5

The Science Content Standards for Grades Nine Through Twelve

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The science content standards for kindergarten through grade eight provide the background for students to succeed with the science content standards for grades nine through twelve. Aligning the high school curriculum to offer standards-based courses for every student will put new demands on schools and science departments. However, the reward for successfully meeting the challenge will be that high school graduates can attain the highest level of science literacy achieved by students in more than two decades.

Changing to a program based on the science content standards will require a restructuring of the high school curriculum, although the science that was generally taught in California before the *Science Content Standards for California Public Schools* was published is mostly included in the standards.[1] The successful implementation of standards-based kindergarten through grade eight programs aligned to this *Science Framework* should enable more students to take standards-based courses in high school. This chapter provides guidance for teaching students who have mastered the kindergarten through grade eight materials. To achieve this mastery will require many years of effort, and school districts should adjust their programs appropriately as their students have the opportunity to learn the prerequisite material in the earlier grades.

School districts are responsible for their curriculum and must decide how to structure their courses to teach the science standards. Traditionally, biology has been taught in the tenth grade, followed by chemistry and then possibly by physics. However, this sequence dates from a time when the content of the biology course was descriptive and that of the physics course was the most quantitative among the science disciplines. The high school science standards allow for other structures. Because districts need flexibility to design their own course structure, this chapter is presented in modular format—no sequence or emphasis is prescribed.

Appropriate to the rigor of the standards, each section covers a particular scientific discipline: physics, chemistry, biology/life sciences, and earth sciences. Along with meeting the subject-matter requirements for science, every student should learn the content in the full set of Investigation and Experimentation standards and have an opportunity to learn the slightly more advanced material in the standards that are marked with an asterisk.

In 1997 California established the Digital High School program, ensuring that all high schools throughout the state would have access to technology to improve student achievement in science and other academic subjects. Many schools purchased materials for scientific-based technology, and their use should be integrated into science programs. Technology can be used to teach some science standards and to assess students' understanding. Science education provides an opportunity to instruct students in gathering, graphing, tracking, and interpreting data through the use of technological tools, such as word processing, spreadsheets, and database development. Related concepts from science, mathematics, and language arts can be merged in the development of a science experiment and its subsequent analysis.

Safety is always the foremost consideration in the design of demonstrations, laboratories, and science experi-ments. The importance of safety is evident because scientists and engineers in universities and industries are required to follow strict health and safety regulations. Safety needs to be taught. Teachers should be familiar with the *Science Safety Handbook for California Public Schools*.[2] It contains specific, useful information relevant to classroom science teachers. School administrators, teachers, parents/guardians, and students have a legal and moral obligation to promote safety in science education. Knowing and following safe practices in science are a part of understanding the nature of science and scientific enterprise.

Physics

Many scientists and engineers consider physics the most basic of all sciences. It covers the study of motion, forces, energy, heat, waves, light, electricity, and magnetism. Physics focuses on the development of models deeply rooted in scientific inquiry, in which mathematics is used to describe and predict natural phenomena and to express principles and theories. Understanding physics requires the ability to use algebra, geometry, and trigonometry. This need for mathematics has kept all but a very few students in this country from studying physics. Other countries, however, have met this challenge by introducing the concepts of physics to students during a period of several years, starting in the earlier grade levels. Topics requiring little or no mathematics are introduced first, and students progress to more sophisticated and quantitative treatments as they learn more mathematics. The California standards emulate this successful approach.

All students can learn high school physics. Many will have enough foundational skills and knowledge of mathematics from their science curriculum in kindergarten through grade eight to study motion, forces, heat, and light. In high school, students should develop a working knowledge of algebra, geometry, and simple trigonometry to understand and gain access to the power of physics. Some will need to learn or relearn algebra, geometry, and trigonometry skills while studying physics. The need for such mathematics review should lessen over time as California's rigorous mathematics standards are implemented. Students who intend to pursue careers in science or engineering will need to master the physics content called for in the California standards, including the standards marked with an asterisk. (Note that equations appearing in this section are numbered consecutively.)

STANDARD SET 1. Motion and Forces

Motion deals with the changes of an object's position over time. Inherent in any useful study of motion is the concept of force, which represents the existence of physical interactions. Although Newton's laws provide a good platform from which to analyze forces, those laws do not address the origin of forces. Fundamental forces in nature govern the physical behavior of the universe. One of these fundamental forces, gravity, influences objects with mass but acts at a distance, or without any direct contact between the objects. The electromagnetic force is also a fundamental force that operates across a distance. These standards on motion and forces provide the foundation for understanding some key similarities—and differences—between these two forces. A working knowledge of basic algebra and geometry is an essential prerequisite for studying these concepts.

In standard sets presented earlier at lower grade levels, students were introduced to the idea that the motion of objects can be observed and measured, and they learned that a force can change the motion of an object by giving it a push or a pull. The topic of "Motion and Forces" at the high school level builds directly on the eighth grade Standard Set 1, "Motion," and Standard Set 2, "Forces," both of which introduce the notions of balanced forces and of net force (see Chapter 4). Students should know the difference between speed and velocity and should be able to interpret graphs for linear motion that plot relationships between two variables, such as speed versus time. Students should also understand the vector nature of forces. The concepts of gravity and of inertia as a resistance to a change in motion should have been introduced in the eighth grade.

1. Newton's laws predict the motion of most objects. As a basis for understanding this concept:

a. *Students know* how to solve problems that involve constant speed and average speed.

The rate at which an object moves is called its *speed.* Speed is measured in distance per unit time (e.g., meters/second). Velocity **v** is a vector quantity and therefore has both a magnitude—the speed—and a direction. If an object travels at a constant speed, a simple linear relationship exists between the speed, or rate of motion r; distance traveled d; and time t, as shown in

$$d = rt. \qquad \text{(eq. 1)}$$

If speed does not remain constant but varies with time, *average speed* can be defined as the total distance traveled divided by the total time required for the trip.

