the French name, Système International). SI units are the outgrowth of the metric system of units. While familiar to scientists, many SI units are not generally familiar to students in high school. The SI units used in this book are the following.

Meter

The meter (m) is the SI unit of length. The standard of length for the metric system originally was defined in terms of the distance from the North Pole to the equator. This distance is close to (or was thought to be at the time) 10 million meters. So one meter equals one ten-millionth of the distance from the North Pole to the equator. A more exact definition is that one meter equals the length of the path traveled by light in a vacuum during a time interval of 1/299 792 458 of a second.

Common SI length units based on the meter are the *centimeter*, *millimeter*, and *kilometer*.

1 centimeter (cm) = 1/100 meter

1 millimeter (mm) = 1/1000 meter

1 kilometer (km) = 1000 meters

Kilogram

The kilogram (kg), the SI unit of mass, is defined as the mass of a block of platinum preserved at the International Bureau of Weights and Measures in France. The kilogram originally was defined as the mass of one liter (1000 cubic centimeters) of water at the temperature at which it is most dense (now known to be 4° Celsius). (The mass of a one-pound object is equal to 0.4536 kilogram.)

Other common mass units are the *gram* and *milligram*.

1 gram (g) = 1/1000 kilogram

1 milligram (mg) = 1/1000 gram
1/1 000 000 kilogram

Second

The second (s) is the SI unit of time. Until 1956 the second was defined in terms of the mean solar day, which was divided into 24 hours. Each hour was divided into 60 minutes and each minute into 60 seconds. Thus there were 86 400 seconds per day, and the second was defined as 1/86 400 of the mean solar day. This was found to be unsatisfactory because the rate of rotation of the earth is gradually becoming slower. In 1956 the mean solar day of the year 1900 was chosen as the standard on which to base the second. Since 1964, the second has been officially defined as the time taken by a cesium-133 atom to make 9 192 631 770 vibrations.

Newton

The newton (N), the SI unit of force, is named after Sir Isaac Newton. One newton is the force required to give an object with a mass of one kilogram an acceleration of one meter per second squared. (One newton is approximately equal to 0.2 pound.)

Joule

The joule (J), the SI unit of energy, is named after James Joule. One joule is equal to the amount of work done by a force of one newton acting over a distance of one meter. For heat energy, the joule replaces the calorie. (One calorie is equal to 4.187 joules.)

The unit for power is derived from the unit for energy. Power is the rate at which energy is expended. Work done at the rate of one joule per second is equal to a power of one *watt* (W). The *kilowatt* (kW) equals 1000 watts. From the definition of power, it follows that energy can be expressed as the product of power and time. Electric energy is often expressed in units of *kilowatt-hours* (kWh), where

1 kilowatt-hour = 3.60×10^6 joules

Ampere

The ampere (A), the SI unit of electric current, is named after André Marie Ampère. In this text the ampere is defined as the rate of flow of one coulomb of charge per second, where one coulomb is the charge of 6.25×10^{18} electrons. The official definition of the ampere is the intensity of constant electric current maintained in two parallel conductors of infinite length and negligible cross section that when placed one meter apart in a vacuum would produce between them a force of 2×10^{-7} newton per meter of length.

Kelvin

The kelvin (K), the SI unit of temperature, is named after the scientist Lord Kelvin. The kelvin is defined as $1/273.16$ of the temperature change between absolute zero (the coldest possible temperature) and the triple point of water (the fixed temperature at which ice, liquid water, and water vapor coexist in equilibrium). Temperatures are expressed in kelvins, and not in "degrees kelvin." On the Kelvin scale, absolute zero is 0 K. The temperature of melting ice at atmospheric pressure is 273.15 K, the triple point of water is 273.16 K, and the temperature of pure boiling water at atmospheric pressure is 373.15 K. There are 100 kelvins between the melting and boiling points of water, just as there are 100 Celsius degrees between these points. Kelvins and Celsius degrees have the same spacings on the temperature scale.

Measurements of Area and Volume

Area Area refers to the amount of surface. The unit of area is the surface of a square that has a standard unit of length as a side. In the SI system it is a square with sides one meter in length, which makes a unit of area of one square meter ($1\ m^2$). A smaller unit area is represented by a square with sides one centimeter in length, which makes a unit of area of one square centimeter ($1\ cm^2$).

The area of a rectangle equals the base times the height. The area of a circle is equal to πr^2, where $\pi = 3.14$ and r is the radius of the circle. Formulas for the surfaces of other shapes can be found in geometry textbooks.

Volume The volume of an object refers to the space it occupies. The unit volume is the space taken up by a cube that has a standard unit of length for its edge. In the SI system, it is the space occupied by a cube whose sides are one meter. This volume is one cubic meter ($1\ m^3$) and is a relatively large volume by everyday standards. A smaller unit volume is the space occupied by a cube whose sides are one centimeter. Its volume is one cubic centimeter ($1\ cm^3$), the space taken up by one gram of water at 4°C.

A liter (L) is equal to $1000\ cm^3$, and is a common measure of volume for liquids.

Appendix B: Working with Units in Physics

A quantity in science is expressed by a number and a unit of measurement. Quantities may be actual measurements, or they may be obtained by performing calculations on measurements. Quantities may be added, subtracted, multiplied, or divided. There are rules for handling both the numbers and the units of measurement during these mathematical operations.

Addition

When you add quantities, all must have the *same* units. Add up the numbers. The sum has the same unit as well.

Example:
(4 m) + (8 m) + (3 m) = 15 m

Subtraction

When you subtract one quantity from another, both must have the *same* units. Subtract the numbers. The difference has the same unit.

Example:
(5.2 s) − (3.8 s) = 1.4 s

Multiplication

Quantities that are multiplied together need *not* have the same units. Multiply the numbers. Multiply the units just as if they are algebraic variables.

When full names of units are used, use a hyphen between the units that are multiplied together.

Example:
(3 newtons) × (2 meters) = 6 newton-meters

When symbols are used, use a raised dot between the unit symbols that are multiplied together.

Example:
(3 N) × (2 m) = 6 N·m

When the units being multiplied are the same, the product is called the square (or cubic) unit. In symbols, a raised 2 after the unit symbol is used for the square. A raised 3 after the unit symbol is used for the cubic unit. These raised numerals are known as *exponents*.

Examples:
(3 meters) × (2 meters) = 6 meter-meters
= 6 square meters

$(3\text{ m}) \times (2\text{ m}) = 6\text{ m}\cdot\text{m} = 6\text{ m}^2$

(3 meters) × (2 meters) × (4 meters)
= 24 meter-meter-meters
= 24 cubic meters

$(3\text{ m}) \times (2\text{ m}) \times (4\text{ m}) = 24\text{ m}\cdot\text{m}\cdot\text{m} = 24\text{ m}^3$

Division

Quantities that are divided by each other need *not* have the same units. Divide the numbers. Divide the units as though they are algebraic variables.

When the units are full names, use the word *per* after the unit that is being divided.

Example:
(100 kilometers) ÷ (2 hours)

$$= \frac{100\text{ kilometers}}{2\text{ hours}}$$

= 50 kilometers per hour

When the units are symbols, use a slash after the unit symbol that is being divided.

Example:

$$(100\text{ km}) \div (2\text{ h}) = \frac{100\text{ km}}{2\text{ h}}$$

= 50 km/h

When both units are the same, they "cancel" out and do not appear in the quotient.

Example:

$$(6\text{ m}) \div (3\text{ m}) = \frac{6\text{ }\cancel{\text{m}}}{3\text{ }\cancel{\text{m}}}$$

= 2

Complicated Multiplication and Division

In multiplication, when the quantities have units which are quotients of units, treat them as algebraic variables. Identical units in the numerator and denominator may be "canceled" out.

Example:
(25 meters per second) × (6 seconds)

$$= \left(25\ \frac{\text{meters}}{\text{second}}\right) \times (6\ \text{seconds})$$

$$= 25 \times 6\ \frac{\text{meters-}\cancel{\text{seconds}}}{\cancel{\text{second}}}$$

$$= 150\ \text{meters}$$

$$(25\ \text{m/s}) \times (6\ \text{s}) = \left(25\ \frac{\text{m}}{\text{s}}\right) \times (6\ \text{s})$$

$$= 25 \times 6\ \frac{\text{m}\cdot\cancel{\text{s}}}{\cancel{\text{s}}}$$

$$= 150\ \text{m}$$

In division, when the quantities have units which are quotients of units, it is easiest to express the division in numerator and denominator form. That is, the number to be divided is the numerator (top value) and the divisor is the denominator (bottom value). Divide the numbers. Treat units as algebraic variables.

Examples:
(8.2 meters per second) ÷ (2.0 seconds)

$$= \frac{8.2\ \text{meters per second}}{2.0\ \text{seconds}}$$

$$= \frac{8.2}{2.0}\ \frac{\text{meters}}{\text{second-second}}$$

$$= 4.1\ \text{meters per second squared}$$

$$(8.2\ \text{m/s}) \div (2.0\ \text{s}) = \frac{8.2\ \text{m/s}}{2.0\ \text{s}}$$

$$= \frac{8.2}{2.0}\ \frac{\text{m}}{\text{s}\cdot\text{s}}$$

$$= 4.1\ \text{m/s}^2$$

Note that when *second* is multiplied by itself in the denominator, it is changed to *per second squared* (and not to *per square second*). Similarly, the symbols "m/s^2" are read as "meters per second squared."

Scientific Notation

It is convenient to use a mathematical abbreviation for large and small numbers. The number 40 000 000 can be obtained by multiplying 4 by 10, and again by 10, and again by 10, and so on until 10 has been used as a multiplier seven times. The short way of showing this is to write the number 40 000 000 as 4×10^7.

The number 0.0004 can be obtained from 4 by using 10 as a divisor four times. The short way of showing this is to write the number 0.0004 as 4×10^{-4}. Thus,

$$2 \times 10^5 = 2 \times 10 \times 10 \times 10 \times 10 \times 10 = 200\,000$$
$$5 \times 10^{-3} = 5/(10 \times 10 \times 10) = 0.005$$

Numbers expressed in this shorthand manner are said to be in *scientific notation*.