1. b. *Students know* that when forces are balanced, no acceleration occurs; thus an object continues to move at a constant speed or stays at rest (Newton's first law).

If an object's velocity v changes with time t, then the object is said to accelerate. For motion in one dimension, the definition of acceleration a is

$$a = \Delta v / \Delta t\,, \qquad \text{(eq. 2)}$$

where the Greek capital letter delta (Δ) stands for "a change of." *Acceleration* is defined as change in velocity per unit time. (Another way to state this definition is that *acceleration* is a change in distance per unit time per unit time, producing acceleration units of, for example, m/s^2 [meters per second squared or meters per second per second].) Acceleration is a vector quantity and therefore has both magnitude and direction. A push or a pull (force) needs to be applied to make an object accelerate. Force is another vector quantity.

A vector quantity, such as force, can be resolved into its x, y, and z components, F_x, F_y, and F_z. More than one force can be applied to an object simultaneously. If the forces point in the same direction, their magnitudes add; if the forces point in opposite directions, their magnitudes subtract. The net (overall) force can be calculated by adding forces along a line algebraically and keeping track of the direction and signs. If an object is subject to only one force, or to multiple forces whose vector sum is not zero, there must be a net force on the object. However, if there is no net force on an object already in motion, that object continues to move at a constant velocity. An object at rest remains at rest if no net force is applied to it. This principle is Newton's first law of motion.

1. c. *Students know* how to apply the law *F* = *ma* to solve one-dimensional motion problems that involve constant forces (Newton's second law).

If a net force is applied to an object, the object will accelerate. The relationship between the net force F applied to an object, the object's mass m, and the resulting acceleration a is given by Newton's second law of motion

$$F = ma\,. \qquad \text{(eq. 3)}$$

If mass is in kilograms (kg) and acceleration is in meters per second squared (m/s^2), then force is measured in Newtons, with 1 Newton = 1 kilogram-meter per second squared ($1\ \text{kg-m/s}^2$).

If the net force on an object is constant, then the object will undergo constant acceleration. When studying constant force, students should be able to make use of the following equations to describe the motion of an object in one dimension at any elapsed time t by calculating its velocity v and distance from the origin d:

$$v = v_0 + at\,, \qquad \text{(eq. 4)}$$

$$i = d_0 + \text{v}_0\text{t} + \tfrac{1}{2}at^2. \qquad \text{(eq. 5)}$$

In these equations m is the mass, v_0 is the initial velocity, d_0 is the initial position (distance from origin) of the object, and t is the time during which the force F is applied.

1. d. *Students know* that when one object exerts a force on a second object, the second object always exerts a force of equal magnitude and in the opposite direction (Newton's third law).

Newton's third law of motion is more commonly stated as, "To every action there is always an equal and opposite reaction." The mutual reactions of two bodies are always equal and point in opposite directions. Mathematically stated, if object 1 pushes on object 2 with a force $\mathbf{F}_{12}$, then object 2 pushes on object 1 with a force $\mathbf{F}_{21}$ such that

$$\mathbf{F}_{21} = -\mathbf{F}_{12}\,. \qquad \text{(eq. 6)}$$

This universal law applies, for example, to every object on the surface of Earth. Trees, rocks, buildings, and cars, even the atmosphere, are all subject to the downward force of gravity. In all cases Earth exerts an equal and opposite upward push on the objects. Stars exist because of the balance between the inward force of gravity and the outward pressure of their hot interior gases.

1.e. *Students know* the relationship between the universal law of gravitation and the effect of gravity on an object at the surface of Earth. (See Standard 1.m.*)

Since the time of Galileo's reputed experiment of dropping objects from the tower of Pisa, it has been understood that in the absence of air resistance, all objects near Earth's surface, regardless of their mass or composition, accelerate downward toward Earth's center at 9.8 m/s^2. Through Newton's second law, this principle can be expressed as

$$F = w = mg \text{ (where g} \approx 9.8\text{m/s}^2 \text{ is the acceleration due to gravity).} \qquad \text{(eq. 7)}$$

The gravitational force pulling on an object is called the object's weight w and is measured in Newtons.

1.f. *Students know* applying a force to an object perpendicular to the direction of its motion causes the object to change direction but not speed (e.g., Earth's gravitational force causes a satellite in a circular orbit to change direction but not speed).

A force that acts on an object may act in any direction. The component of the force parallel to the direction of motion changes the speed of the object, and the components perpendicular to the motion change the direction in which the object travels.

1.g. *Students know* circular motion requires the application of a constant force directed toward the center of the circle.

An object moving with constant speed in a circle is in uniform circular motion. The direction of motion continuously changes because of a force that always points inward toward the center of the circle. Such a centrally directed force is called a *centripetal force.* If the mass of the object is m, its speed is v, and the radius of the circle in which the object travels is r, then the magnitude of the force causing the circular motion is

$$F_c = mv^2/r\,. \qquad \text{(eq. 8)}$$

Examples of centripetal forces are the tension in a string attached to a ball that is swung in a circle, the pull of gravity on a satellite in orbit around Earth, the electrical forces that deflect electrons in a television tube, and the magnetic forces that turn a charged particle.

1.h.* *Students know* Newton's laws are not exact but provide very good approximations unless an object is moving close to the speed of light or is small enough that quantum effects are important.

Newton's laws are not exact but are excellent approximations valid in domains involving low speeds and macroscopic objects. However, when the speed of an object approaches the speed of light (3×10^8 m/s), Einstein's theory of special relativity is required to describe the motion of the object accurately. Among the major differences between Einstein's and Newton's theories of mechanics are that (1) the maximum attainable speed of an object is the speed of light; (2) a moving clock runs more slowly than does a stationary one; (3) the length of an object depends on its velocity with respect to the observer; and (4) the apparent mass of an object increases as its speed increases.

The other domain in which Newtonian mechanics breaks down is that of very small objects, such as atoms or atomic nuclei. Here the wavelike nature of matter becomes important, and quantum mechanics better describes the submicroscopic world. Newtonian mechanics assumes that if the motion of a particle is measured with great accuracy and all the masses and forces that are involved are also known, it is always possible to predict with equally great accuracy the future state of motion of the particle. Quantum mechanics shows that such certainty is not always possible. Sometimes only the probability of an outcome can be predicted.

1. i.* *Students know* how to solve two-dimensional trajectory problems.

Students can consider the problem of a ball of mass m thrown upward into the air at some angle. The motion of the ball will have horizontal and vertical com ponents that are independent of one another. If air resistance is ignored, there will be no horizontal force acting against the ball to slow it down. While the ball is in flight then, only a single vertical force, gravity, is acting on the ball (e.g., $F = w = mg$ downward). If students know the angle and the height from which the ball is thrown and the ball's initial velocity, they will be able to predict the path of the ball and to calculate how high the ball will go, how far it will travel before it strikes the ground, and how long it will be in the air.

1. j.* *Students know* how to resolve two-dimensional vectors into their components and calculate the magnitude and direction of a vector from its components.

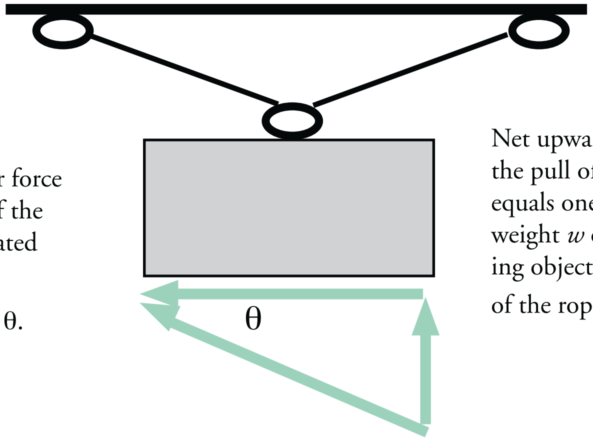
In a two-dimensional system, two quantities are needed to describe a vector. A vector **r** can be completely specified by a magnitude r and an angle Φ or by its x and y components (i.e., r_x and r_y). Simple trigonometry can be applied to resolve a vector into its components (e.g., $r_x = r \cos \Phi$ and $r_y = r \sin \Phi$) and to calculate the magnitude and direction of a vector from its components ($r^2 = r_x^2 + r_y^2$ and $\tan \Phi = r_y/r_x$).

1. k.* *Students know* how to solve two-dimensional problems involving balanced forces (statics).

A body at rest that is subject to no net force is in static equilibrium. Examples of static equilibrium are a book resting on the surface of a table and a ladder leaning at rest against a wall. Because the book and table remain at rest does not imply that no forces act on these objects but does imply that the vector sum of all these forces is zero. In particular, the components of the forces in any particular direction sum to zero. Thus for an object that remains at rest,

$$\sum F_y = 0 \qquad \text{(eq. 9)}$$

where the Greek capital letter sigma (Σ) means to "sum over or add" and F_y represents the components in any chosen direction *y* of the forces acting on the object. One sample problem appears in Figure 2, "Calculation of Force." Students are given the weight of a hanging object, the lengths of the ropes holding it in place, and the distance between the anchors. The students are asked to calculate the forces, called *tension,* along ropes of equal length. Students find this problem difficult because the vector force diagram they should use to solve the problem is often confused with the physical lengths of the ropes.



The tension or force *T* along one of the ropes is calculated using

$\frac{1}{2} w = T \sin \theta$.

Net upward force from the pull of one rope equals one-half the weight *w* of the hanging object (the weight of the ropes is ignored).

Fig. 2. Calculation of Force

1. l.* *Students know* how to solve problems in circular motion by using the formula for centripetal acceleration in the following form: $a = v^2/r$.

The speed of an object undergoing uniform circular motion does not vary, but the object's direction does and hence the object's velocity. Thus the object is constantly accelerating. The magnitude of this centripetal acceleration is

$$a_c = F_c/m = v^2/r\,, \qquad \text{(eq. 10)}$$

and the direction of the centripetal acceleration vector rotates so that it always points inward toward the center of the circle.

1. m.* *Students know* how to solve problems involving the forces between two electric charges at a distance (Coulomb's law) or the forces between two masses at a distance (universal gravitation).

Standard Set 5 for physics, "Electric and Magnetic Phenomena," which appears later in this section, shows that the origin of the force between two masses and between two electric charges is entirely different. However, the forces involved, the gravitational and the electromagnetic forces, are both inverse square relationships. Coulomb's law (in a vacuum) is written

$$F_q = kq_1q_2/r^2 \,, \qquad \text{(eq. 11)}$$

where $k = 9 \times 10^9$ Nm^2/coul^2, q_1 and q_2 are charges (positive [+] or negative [–]), r is the distance separating the charges, and F_q is the force resulting from the two charges. The force is repulsive if the charges are the same sign and attractive if they are different.

Newton's law of universal gravitation states that if two objects have masses m_1 and m_2, with centers of mass separated from each other by a distance r, then each object exerts an attractive force on the other; the magnitude of this force is

$$F_g = Gm_1m_2/r^2 \,, \qquad \text{(eq. 12)}$$

where G is the universal gravitational constant, equal to 6.67×10^{-11} newton-m^2/kg^2. For the case of a small object falling freely near the surface of Earth, students should understand that

$$g = Gm_e/r_e^2 = 9.8 \text{ m/s}^2 \,, \qquad \text{(eq. 13)}$$

where m_e and r_e are the mass and radius of Earth. Students might be interested to know that Henry Cavendish's measurement of G, completed around the year 1800, was the last piece of information needed to calculate the mass of Earth.