1 000 000 =	10 × 10 × 10 × 10 × 10 × 10	$= 10^6$
100 000 =	10 × 10 × 10 × 10 × 10	$= 10^5$
10 000 =	10 × 10 × 10 × 10	$= 10^4$
1 000 =	10 × 10 × 10	$= 10^3$
100 =	10 × 10	$= 10^2$
10 =	10	$= 10^1$
1 =	1	$= 10^0$
0.1 =	1/10	$= 10^{-1}$
0.01 =	1/100	$= 10^{-2}$
0.001 =	1/1 000	$= 10^{-3}$
0.0001 =	1/10 000	$= 10^{-4}$
0.00001 =	1/100 000	$= 10^{-5}$
0.000001 =	1/1 000 000	$= 10^{-6}$

We can use scientific notation to express some of the physical data often used in physics.

Table B-1 Some Important Values in Physics

Speed of light in a vacuum	$= 2.9979 \times 10^{8}$ m/s
Average earth-sun distance (1 astronomical unit (A.U.))	$= 1.50 \times 10^{11}$ m
Average earth-moon distance	$= 3.84 \times 10^{8}$ m
Average radius of the sun	$= 6.96 \times 10^{8}$ m
Average radius of Jupiter	$= 7.14 \times 10^{7}$ m
Average radius of the earth	$= 6.37 \times 10^{6}$ m
Average radius of the moon	$= 1.74 \times 10^{6}$ m
Average radius of the hydrogen atom	$= 5 \times 10^{-11}$ m
Mass of the sun	$= 1.99 \times 10^{30}$ kg
Mass of Jupiter	$= 1.90 \times 10^{27}$ kg
Mass of the earth	$= 5.98 \times 10^{24}$ kg
Mass of the moon	$= 7.36 \times 10^{22}$ kg
Proton mass	$= 1.6726 \times 10^{-27}$ kg
Neutron mass	$= 1.6749 \times 10^{-27}$ kg
Electron mass	$= 9.1 \times 10^{-31}$ kg
Electron charge	$= 1.602 \times 10^{-19}$ C

Appendix C: Vector Applications

Appendix C is a continuation of the material in Chapter 6, "Vectors," and Chapter 27, "Light." One of the most fascinating illustrations of the vector approach to looking at things is the sailboat—how it sails in directions other than with the wind, and even into the wind. Understanding the role of vectors in sailing is a bit more complicated than in other examples treated in Chapter 6, so it is set aside here for more careful study.

Another striking illustration of vectors involves the vector nature of light and its behavior in passing through polarization filters. The vector treatment of light here is a continuation of Chapter 27. Vector explanations for both the sailboat and the transmission of light through polarizing filters involve a blend of geometry and physics.

The Sailboat

Sailors have always known that a sailboat can sail downwind (in the same direction as the wind). The ships of Columbus were designed to sail only downwind. Not until modern times did sailors learn that a sailboat can sail upwind (against the wind). It turns out that many types of sailboats can sail faster "cutting" upwind than when sailing directly with the wind. The oldtimers didn't know this, probably because they didn't understand vectors and vector components. Luckily, we do, and today's sailboats are far more maneuverable than the sailboats of the past.

To understand all this, first consider the relatively simple case of sailing downwind. Figure C-1 shows a force vector *F* due to the impact of the wind against the sail. This force tends to increase the speed of the boat. If it were not for resistive forces, mainly water drag, the speed of the boat would build up to nearly the speed of the wind. (It could be pushed no faster than wind speed because the wind would no longer make impact with the sails. They would sag and the force *F* would shrink to zero.) It is important to note that the faster the boat goes, the smaller will be the magnitude of *F*. So we see that a sailboat sailing directly with the wind can sail no faster than the wind.

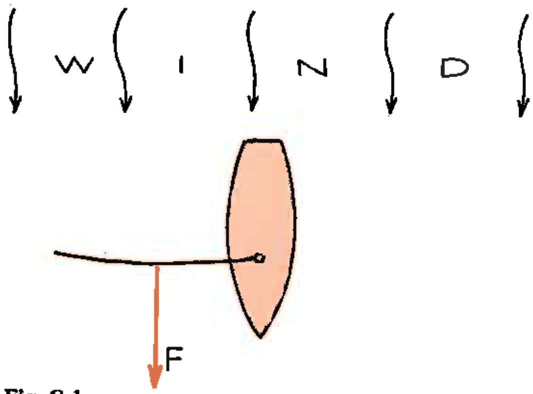

Fig. C-1

If the sail is oriented as shown in Figure C-2 left, the boat will move forward but with less increase in speed for two reasons. First, the force *F* on the sail is less because the sail does not intercept as much wind at this angle. Second, the force on the sail is not in the direction of the boat's motion. It is instead perpendicular to the sail's surface. Generally speaking, whenever any fluid (liquid or gas) interacts with a smooth surface, the force of interaction is perpendicular to the smooth surface. In this case the boat will not move in the direction of *F* because of its deep finlike keel, which knifes through the water and resists motion in sideways directions.

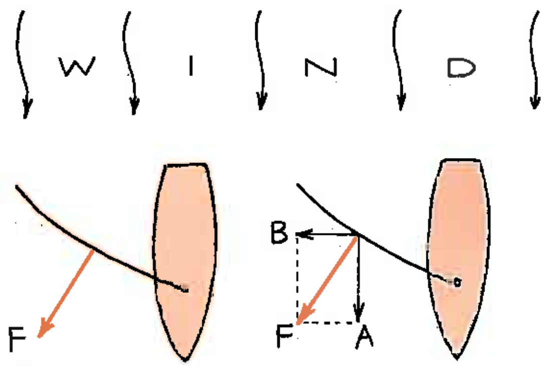

Fig. C-2

We can understand the motion of the boat by resolving *F* into perpendicular components, as shown in Figure C-2 right. The important com-

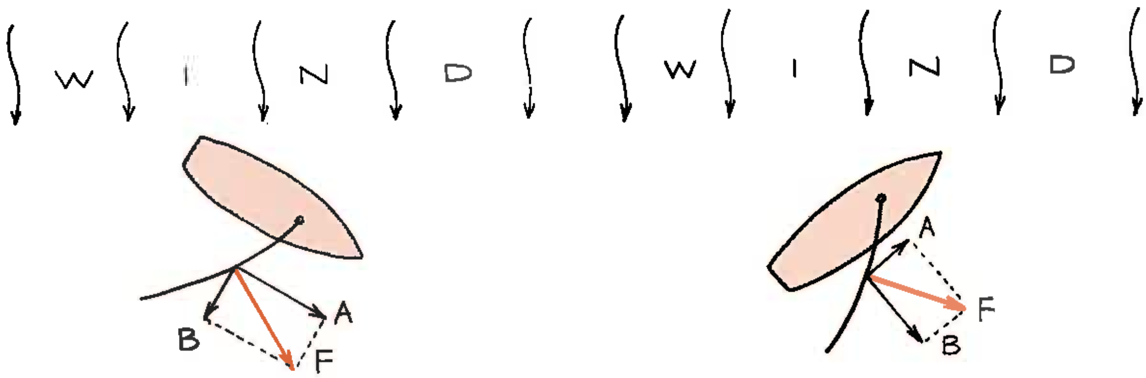

Fig. C-3

ponent is the one parallel to the keel and is labeled *A*. Component *A* propels the boat forward. The other component (*B*) is useless and tends to tip the boat over and move it sideways. The tendency to tip is offset by the heavy deep keel. Again, maximum speed can only approach wind speed.

When a sailboat's keel points in a direction other than exactly downwind and its sails are properly oriented, it can exceed wind speed. In the case of cutting across at an angular direction to the wind (Figure C-3 left), the wind continues to make impact with the sail even after the boat achieves wind speed. A surfer, in a similar way, exceeds the speed of the propelling wave by angling her surfboard across the wave. Greater angles to the propelling medium (wind for the boat, water wave for the surfboard) result in greater speeds. Can you see why a sailcraft can sail faster cutting across the wind than it can sailing downwind?

As strange as it may seem to people who do not understand vectors, maximum speed is attained by cutting into (against) the wind—that is, by angling the sailcraft in a direction upwind (Figure C-3 right)! Although a sailboat cannot sail *directly* upwind, it can reach a destination upwind by angling back and forth in zigzag fashion. This is called *tacking*. As the speed increases, the wind impact, rather than decreasing, actually *increases*. (If you run outdoors in a slanting rain, the drops will hit you harder if you run into the rain than away from the rain!) The faster the boat moves as it tacks upwind, the greater the magnitude of *F*. Thus, component *A* will continue pushing the boat along in the forward direction. The boat reaches its terminal speed when opposing forces, mainly water drag, balance the force of wind impact.

Icecraft which are equipped with runners for sliding on ice encounter no water drag. They can travel at several times wind speed when they tack upwind. Terminal speed is reached not so much because of resistive forces but because the wind direction shifts relative to the moving craft. When this happens, the wind finally moves parallel to the sail rather than against it. This appendix will not go into detail about this complication; nor will it discuss the curvature of the sail, which also plays an important role.

The central idea underlying sailcraft is the concept of vectors. It was this concept that ushered in the era of clipper ships and revolutionized the sailing industry. Sailing, like most things, is more enjoyable if you understand what is happening.

The Vector Nature of Light

Recall from Chapter 27 that light is electromagnetic energy that travels as a transverse, electromagnetic wave. The wave is made up of an oscillating electric field vector and an oscillating magnetic field vector that is at right angles to the electric vector (Figure C-4 on the next page). It is the orientation of the electric vector that defines the direction of polarization of light.