STANDARD SET 2. Conservation of Energy and Momentum

The concept of energy was introduced and discussed several times in the lower grades, from the physical sciences through the life sciences. In fact, every process involves some transfer of energy. In Standard Set 2 *energy* is classified as *kinetic,* meaning related to an object's motion, or as *potential,* meaning related to an object's stored energy. The energy of a closed system is conserved. Another useful conservation law, conservation of momentum, is introduced and is shown to be a direct consequence of Newton's laws. The power and importance of these conservation laws are that they allow physicists to predict the motion of objects without having to know the details of the dynamics and interactions in a given system.

Through the standard sets introduced in the lower grade levels, students should have learned about forces and motion and the idea of energy. They should have been taught the role of energy in living organisms and the effects of energy on Earth's weather. The standards presented earlier also call for student exposure to energy conservation, a concept that is essential to the topics contained in the high school physics standard sets 3, 4, and 5 and in several standard sets in chemistry and earth sciences.

2. The laws of conservation of energy and momentum provide a way to predict and describe the movement of objects. As a basis for understanding this concept:

a. *Students know* how to calculate kinetic energy by using the formula $E = \frac{1}{2} mv^2$.

Kinetic energy is energy of motion. The kinetic energy of an object equals the work that was needed to create the observed motion. This work can be related to the net force applied to the object along the line of the motion. The work done on an object by a force is equal to the component of the force along the direction of motion multiplied by the distance the object moved:

$$W = Fd\,. \qquad \text{(eq. 14)}$$

The work needed to accelerate an object of mass m from rest to a speed v is $\frac{1}{2} mv^2$. This quantity is defined as the kinetic energy E. The units of energy are joules, in which 1 joule = 1 kilogram-meter squared per second squared (1 kg-m^2/s^2) = 1 newton-meter. Energy is a *scalar* quantity, meaning that energy has a magnitude but no direction.

2. b. *Students know* how to calculate changes in gravitational potential energy near Earth by using the formula (change in potential energy) = *mgh* (*h* is the change in the elevation).

Students can combine equations (3) and (14) to find the work done in lifting an object of weight mg through a vertical distance h, as shown in

$$W = mgh\,. \qquad \text{(eq. 15)}$$

Work and energy have the same units. Therefore, one can define mgh as the change in gravitational potential energy associated with the change in elevation h of the mass m.

2. c. *Students know* how to solve problems involving conservation of energy in simple systems, such as falling objects.

Equations (4) and (5) can be used to show that if the object dealt with in Standard 2.b is released from rest and allowed to fall freely, it will strike the ground with a speed

$$v = \sqrt{2\,gh}\,, \qquad \text{(eq. 16)}$$

and its kinetic energy at the instant of impact will be

$$E = \tfrac{1}{2} mv^2 = \tfrac{1}{2} m(2\,gh) = mgh. \qquad \text{(eq. 17)}$$

The total energy T of the object is then defined as the sum of kinetic plus potential energy

$$T = E + PE\,. \qquad \text{(eq. 18)}$$

This sum is conserved in a closed system for such forces as gravity and electromagnetic interactions and those produced by ideal springs. Thus,

$$\Delta E + \Delta PE = 0\,. \qquad \text{(eq. 19)}$$

Therefore, the change in kinetic energy equals the negative of the change in potential energy. This principle is a consequence of the law of the conservation of energy. Energy can be converted from one form to another, but in a closed system the total energy remains the same.

2. d. *Students know* how to calculate momentum as the product *mv.*

The momentum **p** of an object is defined as the product of its mass m and its velocity **v.** Momentum is thus a vector quantity, having both a magnitude and a direction. The units of momentum are kg-m/s. The magnitude of the momentum is mv, the product of the object's mass and its speed.

2. e. *Students know* momentum is a separately conserved quantity different from energy.

If no net force is acting on an object or on a system of objects, the momentum remains constant. That is, neither its magnitude nor its direction changes with time. Conservation of momentum is another fundamental law of physics.

2. f. *Students know* an unbalanced force on an object produces a change in its momentum.

As discussed in the section for Standard 1.c, if the net force on an object is not zero, then its velocity and hence its momentum will change. Motion resulting from a constant force **F** acting on an object for a time Δt causes a change in momentum of $\mathbf{F}\Delta t$. This change in momentum is called an *impulse.* (Note that the units of impulse are the same as those of momentum [i.e., newton-second = kg-m/s].) Depending on the direction of the force, the impulse can increase, decrease, or change the direction of the momentum of an object.

2. g. *Students know* how to solve problems involving elastic and inelastic collisions in one dimension by using the principles of conservation of momentum and energy.

Momentum is always conserved in collisions. Collisions that also conserve kinetic energy are called *elastic collisions;* that is, the kinetic energy before and after the collision is the same. Billiard balls colliding on smooth pool tables and gliders colliding on frictionless air tracks are approximate examples. Collisions in which kinetic energy is not conserved are called *inelastic collisions.* An example is a golf ball colliding with a ball of putty and the two balls sticking together. Some of the kinetic energy in inelastic collisions is transformed into other types of energy, such as thermal or potential energy. In all cases the total energy of the system is conserved.

2. h.* *Students know* how to solve problems involving conservation of energy in simple systems with various sources of potential energy, such as capacitors and springs.

An ideal spring is an example of a conservative system. The force required either to stretch or to compress a spring by a displacement *x* from its equilibrium (unstretched) length is

$$F = kx, \qquad \text{(eq. 20)}$$

where *k* is the spring constant that measures a spring's stiffness. A graph of the magnitude of this force as a function of the compression shows that the force varies linearly from zero to *kx* as the spring is compressed. The area under this graph is the work done in compressing the spring and is equal to

$$\tfrac{1}{2}\,(\text{base})(\text{height}) = \tfrac{1}{2}\,kx^2. \qquad \text{(eq. 21)}$$

This is also the potential energy stored in the spring.

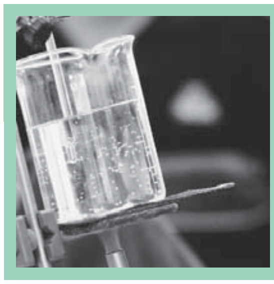
A capacitor stores charge. The charge *Q* that is stored depends on the voltage *V* according to

$$Q = CV, \qquad \text{(eq. 22)}$$

where the constant *C* is called the *capacitance.* (Notice that this equation and the equation for a spring [eq. 20] have the same form.) The energy stored in a capacitor is given by the equation

$$E = \tfrac{1}{2}\,CV^2, \qquad \text{(eq. 23)}$$

which also has the same form as the equation that gives the energy stored by a spring.



STANDARD SET 3. Heat and Thermodynamics

The concept of heat (thermal energy) is related to all scientific disciplines. Energy transfer, molecular motion, temperature, pressure, and thermal conductivity are integral parts of physics, chemistry, biology, and earth science. Thermodynamics deals with exchanges of energy between systems.

If students in high school have not yet covered the chemistry standards, the related topics from those standards should be introduced. (See the following standards for chemistry in this chapter: 4.a through 4.h, "Gases and Their Properties," and 7.a through 7.d, "Chemical Thermodynamics." Specific chemistry topics that are useful or necessary for promoting a more complete understanding of Standard

Set 3 are specifically mentioned, when relevant, under the sections with detailed descriptions.

At the atomic and molecular levels, all matter is continuously in motion. For example, individual molecules of nitrogen, oxygen, and other gases that make up the air inside a balloon move at varying speeds in random directions, vibrating and rotating. The collisions of these molecules with the inner surface of the balloon create the pressure that supports the balloon against atmospheric pressure.

Considerable confusion exists in scientific literature about the definitions of the terms *heat* and *thermal energy.* Some texts define *heat* strictly as "transfer of energy." These science content standards use the term *heat* interchangeably with *thermal energy.* However, it is less confusing to reserve the term *heat* for thermodynamic situations in which energy is transferred either because of differences in temperature or through work done by or on a system. In this sense both *heat* and *work* have meaning only as they describe energy exchanges into and out of the system, adding or subtracting from a system's store of internal energy.

Students, just like scientists of the eighteenth century, might easily fall prey to the misconception that heat is a substance. Students should be cautioned that heat is energy, not a material substance, and that *heat flow* refers not to material flow but to the transfer of energy from one place to another. Confusion is most apt to arise when dealing with heat transfer by convection; that is, when heat is transferred through actual motion of hot and cold material along a thermal gradient. Heating a material such as air causes it to expand and leads to differences in density that drive the movement of heated material.

Students also often confuse temperature and heat. From a molecular viewpoint, *temperature* is a measure of the average translational kinetic energy of a molecule, as shown in equation (27). (See also Standard Set 7 in the chemistry section in this chapter.) Studies of the temperature of materials as they pass through phase transitions may also help students understand the differences and relationships between heat and temperature.

A way to avoid confusion is to reserve the use of the word *heat* for situations in which heat transfer is involved, as described in the next section.

3. Energy cannot be created or destroyed, although in many processes energy is transferred to the environment as heat. As a basis for understanding this concept:

a. *Students know* heat flow and work are two forms of energy transfer between systems.

Heat transfer is energy flow from one system to another because of differences in temperature or because of mechanical work. The energy that flows into a pot of cold water put on a hot stove is an example of heat transfer. This energy increases the kinetic energy of the random motion of the molecules of water and therefore the temperature of the water rises. When the water reaches 100°C, a new phenomenon, a phase transition, occurs: the water vaporizes, or boils. Although energy continues to flow into the water, the kinetic energy of the water molecules does not increase; therefore the temperature of the water remains constant. As the water changes from a liquid to a gas, the energy goes instead into breaking the bonds that hold one molecule of liquid water to another. The energy required (per unit mass or mole of liquid) to change a particular liquid at its boiling temperature into a gas is called the liquid's *latent heat of vaporization.*

Mechanical work can change temperature too (e.g., when the forces of friction heat objects or when a gas is compressed and so warms). Conversely, changes in temperature can do mechanical work (e.g., warming a container of gas that is sealed by a piston will cause the gas to expand and the piston to move).

Heat is energy that moves between a system and its environment because of a temperature difference between them. Every system has its internal energy, that is, the energy required to assemble the system; and this energy is independent of any particular path or means by which the system is assembled. The transfer of internal energy from one system to another, because of a temperature difference, is known as *heat flow.* There are three basic kinds of heat flow: conduction, convection, and radiation. Students should have first learned about these processes in the sixth grade.

As heat is transferred to a system (object), the temperature of the system (object) may increase. Substances vary in the amount of heat necessary to raise their temperatures by a given amount. More mass in the system clearly requires more heat for a given temperature change. An expression that illustrates the relationship between the amount of heat transferred and the corresponding temperature change is shown in equation (24). The change in temperature ΔT is proportional to the amount of heat added. This relationship is specified by

$$Q = mC\Delta T, \qquad \text{(eq. 24)}$$

where Q is the internal energy added by heat transfer to the system from the surroundings, ΔT is the difference in temperature between the final and initial states of the system, m is the system's mass, and C is the specific heat of the substance (in joules/gram-°C or calories/gram-°C). *Specific heat* is a characteristic property of a material. The unit of specific heat is energy divided by mass and temperature change (e.g., calories/gram-degree).