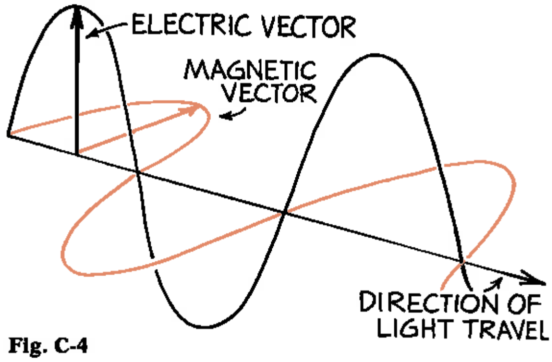

Fig. C-4

The electric vectors in waves of light from the sun or from a lamp vibrate in all conceivable directions as they move. Such light is nonpolarized. When the electric vectors of the waves are aligned parallel to each other, the light is considered to be polarized. Light can be polarized when it passes through polarizing filters. The most familiar are Polaroid sunglasses. Regular light incident upon a polarizing filter emerges as polarized light.

Think of a beam of nonpolarized light coming straight toward you. Consider the electric vectors in that beam. Some of the possible directions of the vibrations are as shown in Figure C-5 left. There are as many vectors in the horizontal direction as there are in the vertical direction, since the light is nonpolarized. The center sketch shows the light falling on a polarizing filter with its polarization axis vertically oriented. Only vertical components of light pass through the filter, and the light that emerges is vertically polarized, as shown on the right.

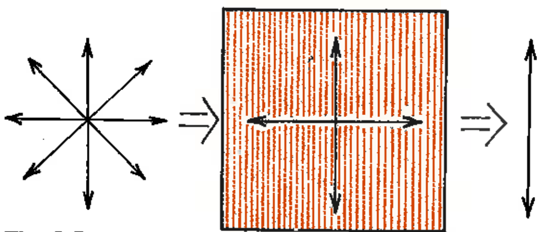
Fig. C-5

Figure C-6 shows that no light can pass through a pair of Polaroid sunglasses when their axes are at a right angle to one another, but some light does pass through when their axes are at a non-

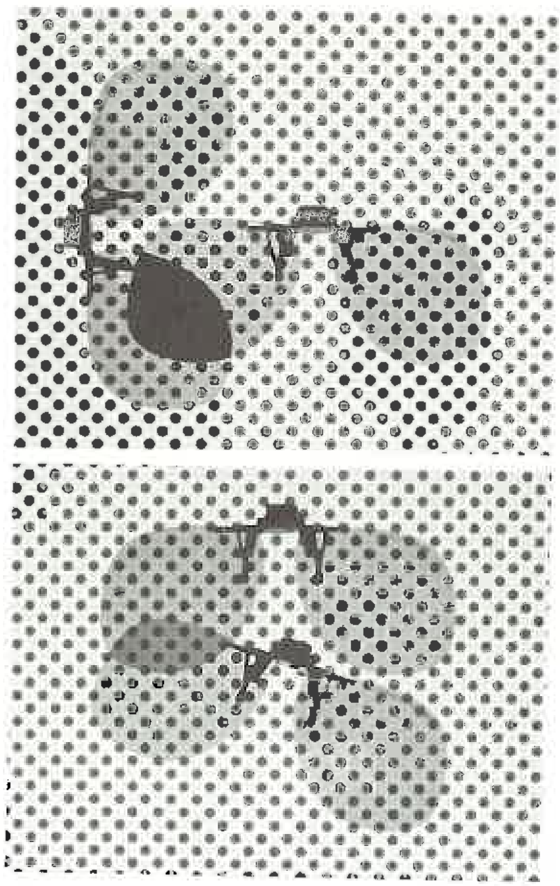
Fig. C-6

right angle. This fact can be understood with vectors and vector components.

Recall from Chapter 6 that any vector can be thought of as the sum of two components at right angles to each other. The two components are often chosen to be in the horizontal and vertical directions, but they can be in *any* two perpendicular directions. In fact, the number of sets of perpendicular components possible for any

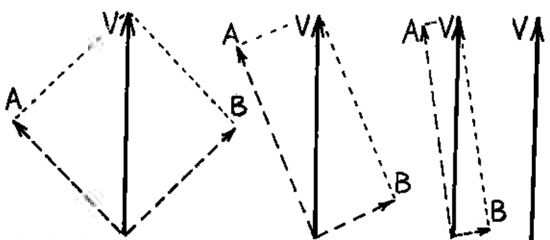

Fig. C-7

vector is infinite. A few of them are shown for the vector *V* in Figure C-7. In every case components *A* and *B* make up the sides of a rectangle that has *V* as its diagonal.

You can see this somewhat differently by thinking of component *A* as always being vertical and *B* as being horizontal, and picturing vector *V* as rotating instead (Figure C-8). This time the different orientations of *V* are superimposed on a polarizing filter with its polarization axis vertical. In the first sketch on the left,

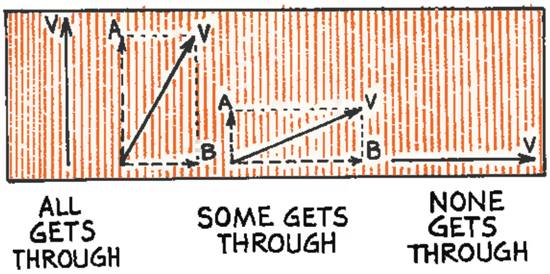

Fig. C-8

all of *V* gets through. As *V* rotates, only the vertical component *A* passes through, and it gets shorter and shorter until it is zero when *V* is completely horizontal.

Can you now understand how light gets through the second pair of Polaroid sunglasses in Figure C-6? Look at Figure C-9, where for clarity the two crossed lenses of Figure C-6 that are one atop the other are instead shown side by side. The vector *V* that emerges from the first lens is vertical. However, it has a component *A* in the direction of the polarization axis of the second lens. Component *A* passes through the second lens, while component *B* is absorbed.

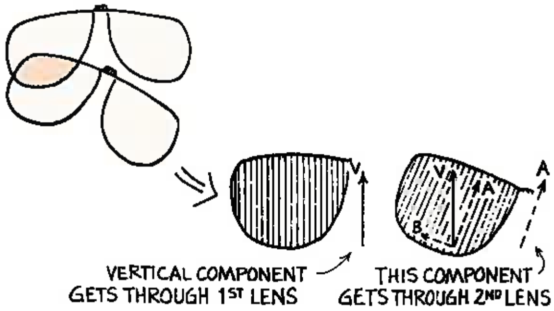

Fig. C-9

To really appreciate this, you must toy around with a couple of polarizing filters, which you can do in a lab exercise. Rotate one above the other and see how you can regulate the amount of light that gets through. Can you think of practical uses for such a system?

▶ **Question**

Consider a pair of polarizing filters crossed so that no light gets through. If you place a third filter *in front of* the pair, still no light gets through. The same is true if you place a third filter *in back of* the pair. But if you sandwich a third filter *between* the two with its polarization axis in a different direction from the other two, light *does* get through! (See Figure 27-20 on page 394.) Magic? No, just physics. Can you explain why this happens?

▶ **Answer**

Work on this one and doodle with vectors. If you solve it, help your classmates if they've tried without success and want help. As a last resort, ask your teacher for help.

Appendix D: Exponential Growth and Doubling Time*

You can't fold a piece of paper in half, then fold it again upon itself successively for 9 times. It gets too thick to keep folding. And if you could fold a fine piece of tissue paper upon itself 50 times, it would be more than 20 million kilometers thick! The continual doubling of a quantity builds up astronomically. Double one penny 30 times, so that you begin with one penny, then have two pennies, then four, and so on, and you'll accumulate a total of $10 737 418.23! One of the most important things we have trouble perceiving is the process of exponential growth, and why it proliferates out of control.

When a quantity such as money in the bank, population, or the rate of consumption of a resource steadily grows at a fixed percent per year, the growth is said to be *exponential*. Money in the bank may grow at 8 percent per year; world population is presently growing at about 2 percent per year; the electric power generating capacity in the United States grew at about 7 percent per year for the first three quarters of the century. The important thing about exponential growth is that the time required for the growing quantity to double in size (increase by 100 percent) is constant. For example, if the population of a growing city takes 10 years to double from 10 000 to 20 000 people and its growth remains steady, in the next 10 years the population will double to 40 000, and in the next 10 years to 80 000, and so on.

There is an important relationship between the percent growth rate and its *doubling time*, the time it takes to double a quantity:**

$$\text{doubling time} = \frac{69.2\%}{\text{percent growth per unit time}} \approx \frac{70\%}{\text{percent growth rate}}$$

This means that to estimate the doubling time for a steadily growing quantity, we simply divide 70% by the percentage growth rate. For example, the 7-percent-per-year growth rate of electric power generating capacity in the United States means that in the past the capacity has doubled every 10 years (since [70%]/[7%/year] = 10 years). A 2-percent-per-year growth rate for world population means that the population of the world doubles every 35 years (since [70%]/[2%/year] = 35 years). A city planning commission that accepts what seems like a modest 3.5-percent-per-year growth rate may not realize that this means that doubling will occur in 20 years (since [70%]/[3.5%/year] = 20 years). That means double capacity for such things as water supply, sewage-treatment plants, and other municipal services every 20 years.

Steady growth in a steadily expanding environment is one thing, but what happens when steady growth occurs in a finite environment? Consider the growth of bacteria that grow by division, so that one bacterium becomes two, the two divide to become four, the four divide to become eight, and so on. Suppose the division time for a certain kind of bacteria is one minute. This is then steady growth—the number of bacteria grows exponentially with a doubling time of one minute. Further, suppose that one bacterium is put in a bottle at 11:00 a.m. and that growth

▸ **Question**
When was the bottle half full?

▸ **Answer**
At 11:59 a.m., since the bacteria will double in number every minute!

* This appendix is adapted from material written by University of Colorado physics professor Albert A. Bartlett, who strongly asserts, "The greatest shortcoming of the human race is man's inability to understand the exponential function." Look up Professor Bartlett's still timely and provocative article, "Forgotten Fundamentals in the Energy Crisis," in the September 1978 issue of the *American Journal of Physics*, or his revised version in the January 1980 issue of the *Journal of Geological Education*.

** For exponential decay we speak about *half life*, the time for a quantity to reduce to half its value. An example of this case is radioactive decay, treated in Chapter 39.

continues steadily until the bottle becomes full of bacteria at 12 noon. Consider the question at the bottom of the previous page.