Water, which serves as a standard against which all other materials may be compared, has a specific heat of one calorie/gram-degree. In other words, one calorie of heat is required to raise one gram of water one degree Celsius. When a gram of water cools one degree, one calorie is liberated. This value is large compared with those of other substances. Therefore, it takes much more heat to warm water than it does to raise the temperature of the same amount of most other substances. This fact has important implications for weather and climate and is one reason the weather is "tempered" in coastal areas (e.g., summers are cooler and winters are warmer than they are in inland areas at a similar latitude).

Equation (24) makes the distinction between heat and temperature quite clear. It specifies that heat can flow in or out of a system because of temperature difference alone. There are, however, other situations in which the addition or removal of heat is not accompanied by changes in temperature. These situations occur when a substance undergoes a change of phase, or state, such as when water evaporates or freezes. During phase changes, the absorption or release of heat takes place while the system remains at a constant temperature. For example, when ice melts in a glass of water that is sufficiently well mixed, the temperature of the water remains at the freezing point of water. Additional heating of the water raises its temperature only after the ice has melted.

3. b. *Students know* that the work done by a heat engine that is working in a cycle is the difference between the heat flow into the engine at high temperature and the heat flow out at a lower temperature (first law of thermodynamics) and that this is an example of the law of conservation of energy.

The total energy of an isolated system is the sum of the kinetic, potential, and thermal energies. A system is isolated when the boundary between the system and the surroundings is clearly defined. Total energy is conserved in all classical processes. Thus, the law of conservation of energy can be restated as the first law of thermodynamics; that is, for a closed system the change in the internal energy ΔU is given by the expression

$$\Delta U = Q - W, \qquad \text{(eq. 25)}$$

where Q is the internal energy added by heat transfer to the system from the surroundings and W is the work done by the system. The quantities ΔU, Q, and W in equation (25) can be negative or positive, depending on whether energy is converted from mechanical form into heat, as when work is done on the system, or on whether heat is transformed into mechanical energy, as when the system is doing work. By convention, Q is positive for heat added to the system and negative for heat transferred to the surroundings, and W is positive for work done by the system and negative for work done on the system. As a practical matter, energy that cannot be obtained as work is considered a loss to the system. Thus, the first law of thermodynamics indicates how much energy is available to do work.

A heat engine is a device for getting useful mechanical work from thermal energy. While part of the input heat energy Q_H, sometimes known as *heat of combustion,* is converted into useful work W, the remaining heat is lost to the environment as exhaust heat Q_L. That is, the work done by a heat engine is the difference between thermal energy flowing in at higher temperature and heat flowing out at lower temperature, as shown in the following equation:

$$W = Q_H - Q_L. \qquad \text{(eq. 26)}$$

This simple relationship is valid for an idealized engine, also called a *Carnot engine.*

3. c. *Students know* the internal energy of an object includes the energy of random motion of the object's atoms and molecules, often referred to as *thermal energy.* The greater the temperature of the object, the greater the energy of motion of the atoms and molecules that make up the object.

The internal energy of objects is in the motion of their atoms and molecules and in the energy of the electrons in the atoms. For ideal gases, nearly realized by air molecules, heat transferred to the gas increases the average speed of the gas molecules. The higher the temperature, the greater the average speed. If it were possible to observe the motion of molecules in a gas at a fixed temperature, one would see molecules with different masses moving on average at different speeds. More massive molecules, for example, move more slowly because the average kinetic energy of each type of molecule is the same in the gas, and the kinetic energy is proportional to the product of the mass and the square of the velocity of the gas molecules. The pressure of a gas results from individual molecules bumping against containing walls and other objects. Each hit and change of direction causes a change in momentum and therefore a net force or push on the object hit. One molecule's contribution to total pressure is very small, but measurable pressures result when large numbers of fast-moving atoms or molecules participate in these collisions.

For an ideal gas system at thermal equilibrium, the kinetic energy of an individual gas molecule averaged over time is

$$E = \tfrac{3}{2}kT, \qquad \text{(eq. 27)}$$

where $k = 1.38 \times 10^{-23}$ joule/K, and T is the absolute temperature in Kelvin (K). The Kelvin temperature scale and its conversion to the customary Fahrenheit and Celsius scales are discussed in standards 4.d and 4.e in the chemistry section in this chapter.

3. d. *Students know* that most processes tend to decrease the order of a system over time and that energy levels are eventually distributed uniformly.

Energy in the form of heat transfers from hot to cold, but not from cold to hot, regardless of whether that energy transfers by radiation, conduction, or convection. Why? Matter exists in discrete energy states (or levels). For tiny objects, such as a single electron, the difference in energy between one state and the next is big enough to be detected and measured. For the larger objects of everyday experience, such as a pebble, the difference is too small to detect; still, the discrete states exist, and it makes sense to speak of the probability with which any given system is to be found in any one of its possible states.

A system of many components has many states of given total energy because some components can have a larger fraction of that energy if others have less. Such a system evolves so that all states with the same total energy become equally probable. Heat flows from hot to cold because states in which components share energy equally vastly outnumber states in which they do not. A copper bar with one end hot and the other cold has many atoms with more kinetic energy on the hot end and many atoms with less kinetic energy on the cold end. Later, however, because the kinetic energy has been transferred from the hot end of the bar to the cold end, all the atoms will have nearly the same kinetic energy. The change can be interpreted as heat flowing from hot to cold until the temperature of the bar is uniform. Similarly, most physical processes disorder a system because disordered states vastly outnumber ordered ones. A drop of perfume evaporates because states in which molecules of perfume are scattered throughout a large volume of air vastly outnumber states in which the molecules are confined in the tiny volume of a drop.

3. e. *Students know* that entropy is a quantity that measures the order or disorder of a system and that this quantity is larger for a more disordered system.

Students know from Standard 3.d that energy transferred as heat leads to the redistribution of energy among energy levels in the substances that compose the system. This redistribution increases the disorder of material substances. A quantity called *entropy* has been defined to track this process and to measure the randomness, or disorder, of a system. Entropy is larger for a disordered system than for an ordered one. Thus, a positive change in entropy, in which the final entropy is larger than the initial entropy, indicates decreasing order, also considered as increasing disorder. The properties of entropy fix the maximum efficiency with which energy stored as a temperature difference can be converted into work.

For a system at constant temperature, such as during melting or boiling, the change in entropy ΔS is given by

$$\Delta S = Q/T, \qquad \text{(eq. 28)}$$

where Q is the heat (thermal energy) that flows into or out of the system and T is the absolute temperature. The units of entropy are joules/K. All processes that require energy, for example, biochemical reactions that support life, occur only because the entropy increases as a result of the process.

3. f.* *Students know* the statement "Entropy tends to increase" is a law of statistical probability that governs all closed systems (second law of thermodynamics).

The second law of thermodynamics states that all spontaneous processes lead to a state of greater disorder. When an ice cube melts and the water around it becomes cooler, for example, the internal energy of the ice-water system becomes more uniformly spread, or more disordered. Most processes in nature are irreversible because they move toward a state of greater disorder. A broken egg, for instance, is almost impossible to restore to its original ordered state.

Another statement of the second law of thermodynamics is that in a closed system all states tend to become equally probable. Calculating the statistical probability of a condition involves counting all the ways to distribute energy in a system, and that procedure involves mathematics that is more complex than most students will have mastered. However, most students can recognize that there are many more ways to distribute energy approximately evenly within a system than there are ways to have energy concentrated. As spontaneous processes make all ways equally probable, a system thus becomes more likely to be found with its energy distributed than concentrated, and so the system becomes disordered.

Students who complete these standards will have learned the first and second laws of thermodynamics. They should understand that when physical change occurs, energy must be conserved, and some of this energy cannot be recovered for useful work because it has added to the disorder of the universe.

3. g.* *Students know* how to solve problems involving heat flow, work, and efficiency in a heat engine and know that all real engines lose some heat to their surroundings.

As implied in Standard 3.b, when heat flows from a body at high temperature to one at low temperature, some of the heat can be transformed into mechanical work. This principle is the basic concept of the heat engine. The remainder of the heat is transferred to the surroundings and therefore is no longer available to the system to do work. This transferred heat is never zero; therefore, some heat must always be transferred to the surroundings. Examples of practical heat engines are steam engines and internal combustion engines. Steam at a high temperature T_H pushes on a piston or on a turbine and does work. Steam at a lower temperature T_L is then drawn off from the engine into the air. When an idealized (i.e., reversible) engine completes a cycle, the change in entropy is zero. Equation (28) shows that

$$Q_H/T_H = Q_L/T_L\,. \qquad \text{(eq. 29)}$$

When this relation is combined with the conservation law of equation (26), the maximum possible efficiency, denoted as "eff," can be calculated as

$$\text{eff (\%)} = 100 \times W/Q_H = 100 \times (T_H - T_L)/T_H, \qquad \text{(eq. 30)}$$

where efficiency is the ratio of work done by the engine to the heat supplied to the engine. The efficiency of converting heat to work is proportional to the difference between the high and low temperatures of the engine's working fluids, usually gases. For a Carnot engine to be 100 percent efficient, the temperature of the exhaust heat needs to be absolute zero, an impossible occurrence.

STANDARD SET 4. Waves

Students can be introduced to this standard set by learning to distinguish between mechanical and electromagnetic waves. In general, a *wave* is defined as the propagation of a disturbance. The nature of the disturbance may be mechanical or electromagnetic. Mechanical waves, such as ocean waves, acoustic waves, seismic waves, and the waves that ripple down a flag stretched taut by a wind, require a medium for their propagation and gradually lose energy to that medium as they travel. Electromagnetic waves can travel in a vacuum and lose no energy even over great distances. When electromagnetic waves travel through a medium, they lose energy by absorption, a phenomenon that explains why light signals sent through the most transparent of optical fibers still need to be amplified and repeated. In contrast, light emitted from distant galaxies has traveled great distances without the aid of amplification, an indication that a relatively small amount of material is in the light's path.

Waves transfer energy from one place to another without net circulation or displacement of matter. Light, sound, and heat energy can be transmitted by waves across distances measured from fractions of a centimeter to many millions of kilometers. Exertion of a direct mechanical force, such as a push or a pull, on a physical body is an example of energy transfer by direct contact. However, for transfer to occur, objects do not need to be in direct physical contact with a source of energy. For instance, light transmits from a distant star, heat radiates from a fire, and sound propagates from distant thunder. Energy may be transferred by radiation, for example, from the Sun to Earth; therefore, radiation is also an example of a noncontact energy transfer. Both sight and hearing are senses that can perceive energy patterned to convey information without direct contact between the source and the sensing organ.

If students take physics before they have studied other high school science courses, the teacher may find it useful to cross-reference materials on pressure, heat, and solar radiation from the following standards in this chapter: 4.a and 7.a in the chemistry section and 4.a through 4.c in the earth sciences section. Algebra, geometry, and simple trigonometric skills are required for some of the advanced topics in this standard set. Students with a good foundation in algebra and geometry can be taught the trigonometry necessary to solve problems in this standard set.

4. Waves have characteristic properties that do not depend on the type of wave. As a basis for understanding this concept:

a. *Students know* waves carry energy from one place to another.

Waves may transport energy through a vacuum or through matter. Light waves, for example, transport energy in both fashions, but sound waves and most other waves occur only in matter. However, even waves propagating through matter transport energy without any net movement of the matter, thus differing from other means of energy transport, such as convection, a waterfall, or even a thrown object.

4. b. *Students know* how to identify transverse and longitudinal waves in mechanical media, such as springs and ropes, and on the earth (seismic waves).