It is startling to note that at 2 minutes before noon the bottle was only ¼ full, and at 3 minutes before noon only ⅛ full. Table D-1 summarizes the amount of space left in the bottle in the last few minutes before noon. If bacteria could think, and if they were concerned about their future, at which time do you think they would sense they were running out of space? Do you think a serious problem would have been evident at, say, 11:55 a.m., when the bottle was only 3-percent full (1/32) and had 97 percent open space (just yearning for development)? The point here is that there isn't much time between the moment the effects of growth become noticeable and the time when they become overwhelming.

Table D-1 The last minutes in the bottle

Time	Portion full		Portion empty	
11:54 a.m.	1/64	(1.5%)	63/64	(98.5%)
11:55 a.m.	1/32	(3 %)	31/32	(97 %)
11:56 a.m.	1/16	(6 %)	15/16	(94 %)
11:57 a.m.	⅛	(12 %)	⅞	(88 %)
11:58 a.m.	¼	(25 %)	¾	(75 %)
11:59 a.m.	½	(50 %)	½	(50 %)
12:00 noon	Full	(100 %)	None	(0 %)

Suppose that at 11:58 a.m. some farsighted bacteria see that they are running out of space and launch a full-scale search for new bottles. And further suppose they consider themselves lucky, for they find three new empty bottles. This is three times as much space as they have ever known. It may seem to the bacteria that their problems are solved—and just in time.

▶ **Question**
If the bacteria are able to migrate to the new bottles and their growth continues at the same rate, what time will it be when the three new bottles are filled to capacity?

▶ **Answer**
All four bottles will be filled to capacity at 12:02 p.m.!

Table D-2 illustrates that the discovery of the new bottles extends the resource by only two doubling times. In this example the resource is

Table D-2 Effects of the discovery of three new bottles

Time	Effect
11:58 a.m.	Bottle 1 is ¼ full; bacteria divide into four bottles, each 1/16 full
11:59 a.m.	Bottles 1, 2, 3, and 4 are each ⅛ full
12:00 noon	Bottles 1, 2, 3, and 4 are each ¼ full
12:01 p.m.	Bottles 1, 2, 3, and 4 are each ½ full
12:02 p.m.	Bottles 1, 2, 3, and 4 are each all full

space—such as land area for a growing population. But it could be coal, oil, uranium, or any nonrenewable resource.

Continued growth and continued doubling lead to enormous numbers. In two doubling times, a quantity will double twice ($2^2 = 4$), or quadruple in size; in three doubling times, its size will increase eightfold ($2^3 = 8$); in four doubling times, it will increase sixteenfold ($2^4 = 16$); and so on.

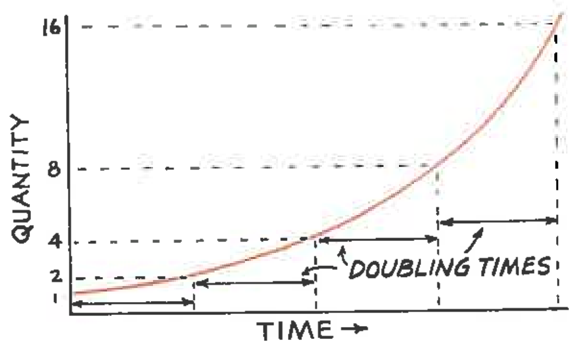

Fig. D-1 Graph of a quantity that grows at an exponential rate. Notice that the quantity doubles during each of the successive equal time intervals marked on the horizontal scale. Each of these time intervals represents the doubling time.

▶ **Question**

According to a French riddle, a lily pond starts with a single leaf. Each day the number of leaves doubles, until the pond is completely full on the thirtieth day. On what day was the pond half covered? One-quarter covered?

This is best illustrated by the story of the court mathematician in India who years ago invented the game of chess for his king. The king was so pleased with the game that he offered to repay the mathematician, whose request seemed modest enough. The mathematician requested a single grain of wheat on the first square of the chessboard, two grains on the second square, four on the third square, and so on, doubling the number of grains on each succeeding square until all squares had been used. At this rate there would be 2^{63} grains of wheat on the sixty-fourth square alone. The king soon saw that he could not fill this "modest" request, which amounted to more wheat than had been harvested in the entire history of the earth!

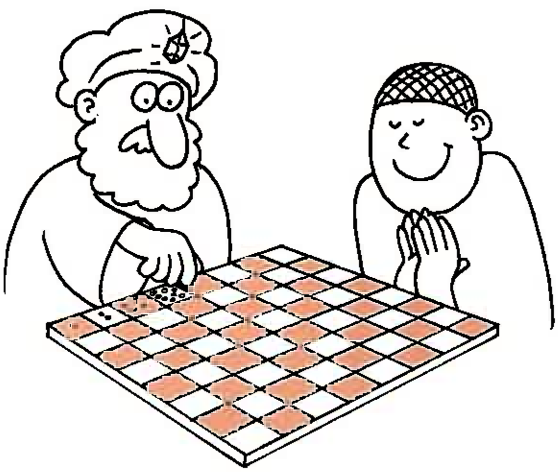

Fig. D-2 A single grain of wheat placed on the first square of the chess board is doubled on the second square, and this number is doubled on the third square, and so on. There is not enough wheat in the world for this process to continue to the 64th square!

As Table D-3 shows, the number of grains on any square is one grain more than the total of all grains on the preceding squares. This is true anywhere on the board. For example, when four grains are placed on the third square, that number of grains is one more than the total of three grains already on the board. The number of grains (eight) on the fourth square is one more than the total of seven grains already on the board. The same pattern occurs everywhere on the board. In any case of exponential growth, a greater quantity is represented in one doubling time than in all the preceding growth. This is important enough to be repeated in different words: Whenever steady growth occurs, the numerical count of a quantity that exists after a single doubling time is one greater than the total count of that quantity in the entire history of growth.

Table D-3 Filling the squares on the chessboard

Square number	Grains on square	Total grains thus far
1	1	1
2	2	3
3	$4 = 2^2$	7
4	$8 = 2^3$	15
5	$16 = 2^4$	31
6	$32 = 2^5$	63
7	$64 = 2^6$	127
•	•	•
•	•	•
•	•	•
64	2^{63}	$2^{64} - 1$

The consequences of unchecked exponential growth are staggering. It is very important to ask: Is growth really good? Is bigger really better? Is it true that if we don't continue growing we will stagnate?

▶ **Answer**

The pond was half covered on the 29th day, and was one-quarter covered on the 28th day!

Glossary

This glossary gives meanings for all terms printed in boldface within the text, and explains commonly used symbols as well. The section reference at the end of each meaning is that of the section where the term is introduced.

A simple, phonetic spelling is given for the terms that may be unfamiliar or hard to pronounce. CAPITAL LETTERS indicate the syllable that receives the heaviest stress. Accent marks are used when two syllables in a word are stressed; a lower-case syllable followed by an accent mark receives the secondary stress. The phonetic spellings are simple enough so that most can be interpreted without referring to the following key, which gives examples for the vowel sounds and for consonants that are commonly used for more than one sound.

Pronunciation Key

a	cat	ew	new	or	for
ah	father	g	grass	ow	now
ar	car	i, ih	him	oy	boy
aw	walk	ī	kite	s	so
ay	say	j	jam	sh	shine
ayr	air	ng	sing	th	thick
e, eh	hen	o	hot	u, uh	sun, forces
ee	meet	ō	hole	z	zebra
eer	deer	oo	moon	zh	pleasure
er	her	o͝o	pull		

A The symbol for *ampere.* (34.2) Also, when in lower-case italic, the symbol for *acceleration.* (2.4)

aberration (ab-er-RAY-shun) The unavoidable distortion in an image produced by a lens. (30.8)

absolute zero The temperature at which a substance has no kinetic energy to give up. This temperature corresponds to 0 K, or to -273°C. (21.1)

acceleration (ak-sel'-er-RAY-shun) The rate at which velocity is changing. The change may be in magnitude, direction, or both. (2.4)

action force One of the pair of forces described in Newton's third law. (5.2)

air resistance The friction that acts on something moving through air. (4.5)

alternating current (ac) Electric current that rapidly reverses in direction, usually at the rate of 60 hertz (in North America) or 50 hertz (in most other places). (34.7)

ampere (AM-peer) The SI unit of electric current. One ampere (symbol A) is equal to a flow of one coulomb of charge per second. (34.2)

amplitude (AMP-lih-tewd) The distance from the midpoint to the crest of a wave or, equivalently, from the midpoint to the trough. (25.2)

aneroid barometer (AN-er-oyd buh-ROM-uh-ter) An instrument used to measure atmospheric pressure; based on the movement of the lid of a metal box, rather than the movement of a liquid. (20.4)

angle of incidence (IN-sih-dens) The angle between an incident ray and the normal to a surface (see Figure 29–3). (29.2)

angle of reflection The angle between a reflected ray and the normal to a surface (see Figure 29–3). (29.2)

angular momentum (mo-MEN-tum) The "inertia of rotation" of a rotating object, equal to the product of rotational inertia and rotational velocity. (14.6)

apogee (AP-uh-jee) The point in an elliptical orbit where an object is farthest away from the object about which it orbits. (12.4)

apparent weightlessness The feeling of weightlessness that one has when falling toward or around the earth (as in an orbiting spacecraft). True weightlessness, however, requires that an object be far out in space, where gravitational forces are negligible. (11.3)

Archimedes' principle (ark-uh-MEE-deez) The relationship between buoyancy and displaced fluid: An immersed object is buoyed up by a force equal to the weight of the fluid it displaces. (19.3)

astigmatism (uh-STIG-muh-tizm) A defect of the eye caused when the cornea is curved more in one direction than in another. (30.7)

atom The smallest particle of an element that can be identified with that element. It consists of protons and neutrons in a nucleus surrounded by electrons. (17.1)

atomic mass number The total number of nucleons (neutrons and protons) in the nucleus of an atom. (39.4)

atomic number The number of protons in the nucleus of an atom. (17.7, 39.4)

average speed The total distance covered divided by the time interval. (2.2)

axis (AK-sis) The straight line about which rotation takes place. (13.1)

barometer An instrument used for measuring the pressure of the atmosphere. (20.3)

beats A throbbing variation in the loudness of sound caused by interference when two tones of slightly different frequencies are sounded together. (26.9)

Bernoulli's principle (ber-NOO-leez) The statement that the pressure in a fluid decreases as the speed of the fluid increases. (20.7)

bimetallic strip (bī'-meh-TAL'-ik) Two strips of different metals, such as one of brass and one of iron, that are welded or riveted together; used in thermostats. Because the two substances expand at different rates, when heated or cooled they bend in different directions. (22.1)

black hole A massive star that has collapsed to so great a density that its enormous local gravitational field prevents light from escaping and it thus appears black. (11.6)

blue shift An increase in the measured frequency of light from an approaching source; called the *blue shift* because the increase is toward the high-frequency, or blue, end of the spectrum. (25.9)

boiling The change of state from liquid to gas that occurs beneath the surface of the liquid. The gas that forms beneath the surface occurs as bubbles, which rise to the surface and escape. (24.4)

bow wave The V-shaped wave produced by an object moving across a liquid surface at a speed greater than the wave speed. (25.10)

Boyle's law The statement that the product of pressure and volume for a given mass of gas is a constant as long as the temperature does not change. (20.5)

breeder reactor A nuclear fission reactor that not only produces power but produces more nuclear fuel than it consumes by converting a nonfissionable uranium isotope into a fissionable plutonium isotope. (40.4)

Brownian motion The random movement observed among microscopic particles suspended in a fluid medium. (17.4)

buoyancy (BOY-un-see) The apparent loss of weight of an object submerged in a fluid. (19.2)

buoyant force (BOY-unt) The net upward force exerted by a fluid on a submerged object. (19.2)

C The symbol for *coulomb*. (32.3) Also, when preceded by the degree symbol °, the symbol for *Celsius*. (21.1)

cal The symbol for *calorie*. (21.5)

calorie (KAL-er-ee) A unit of heat. One calorie (symbol cal) is the amount of heat required to raise the temperature of one gram of water by 1°C. One Calorie (with a capital *C*) is equal to one thousand calories and is the unit used in describing the energy available from food. (21.5)

Celsius scale (SEL-see-us) A temperature scale in which the number 0 is assigned to the temperature at which water freezes, and the number 100 is assigned to the temperature at which water boils (at standard pressure). (21.1)

center of gravity The point at the center of an object's weight distribution, where the force of gravity can be considered to act. (9.1)

center of mass The point at the center of an object's mass distribution, where all its mass can be considered to be concentrated. For everyday conditions, it is the same as the center of gravity. (9.2)

centrifugal force (sen-TRIH-fuh-gul) An apparent outward force experienced by a rotating body. It is ficticious in the sense that it is not part of an interaction but is due to the tendency of a moving body to follow a straight-line path. (13.4)

centripetal force (sen-TRIH-peh-tul) A center-seeking force that causes an object to follow a circular path. (13.3)

chain reaction A self-sustaining reaction that, once started, steadily provides the energy and matter necessary to continue the reaction. (40.1)

charge The property to which is attributed the mutual repulsion of two electrons or two protons, and the mutual attraction of an electron and a proton. Also, the sum of all the electron and proton charges on an object (allowing for the cancelling effect of equal numbers of like and unlike charges). (32.1)

chemical formula A description, in terms of numbers and of symbols for elements, of the proportions of each kind of atom in a compound. (17.6)

circuit (SER-kit) Any complete path along which charge can flow. (35.1)

coherent (kō-HEER-ent) Type of light beam in which the waves all have the same frequency, phase, and direction. Lasers produce coherent light. (31.7)

complementary colors (kom'-pluh-MENT'-uh-ree) Two colors of light beams which when added together appear white. (28.6)

component (kom-PŌ-nent) One of the vectors in different directions whose vector sum is equal to a given vector. Any single vector may be regarded as the vector sum of two components, each of which acts in a different direction. (6.6)

compound A chemical substance made of atoms of two or more different elements combined in a fixed proportion. (17.6)

condensation (kon'-den-SAY'-shun) (a) The change of state of a gas into a liquid; the opposite of evaporation. (24.2) (b) In sound, a pulse of compressed air (or other matter). (26.2)

conduction A means of heat transfer within certain materials and from one material to another when the two are in direct contact. It involves the transfer of energy from atom to atom. (23.1)

conductor (a) A material through which heat can flow. (23.1) (b) A material, usually a metal, through which electric charge can flow. Good conductors of heat are generally good conductors of charge. (32.4)

conservation of charge The principle that net electric charge is neither created nor destroyed but simply transferred from one material to another. (32.2)

conserved Term applied to a physical quantity, such as momentum, energy, or electric charge, that remains unchanged after some interaction. (7.4)

constructive interference Addition of two waves when the crest of one wave overlaps the crest of another, so that their individual effects add together. The result is a wave of increased amplitude. (25.7)

convection A means of heat transfer by movement of the heated substance itself, such as by currents in a fluid. (23.2)

converging lens A lens that is thickest in the middle and that causes parallel rays of light to converge to a focus. (30.1)

cornea (KOR-nee-uh) The transparent covering over the eye. (30.6)

correspondence principle The principle that for a new theory to be valid, it must account for the verified results of the old theory in the region where both theories are applicable. (16.4)

coulomb (KOO-lōm) The SI unit of charge. One coulomb (symbol C) is equal to the total charge of 6.25×10^{18} electrons. (32.3)

Coulomb's law The relationship among electrical force, charges, and distance: The electrical force between two charges varies directly as the product of the charges and inversely as the square of the distance between them. (32.3)

crest One of the places in a wave where the wave is highest or the disturbance is greatest. (25.2)

critical angle The minimum angle of incidence at which a light ray is totally reflected within a medium. (29.12)

critical mass The minimum mass of fissionable material in a nuclear reactor or nuclear bomb that will sustain a chain reaction. (40.1)

crystal (KRIS-tŭl) A regular geometric shape found in a solid in which the component particles are arranged in an orderly, three-dimensional, repeating pattern. (18.1)

current See *electric current*.

density (DEN-sih-tee) A property of a substance, equal to the mass divided by the volume; commonly thought of as the "lightness" or "heaviness" of a substance. (18.2)

destructive interference Addition of two waves when the crest of one wave overlaps the trough of another, so that their individual effects cancel each other. The result is a wave of decreased amplitude. (25.7)

diffraction (dih-FRAK-shun) The bending of a wave around a barrier, such as an obstacle or the edges of an opening. (31.2)

diffraction grating A series of closely-spaced parallel slits which are used to separate colors of light by interference. (31.4)

diffuse reflection (dih-FYOOS) The reflection of waves in many directions from a rough surface (see Figure 29–7). (29.4)

direct current (dc) Electric current whose flow of charge is always in one direction only. (34.7)

dispersion (dih-SPER-zhun) The separation of light into colors arranged according to their frequency, for example by interaction with a prism or diffraction grating. (29.10)

displaced Term applied to the fluid that is moved out of the way when an object is placed in the fluid. A completely submerged object always displaces a volume of fluid equal to its own volume. (19.2)

diverging lens A lens that is thinnest in the middle and that causes parallel rays of light to diverge. (30.1)

Doppler effect (DOP-ler) The apparent change in frequency of a wave due to the motion of the source or the receiver. (25.9)

eddy Changing, curling paths in turbulent flow of a fluid. (20.7)

efficiency The ratio of useful work output to total work input, or the percentage of the work put into a machine that is converted to useful work output. (8.8)

elapsed time The time that has passed, or elapsed, since the beginning of the time measurement. (2.5)

elastic Term applied to a material that returns to its original shape after it has been stretched or compressed. (18.3)

elastic collision A collision in which colliding objects rebound without lasting deformation or the generation of heat. (7.5)

elasticity (ih-las-TIH-sih-tee) The property of a body or material by which it experiences a change in shape when a deforming force acts on it and by which it returns to its original shape when the deforming force is removed. (18.3)

elastic limit The distance of stretching and compressing beyond which an elastic material will not return to its original state. (18.3)

electrical force A force one electric charge exerts on another. When the charges are both positive or both negative, the force is repulsive; when the charges are unlike, the force is attractive. (32.1)

electrical resistance The resistance of a material to the flow of an electric current through it; measured in ohms. (34.4)

electrically polarized Term applied to an atom or molecule in which the charges are aligned so that one side is slightly more positive or negative than the opposite side. (32.7)

electric charge See *charge*.

electric current The flow of electric charge; measured in amperes. (34.2)

electric field A force field that fills the space around every electric charge or group of charges. Another electric charge introduced into this region will experience an electric force acting on itself. (33.1)

electric potential The electric potential energy per charge at a location in an electric field; measured in volts and often called *voltage*. (33.5)

electric potential energy The energy a charge possesses by virtue of its location in an electric field. (33.4)

electric power The rate at which electric energy is converted into another form, such as light, heat, or mechanical energy (or converted *from* another form). (34.10)

electromagnet (ih-lek′-trō-MAG′-net) A magnet whose field is produced by an electric current. Usually in the form of a wire coil with a piece of iron inside the coil. (36.5)

electromagnetic induction (ih-lek′-trō-mag-NET′-ik in-DUK-shun) The phenomenon of inducing a voltage in a conductor by changing the magnetic field around the conductor. (37.1)

electromagnetic spectrum The range of electromagnetic waves extending from radio waves to gamma rays. (27.3)

electromagnetic wave A wave that is partly electric and partly magnetic and that carries energy emitted by vibrating electric charges in atoms. (27.3)

electrostatics (ih-lek′-trō-STAT′-iks) The study of electric charges at rest. (32.1)

element A substance made of only one kind of atom. Examples of elements are carbon, hydrogen, oxygen, and nitrogen. (17.1)

ellipse (ih-LIPS) An oval-shaped curve that is the path taken by a point that moves such that the sum of its distances from two fixed points (foci) is constant (see Figure 12–7). (12.3)

energy That property of an object or a system which enables it to do work; measured in joules. (8.3)

equilibrium (ee-kwih-LIH-bree-um) In general, a state of balance. In particular: (a) The state of a body on which no net force acts. (6.5) (b) The state of a body on which no net torque acts. (14.2) (c) The state of a liquid in which the processes of evaporation and condensation are taking place at equal rates. (24.3)

escape speed The minimum speed necessary for an object to escape permanently from a gravitational field which holds it. (12.5)

evaporation (ih-vap′-or-AY′-shun) The change of state from liquid to gas that takes place at the surface of a liquid. (24.1)

eyepiece The lens of a telescope that is closer to the eye; enlarges the real image formed by the first lens. (30.5)

fact A close agreement by competent observers of a series of observations of the same phenomena. (1.4)

Fahrenheit scale (FA-ren-hīt) The temperature scale in common use in the United States. The number 32 is assigned to the freezing point of water, and the number 212 to the boiling point of water (at standard atmospheric pressure). (21.1)

family A group of elements in the same column of the periodic table. Elements within a family have similar chemical properties and have the same number of electrons in the outer shell. (17.8)

Faraday's law (FA-ruh-dayz) The statement that the induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field changes within those loops. (37.2) In general, the statement that an electric field is induced in any region of space in which a magnetic field is changing with time. The magnitude of the induced electric field is proportional to the rate at which the magnetic field changes. (37.7)

farsighted Term applied to a person who has trouble focusing on nearby objects because the eyeball is so short that images form behind the retina. (30.7)

field See *force field*.

first postulate of special relativity The statement that all the laws of nature are the same in all uniformly moving frames of reference. (15.4)

fission See *nuclear fission*.

fluid Anything that flows; in particular, any liquid or gas. (4.5)

focal length The distance between the center of a lens and either focal point. (30.1)

focal plane A plane that passes through either focal point of a lens and is perpendicular to the principal axis. For a converging lens, any incident parallel beam of light converges to a point somewhere on a focal plane. For a diverging lens, such a beam appears to come from a point on a focal plane. (30.1)

focal point For a converging lens, the point at which a beam of light parallel to the principal axis converges. For a diverging lens, the point from which such a beam appears to come. (30.1)

focus (FŌ-kus); pl. foci (FŌ-sī) For an ellipse, one of the two points for which the sum of the distances to any point on the ellipse is a constant. A satellite orbiting the earth moves in an ellipse which has the earth at one focus. (12.3)

force Any influence that tends to accelerate an object; commonly, a push or pull; measured in newtons. (3.3)

forced vibration The vibration of an object that is made to vibrate by another vibrating object that is nearby. The sounding board in a musical instrument amplifies the sound through forced vibration. (26.5)

force field What fills the space around a mass, electric charge, or magnet, so that another mass, electric charge, or magnet introduced to this region will experience a force. Examples of force fields are gravitational fields, electric fields, and magnetic fields. (11.2)

free fall Motion under the influence of the gravitational force only. (2.5)

freezing The change in state from liquid to solid. (24.5)

frequency (FREE-kwen-see) The number of vibrations per unit of time; measured in hertz. (25.2)

friction The force that acts to resist the relative motion (or attempted motion) of objects or materials that are in contact. (3.3)

fulcrum (FOOL-krum) The pivot point of a lever. (8.7)

fusion See *nuclear fusion*.

g The symbol for *gram*. Also, when in lower-case italic, the symbol for *the acceleration due to gravity at the earth's surface*, that is, 9.8 m/s^2. (2.5) When in upper-case italic, the symbol for *the universal constant of gravitation*, that is, $6.67 \times 10^{-11}\ N{\cdot}m^2/kg^2$. (10.4)

generator A machine that produces electric current by rotating a coil within a stationary magnetic field. (37.3)

gravitational field (grav'-ih-TAY'-shun-ul) A force field that fills the space around every mass. Another mass in this region will experience a gravitational force. (11.2)

greenhouse effect The warming effect whose cause is that short-wavelength radiant energy from the sun can enter the atmosphere and be absorbed by the earth more easily than long-wavelength energy from the earth can leave. (23.7)

grounding Allowing charges to move freely along a connection between a conductor and the ground. (32.6)

h The symbol for *hour*. (2.2) Also, when in italic, the symbol for *Planck's constant*. (38.2)

half life The time required for half the atoms of a radioactive isotope of an element to decay. (39.5)

heat The energy that is transferred from one material to another because of a temperature difference between the materials. Once the energy is absorbed by matter, it is internal energy. (21.2)

hertz (HERTS) The SI unit of frequency. One hertz (Hz) equals one vibration per second. (25.2)

hologram (HOL-uh-gram) A three-dimensional version of a photograph produced by interference patterns of laser beams. (31.8)

Hooke's law The statement that the amount of stretch or compression of an elastic material is directly proportional to the applied force. (18.3)

Huygens' principle (HĪ-gunz) The statement that every point on any wave front can be regarded as a new point source of secondary waves. (31.1)

hypothesis (hī-POTH-uh-sis) An educated guess; a reasonable explanation of an observation or experimental result that is not fully accepted as factual until tested over and over again by experiment. (1.3)

Hz The symbol for *hertz*. (25.2)

impulse (IM-puls) The product of force multiplied by the time interval during which the force acts. The impulse is equal to the change in momentum. (7.2)

incoherent (in'-kō-HEER'-ent) Type of light beam in which the waves are out of phase with each other. (31.7)

induced (in-DEWSD) Term applied to electric charge that has been redistributed on an object because of the presence of a charged object nearby. (32.6) Also, term applied to a voltage, electric field, or magnetic field that is created due to a change in or motion through a magnetic field or electric field. (37.1, 37.7)

induction (in-DUK-shun) The charging of an object without direct contact. (32.6) See also *electromagnetic induction*.

inelastic Term applied to a material that does not return to its original shape after it has been stretched or compressed. (18.3)

inelastic collision A collision in which the colliding objects become distorted and generate heat during the collision. (7.5)

inertia (ih-NER-shuh) The resistance of any material object to change in its state of motion. (3.3)

infrared Electromagnetic waves of frequencies lower than the red of visible light. (27.3)

infrasonic (in'-fruh-SON'-ik) Term applied to sound of pitch too low to be heard by the human ear, that is, of pitch below 20 hertz. (26.1)

in parallel Term applied to portions of an electric circuit that are connected at two points and provide alternative paths to the current between those two points. (35.2)

in phase (FAYZ) Term applied to two or more water waves whose crests (and troughs) arrive at a place at the same time, so that their effects reinforce each other. (25.7)

in series Term applied to portions of an electric circuit that are connected in a row so that the current that goes through one must go through all of them. (35.2)

instantaneous speed (in-stan-TAY-nee-us) The speed at any instant of time. (2.2)

insulator (IN-suh-lay-ter) A material that is a poor conductor of heat and that delays the transfer of heat. (23.1) Also, a material that is a poor conductor of electricity. (32.4)

interference pattern (in'-ter-FEER'-ens) A pattern formed by the overlapping of two or more waves that arrive in a region at the same time. (25.7)

internal energy The total energy inside a substance. (21.4)

√**inversely** When two values change in opposite directions, so that if one is doubled, the other is reduced to one half, they are said to be inversely proportional to each other. (4.2)

ion (Ī-un) An atom (or group of atoms bound together) with a net electric charge, due to the loss or gain of electrons. (17.8)

iridescence (ih-rih-DES-ens) The phenomenon whereby the interference of light waves of mixed frequencies reflected from the top and bottom of thin films causes a spectrum of colors. (31.6)

iris (Ī-ris) The colored part of the eye, which surrounds the black opening through which light passes and which regulates the amount of light entering the eye. (30.6)

isotope (Ī-suh-tōp) A form of an element having a particular number of neutrons in the nuclei of its atoms. Different isotopes of a particular element have the same atomic number but different atomic mass numbers. (17.7, 39.4)

J The symbol for *joule*. (8.1)

joule (JOOL) The SI unit of work and of all other forms of energy as well. One joule (symbol J) of work is done when a force of one newton is exerted on an object that moves a distance of one meter in the direction of the force. (8.1)

K The symbol for *kelvin*. (21.1) Also, when in lower case, the symbol for the prefix *kilo-*.

kcal The symbol for *kilocalorie*. (21.5)

kelvin (KEL-vin) The SI unit of temperature. A temperature measured in kelvins (symbol K) indicates the number of units above absolute zero. Since the divisions on the Kelvin scale and the Celsius scale are the same size, a change in temperature of one kelvin is equal to a change in temperature of 1°C. (21.1)

Kelvin scale A temperature scale calibrated in terms of energy itself as well as in terms of the freezing and boiling points of water. Absolute zero (-273°C) is taken as 0 K. There are no negative temperatures on the Kelvin scale. (21.1)

kg The symbol for *kilogram*. (3.5)

kilocalorie (KIL'-uh-kal'-er-ee) A unit of heat. One kilocalorie equals 1000 calories, or the amount of heat required to raise the temperature of one kilogram of water by 1°C. (21.5)

kilogram (KIL-uh-gram) The fundamental SI unit of mass. One kilogram (symbol kg) is the amount of mass in one liter of water at 4°C. (3.5)

kinetic energy (kih-NET-ik) The energy of motion. It is equal to half the mass multiplied by the square of the speed. (8.5)

km The symbol for *kilometer*. (2.2)

L The symbol for *liter*. (19.3)

laser (LAY-zer) An optical instrument that produces a beam of coherent light, that is, a beam in which the waves all have the same frequency, phase, and direction. (31.7)

law A general hypothesis or statement about the relationship of natural quantities that has been tested over and over again and has not been contradicted. Also known as a *principle*. (1.4)

law of conservation of angular momentum The statement that an object or system of objects will maintain a constant angular momentum unless acted upon by an unbalanced external torque. (14.7)

law of conservation of energy The statement that energy cannot be created or destroyed; it may be transformed from one form into another, but the total amount of energy never changes. (8.6)

law of conservation of momentum The statement that in the absence of a net external force, the momentum of an object or system of objects remains unchanged. (7.4)

law of inertia The statement that every body continues in its state of rest, or of motion in a straight line at constant speed, unless it is compelled to change that state by a net force exerted upon it. Also known as *Newton's first law*. (3.4)

law of reflection The statement that when a wave strikes a surface, the angle of incidence is equal to the angle of reflection. It holds true for both partially and totally reflected waves. (29.2)

law of universal gravitation The statement that for any pair of objects, each object attracts the other object with a force that is directly proportional to the mass of each object, and inversely proportional to the square of the distance between their centers of mass. (10.4)

lens (LENZ) A piece of glass (or other transparent material) that can bend parallel rays of light so that they cross, or appear to cross, at a single point. (30.1)

lever (LEH-ver, LEE-ver) A simple machine, made of a bar that turns about a fixed point. (8.7)

lever arm For a force that tends to cause rotation about an axis and that is perpendicular to the line between the point of contact and the axis, the length of that line. (14.1)

lift In the application of Bernoulli's principle, the net upward force produced by the difference between upward and downward pressures. When the lift equals the weight, horizontal flight is possible. (20.8)

light year The distance traveled by light in one year. (27.2)

line spectrum The pattern of distinct lines of color, corresponding to particular wavelengths, that are seen in the spectroscope when a hot gas is viewed. (28.11)

linear momentum The product of the mass and the velocity of an object. Also called simply *momentum*. (14.6)

linear speed The distance moved per unit of time. Also called simply *speed*. (13.2)

longitudinal wave (lon-jih-TEWD-ih-nul) A wave in which the vibration is in the same direction as that in which the wave is traveling, rather than at right angles to it. (25.6)

lunar eclipse The cutoff of light from the full moon when the earth is directly between the sun and the moon, so that the earth's shadow is cast on the moon. (11.4)

m The symbol for *meter*. (2.2) Also, when in italic, the symbol for *mass*. (3.5)

machine A device for multiplying (or decreasing) forces or simply changing the direction of forces. (8.7)

magnetic domain A microscopic cluster of atoms with their magnetic fields aligned. (36.4)

magnetic field A force field that fills the space around every magnet or current-carrying wire. Another magnet or current-carrying wire introduced into this region will experience a magnetic force acting on itself. (36.2)

magnetic pole One of the regions on a magnet that produce magnetic forces. (36.1)

mass A measure of the quantity of matter a body contains; may also be considered a measure of the inertia of an object. (3.5)

mechanical advantage The ratio of output force to input force for a machine. (8.7)

mechanical energy The energy due to the position or the movement of something; potential or kinetic energy (or a combination of both). (8.3)

mirage (mih-RAHZH) A floating image that appears in the distance and is due to the refraction of light in the earth's atmosphere. (29.9)

molecule (MOL-uh-kyool) Two or more atoms of the same or different elements joined to form a larger particle. (17.5)

momentum The product of the mass and the velocity of an object. Has direction as well as size. Also called *linear momentum*. (7.1)

monochromatic (mon'-ō-krō-MAT'-ik) Having a single color or frequency. (31.4)

N The symbol for *newton*.

natural frequency A frequency at which an elastic object naturally tends to vibrate, so that minimum energy is required to produce a forced vibration or to continue vibration at that frequency. (26.6)

neap tide A tide that occurs when the moon is halfway between a new and full moon, in either direction. The tides due to the sun and the moon partly cancel, so that the high tides are lower than average and the low tides are not as low as average. (11.4)

nearsighted Term applied to a person who can see nearby objects clearly but not distant objects. (30.7)

net force The combination of all the forces that act on an object. (4.1)

neutral equilibrium The state of an object balanced so that any small rotation neither raises nor lowers its center of gravity. (9.5)

neutron An electrically neutral particle that is one of the two kinds of particles found in the nucleus of an atom. (17.7)

newton The SI unit of force. One newton (symbol N) is the force that will give an object of mass one kilogram an acceleration of one meter per second squared. (3.5)

Newton's first law See *law of inertia*. (3.4)

Newton's law of cooling The statement that the rate of cooling of an object—whether by conduction, convection or radiation—is approximately proportional to the temperature difference between the object and its surroundings. (23.6)

Newton's second law The statement that the acceleration produced by a net force on a body is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the body. (4.3)

Newton's third law The statement that whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first. (5.2)

node Any part of a standing wave that remains stationary. (25.8)

normal A line that is perpendicular to a surface. (29.2)

normal force For an object resting on a horizontal surface, the upward force that balances the weight of the object. Also called the *support force*. (4.4)

nuclear fission (FIH-shun) The splitting of an atomic nucleus, particularly that of a heavy element such as uranium-235, into two main parts, accompanied by the release of much energy. (40.1)

nuclear fusion (FYOO-zhun) The combining of nuclei of light atoms, such as hydrogen, into heavier nuclei, accompanied by the release of much energy. (40.6)

nucleon (NEW-klee-on) The principal building block of the nucleus; a neutron or a proton. (17.7, 39.1)

nucleus The positively charged center of an atom, which contains protons and neutrons and has almost all the mass of the entire atom but only a tiny fraction of the volume. (17.7)

objective lens In an optical device using compound lenses, the lens closest to the object observed. (30.5)

ohm (ŌM) The SI unit of electrical resistance. One ohm (symbol Ω) is the resistance of a device that draws a current of one ampere when a voltage of one volt is impressed across it. (34.4)

Ohm's law The statement that the current in a circuit is directly proportional to the voltage impressed across the circuit and inversely proportional to the resistance of the circuit. (34.5)

opaque Term applied to materials that absorb light without re-emission and thus do not allow light through them. (27.5)

optical fiber A transparent fiber, usually of glass or plastic, that can transmit light down its length by means of total internal reflection. (29.12)

out of phase Term applied to two waves for which the crest of one wave arrives at a point at the same time as a trough of the second wave arrives. Their effects cancel each other. (25.7)

parallel circuit An electric circuit in which devices are connected to the same two points of the circuit, so that any single device completes the circuit independently of the others. (35.4)

pascal (pas-KAL) The SI unit of pressure. One pascal (symbol Pa) of pressure exerts a force of one newton per square meter of surface. (4.6)

Pascal's principle The statement that changes in pressure at any point in an enclosed fluid at rest are transmitted undiminished to all points in the fluid and act in all directions. (19.6)

penumbra A partial shadow which appears where some of the light is blocked and other light fills it in. (27.6)

perigee (PEH-rih-jee) The point in an elliptical orbit where an object is nearest the object about which it orbits. (12.4)

period The time required for a complete orbit. (12.2) Also, the time required for a pendulum to make one to-and-fro swing. In general, the time required to complete one cycle. (25.1)

periodic table A chart that lists elements by their atomic number and by their electron arrangements, so that elements with similar chemical properties are in the same column (see Figure 17–11). (17.8)

perturbation The deviation of an orbiting object from its normal path, caused by an additional gravitational force. (10.6)

photoelectric effect The ejection of electrons from certain metals when exposed to light. (38.3)

photon (FŌ-ton) In the particle model of electromagnetic radiation, a particle that travels at the speed of light and whose energy is related to the frequency of the radiation in the wave model. (27.1, 38.2)

pigment A material that selectively absorbs colored light. (28.3)

pitch Term that refers to how high or low a sound appears to be. (26.1)

Planck's constant The quantity that results when the energy of a photon is divided by its frequency. (38.2)

plasma (PLAZ-muh) A fourth state of matter, in addition to a solid, liquid, and gas. In the plasma state, which exists only at high temperatures, matter consists of bare atomic nuclei and free electrons. (17.9)

polarization (pō′-ler-ih-ZAY′-shun) The filtering out of all vibrations in a transverse wave, such as a light wave, that are not in a given direction. (27.7)

postulate (POS-tyoo-lit) A fundamental assumption. (15.3)

potential See *electric potential.*

potential difference The difference in electric potential, or voltage, between two points. Charge will flow when there is a difference, and will continue until both points reach a common potential. (34.1)

potential energy Energy that is stored and held in readiness by an object by virtue of its position. In this stored state it has the potential for doing work. (8.4)

power The rate at which work is done, equal to the amount of work done divided by the amount of time during which the work is done; measured in watts. (8.2)

pressure The force per unit of surface area, where the force is perpendicular to the surface; measured in pascals. (4.6)

principal axis The line joining the centers of curvature of the surfaces of a lens. (30.1)

principle A general hypothesis or statement about the relationship of natural quantities that has been tested over and over again and has not been contradicted. Also known as a *law.* (1.4)

principle of flotation The statement that a floating object displaces a quantity of fluid of weight equal to its own weight. (19.5)

projectile Any object that is projected by some force and continues in motion by its own inertia. (6.8)

proton A positively charged particle that is one of the two kinds of particles found in the nucleus of an atom. (17.7)

pulley A type of lever that is a wheel with a groove in its rim and that is used to change the direction of a force. A pulley or system of pulleys can also multiply forces. (8.7)

pupil The opening in the eyeball through which light passes. (30.6)

quantum (pl. quanta) (KWONT-um) An elemental unit; the smallest amount of something. One quantum of light energy is called a *photon.* (38.2)

quantum mechanics The branch of physics that is the study of the motion of quanta in the microworld of the atom. (38.8)

quantum physics The branch of physics that is the general study of quanta in the microworld of the atom. (38.8)

quark (KWORK, KWARK) One of the elementary particles of which all nucleons (protons and neutrons) are made. (39.1)

radiant energy Any energy, including heat, light, and X rays, that is transmitted by radiation. It occurs in the form of electromagnetic waves. (23.3)

radiation (a) The transmission of energy by electromagnetic waves. (23.3) (b) The particles given off by radioactive atoms such as uranium and radium. (39.2)

radioactive Term applied to an atom with a nucleus that is unstable and that can spontaneously emit a particle and become the nucleus of another element. (39.2)

rarefaction (rayr-uh-FAK-shun) A disturbance in air (or other matter) in which the pressure is lowered. (26.2)

rate How fast something happens, or how much something changes per unit of time; a change in a quantity divided by the time it takes for the change to occur. (2.1)

ray A thin beam of light. (27.6)

ray diagram A diagram showing the principal rays that can be drawn to determine the size and location of an image formed by a mirror or lens. (30.3)

reaction force The force that is equal in strength and opposite in direction to the action force and that acts on whatever is exerting the action force. (5.2)

real image An image that is formed by converging light rays and that can be displayed on a screen. (30.2)

red shift A decrease in the measured frequency of light (or other radiation) from a receding source; called the *red shift* because the decrease is toward the low-frequency, or red, end of the color spectrum. (25.9)

reflection The bouncing back of a particle or wave that strikes the boundary between two media. (29.1)

refraction The change in direction of a wave as it crosses the boundary between two media in which it travels at different speeds. (29.6)

regelation The phenomenon of ice melting under pressure and freezing again when the pressure is reduced. (24.7)

relative Regarded in relation to something else. (2.1)

relative humidity A ratio between how much water vapor is in the air, and the limit for the same air temperature. (24.2)

relativistic mass The total mass of a moving object, taking into account any increase in mass due to its kinetic energy. (16.2)

resolution (rez-uh-LOO-shun) The process of breaking up a vector into components. (6.6)

resonance (REZ-uh-nuns) A phenomenon that occurs when the frequency of forced vibrations on an object matches the object's natural frequency, and a dramatic increase in amplitude results. (26.7)

rest mass The mass of an object at rest. (16.2)

resultant (rih-ZUL-tunt) The geometric sum of two vectors. (6.2)

retina (RET-ih-nuh) The layer of light-sensitive tissue at the back of the eye. (30.6)

reverberation (rih-verb-er-AY-shun) The persistance of a sound, as in an echo, due to multiple reflections. (29.5)

revolution Motion in which an object turns about an axis outside the object. (13.1)

rotation The spinning motion that takes place when an object moves about an axis that is located within the object. (13.1)

rotational inertia The resistance of an object to changes in its state of rotation, determined by the distribution of the mass of the object and the location of the axis of rotation or revolution. (14.4)

rotational speed The number of rotations or revolutions per unit of time; often measured in rotations or revolutions per second or per minute. (13.2)

rotational velocity Rotational speed, together with a direction of rotation or revolution. (14.6)

s The symbol for *second*. (2.2)

saturated Term applied to a substance, such as air, that contains the maximum amount of another substance, such as water vapor, at a given temperature. (24.2)

scalar quantity A quantity in physics, such as mass, volume, and time, that can be completely specified by its magnitude, without regard to direction. (6.1)

scaling The study of how size affects the relationship between weight, strength, and surface area. (18.5)

scatter To absorb sound or light and re-emit it in all directions. (28.8)

schematic diagram Diagram that describes an electric circuit, using special symbols to represent different devices in the circuit. (35.5)

scientific method An orderly method for gaining, organizing, and applying new knowledge. (1.3)

second postulate of special relativity The statement that the speed of light in empty space will always have the same value regardless of the motion of the source or the motion of the observer. (15.5)

semiconductor Material that can be made to behave as either a conductor or an insulator of electricity. (32.4)

series circuit An electric circuit in which devices are arranged so that charge flows through each in turn. If one part of the circuit should stop the current, it will stop throughout the circuit. (35.3)

shadow A shaded region that results when light falls on an object and thus cannot reach into the region on the far side of the object. (27.6)

shell model of the atom A model in which the electrons of an atom are pictured as grouped in concentric, spherical shells around the nucleus. (17.8)

shock wave A cone-shaped wave produced by an object moving at supersonic speed through a fluid. (25.11)

sine curve A curve whose shape represents the crests and troughs of a wave traced out by a swinging pendulum that drops a trail of sand over a moving conveyor belt. (25.2)

solar eclipse The cutoff of light from the sun to an observer on the earth when the moon is directly between the sun and the earth. (11.4)

sonic boom The sharp crack heard when the shock wave that sweeps behind a supersonic aircraft reaches the listener. (25.11)

spacetime A combination of space and time, which are viewed in special relativity as two parts of one whole. (15.1)

special theory of relativity The theory, introduced in 1905 by Albert Einstein, that describes how time is affected by motion in space at a constant velocity, and how mass and energy are related. (15.1)

specific heat The quantity of heat required to raise the temperature of a unit mass of a substance by one degree. (21.6)

spectroscope An instrument used to separate the light from a hot gas or other light source into its constituent frequencies. (28.11)

spectrum For sunlight and other white light, the spread of colors seen when the light is passed through a prism. In general, the spread of radiation by frequency, so that each frequency appears at a different position. (28.1)

speed How fast something is moving; the distance moved per unit of time. (2.2)

spring tide A high or low tide that occurs when the sun, earth, and moon are all lined up, so that the tides due to the sun and moon coincide, making the high tides higher than average and the low tides lower than average. (11.4)

stable equilibrium The state of an object balanced so that any small rotation raises its center of gravity. (9.5)

standing wave Wave in which parts of the wave remain stationary and the wave appears not to be traveling. The result of interference between an incident (original) wave and a reflected wave. (25.8)

state One of the four possible forms of matter: solid, liquid, gas, and plasma. (24.1)

streamline The smooth path of a small region of fluid in steady flow. (20.7)

strong force The force that attracts nucleons to each other within the nucleus, and that is very strong at close distances but decreases rapidly as the distance increases. (39.1)

superconductor Material that has near infinite conductivity at very low temperatures, so that charge flows through it without resistance. (32.4)

support force Force that completely balances the weight of an object at rest. (4.4)

tangential velocity For an object orbiting around another object, the sideways component of velocity; that is, the component of velocity parallel to the second object's surface and thus perpendicular to the line joining the centers of the two objects. (10.2)

telescope Optical instrument that forms enlarged images of very distant objects. (30.5)

temperature The property of a material that tells how warm or cold it is with respect to some standard. (21.1)

terminal speed The speed at which the acceleration of a falling object terminates because friction balances the weight. (4.8)

terminal velocity Terminal speed together with the direction of motion (down for falling objects). (4.8)

terrestrial radiation Radiant energy emitted from the earth after having been absorbed from the sun. (23.7)

theory A synthesis of a large body of information that encompasses well-tested and verified hypotheses about certain aspects of the natural world. (1.4)

thermal contact The state of two or more objects or substances in contact such that it is possible for heat to flow from one object or substance to another. (21.2)

thermal equilibrium The state of two or more objects or substances in thermal contact when they have reached a common temperature. (21.3)

thermonuclear fusion A nuclear fusion reaction brought about by extremely high temperatures. (40.6)

thermostat A type of valve or switch that responds to changes in temperature and that is used to control the temperature of something. (22.1)

time dilation An observable stretching, or slowing, of time in a frame of reference moving past the observer at a speed approaching the speed of light. (15.1)

torque (TORK) The tendency of a force to cause rotation about an axis; the product of the force and the lever arm; measured in newton-meters. (14.1)

total internal reflection The 100% reflection (with no transmission) of light that strikes the boundary between two media at an angle greater than the critical angle. (29.12)

transformer A device for increasing or decreasing voltage by means of electromagnetic induction. (37.5)

transmutation The conversion of an atomic nucleus of one element into an atomic nucleus of another element through a loss or gain in the number of protons. (39.6)

transparent Term applied to materials that allow light to pass through them in straight lines. (27.4)

transverse wave A wave in which the vibration is at right angles to the direction in which the wave is traveling. (25.5)

trough (TRAWF) One of the places in a wave where the wave is lowest or the disturbance is greatest in the opposite direction from a crest. (25.2)

ultrasonic Term applied to sound frequencies above 20 000 hertz, the normal upper limit of human hearing. (26.1)

ultraviolet Electromagnetic waves of frequencies higher than those of violet light. (27.3)

umbra The darker part of a shadow where all the light is blocked. (27.6)

unstable equilibrium The state of an object balanced so that any small rotation lowers its center of gravity. (9.5)

universal constant of gravitation The constant *G* in the equation for Newton's law of universal gravitation; changes the units of mass and distance on the right side of the equation to the units of force on the left side. (10.4)

V The symbol for *volt*. (33.5) Also, when in lower-case italic, the symbol for *speed* or *velocity*. (2.2, 2.3) When in upper-case italic, the symbol for *voltage*. (33.5)

vector An arrow whose length represents the magnitude of a quantity and whose direction represents the direction of the quantity. (6.1)

vector quantity A quantity in physics, such as force or velocity, that has both magnitude and direction. (6.1)

velocity Speed together with the direction of motion. (2.3)

vibration A "wiggle in time"; a repeating, to-and-fro motion of something (such as a pendulum or the particles of an elastic body or a fluid) when displaced from the position of equilibrium. (25.1)

virtual image An image formed through reflection or refraction that can be seen by an observer but that cannot be projected on a screen because light from the object does not actually come to a focus. (29.3)

volt The SI unit of electric potential. One volt (symbol V) is the electric potential at which one coulomb of charge would have one joule of potential energy. (33.5)

voltage (VŌL-tij) (a) Electric potential; measured in volts. (33.5) (b) Potential difference; measured in volts. (34.1)

voltage source A device, such as a dry cell, battery, or generator, that provides a potential difference. (34.3)

W The symbol for *watt*. (8.2) Also, when in italic, the symbol for *work*. (8.1)

watt (WAWT) The SI unit of power. One watt of power is expended when one joule of work is done in one second. (8.2)

wave A "wiggle in space and time"; a disturbance that repeats regularly in space and time and that is transmitted progressively from one particle or region in a medium to the next with no actual transport of matter. (25.1)

wave front The crest, trough, or any continuous portion of a two-dimensional or three-dimensional wave in which the vibrations are all the same way at the same time (see Figure 29–14). (29.6)

wavelength The distance from the top of crest of a wave to the top of the following crest, or equivalently, the distance between successive identical parts of the wave. (25.2)

weight The force on a body of matter due to the gravitational attraction of another body (commonly the earth). (3.5)

weight density The weight of a substance divided by its volume. (18.2)

white light Light, such as sunlight, that is a combination of all the colors. Under white light, white objects appear white and colored objects appear in their individual colors. (28.1)

work The product of the force on an object and the distance through which the object is moved (when the force is constant and the motion takes place in a straight line in the direction of the force); energy expended when the speed of something is increased or when something is moved against the influence of an opposing force; measured in joules. (8.1)

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