Waves that propagate in mechanical media are either longitudinal or transverse waves. The disturbance in longitudinal waves is parallel to the direction of propagation and causes compression and expansion (rarefaction) in the medium carrying the wave. The disturbance in transverse waves is perpendicular to the direction of propagation of the wave. Examples of longitudinal waves are sound waves and *P*-type earthquake waves. In transverse waves a conducting medium, or a test particle inserted in the wave, moves perpendicular to the direction in which the wave propagates. Examples of transverse waves are *S*-type earthquake waves and electromagnetic (or light) waves.

4. c. *Students know* how to solve problems involving wavelength, frequency, and wave speed.

All waves have a velocity **v** (propagation speed and direction), a property that represents the rate at which the wave travels. Only periodic, sustained waves can be easily characterized through the properties of wavelength and frequency. However, most real waves are *composite,* meaning they can be understood as the sum of a few or of many waveforms, each with an amplitude, a wavelength, and a frequency.

Wavelength λ is the distance between any two repeating points on a periodic wave (e.g., between two successive crests or troughs in a transverse wave or between adjacent compressions or expansions [rarefactions] in a longitudinal wave). Wavelength is measured in units of length.

Frequency f is the number of wavelengths that pass any point in space per second. A wave will make any particle it encounters move in regular cycles, and frequency is also the number of such cycles made per second and is often abbreviated as cycles per second. The unit of frequency is the inverse second (s^{-1}), a unit also called the hertz (Hz).

Periodic wave characteristics are related to each other. For example,

$$v = f\lambda . \qquad \text{(eq. 31)}$$

4. d. *Students know* sound is a longitudinal wave whose speed depends on the properties of the medium in which it propagates.

Sound waves, sometimes called *acoustic waves,* are typically produced when a vibrating object is in contact with an elastic medium, which may be a solid, a liquid, or a gas. A sound wave is longitudinal, consisting of regions of high and low pressure (and therefore of compression and rarefaction) that propagate away from the source. (Note that sound cannot travel through a vacuum.) In perceiving sound, the human eardrum vibrates in response to the pattern of high and low pressure. This vibration is translated into a signal transmitted by the nervous system to the brain and interpreted by the brain as the familiar sensation of sound. Microphones similarly translate vibrations into electrical current. Sound speakers reverse the process and change electrical signals into vibrational motion, recreating sound waves.

An acoustic wave attenuates, or reduces in amplitude, with distance because the energy in the wave is typically spread over a spherical shell of ever-increasing area and because interparticle friction in the medium gradually transforms the wave's energy into heat. The speed of sound varies from one medium to another, depending primarily on the density and elastic properties of the medium. The speed of sound is typically greater in solid and liquid media than it is in gases.

4. e. *Students know* radio waves, light, and X-rays are different wavelength bands in the spectrum of electromagnetic waves whose speed in a vacuum is approximately 3×10^8 m/s (186,000 miles/second).

Electromagnetic waves consist of changing electric and magnetic fields. Because these fields are always perpendicular to the direction in which a wave moves, an electromagnetic wave is a transverse wave. The electric and magnetic fields are also always perpendicular to each other. Concepts of electric and magnetic fields are introduced in Standard Set 5, "Electric and Magnetic Phenomena," in this section. The range of wavelengths for electromagnetic waves is very large, from less than nanometers (nm) for X-rays to more than kilometers for radio waves. The human eye senses only the narrow range of the electromagnetic spectrum from 400 nm to 700 nm. This range generates the sensation of the rainbow of colors from violet through the respective colors to red. In a vacuum all electromagnetic waves travel at the same speed of 3×10^8 m/s (or 186,000 miles per second). In a medium the speed of an electromagnetic wave depends on the medium's properties and on the frequency of the wave. The ratio of the speed of a wave of a given frequency in a vacuum to its speed in a medium is called that medium's *index of refraction.* For visible light in water, this number is approximately 1.33.

4. f. *Students know* how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization.

A characteristic and unique property of waves is that two or more can occupy the same region of space at the same time. At a particular instant, the crest of one wave can overlap the crest of another, giving a larger displacement of the medium from its condition of equilibrium *(constructive interference);* or the crest of one wave can overlap the trough of another, giving a smaller displacement *(destructive interference).* The effect of two or more waves on a test particle is that the net force on the particle is the algebraic sum of the forces exerted by the various waves acting at that point.

If two overlapping waves traveling in opposite directions have the same frequency, the result is a standing wave. There is a persistent pattern of having no displacement in some places, called *nulls* or *nodes,* and large, oscillating displacements in others, called *maxima* or *antinodes.* If two overlapping waves have nearly the same frequency, a node will slowly change to a maximum and back to a node, and a maximum will slowly change to a node and back to a maximum. For sound waves this periodic change leads to audible, periodic changes from loud to soft, known as *beats.*

Diffraction describes the constructive and destructive patterns of waves created at the edges of objects. Diffraction can cause waves to bend around an obstacle or to spread as they pass through an aperture. The nature of the diffraction patterns of a wave interacting with an object depends on the ratio of the size of the obstacle to the wavelength. If this ratio is large, the shadows are nearly sharp; if it is small, the shadows may be fuzzy or not appear at all. Therefore, a hand can block a ray of light, whose average wavelength is about 500 nm, but cannot block an audible sound, whose average wavelength is about 100 cm. The bending of water waves around a post and the diffraction of light waves when passing through a slit in a screen are examples of diffraction patterns.

Refraction describes a change in the direction of a wave that occurs when the wave encounters a boundary between one medium and another provided that the media have either different wave velocities or indexes of refraction and provided that the wave arrives at some angle to the boundary other than perpendicular. At a sharp boundary, the change in direction is abrupt; however, if the transition from one medium to another is gradual, so that the velocity of the wave changes slowly, then the change in the wave's direction is also gradual. Therefore, a ray of light that passes obliquely from air to water changes its direction at the water's surface, but a ray that travels through air that has a temperature gradient will follow a bent path. A ray of light passing through a saturated solution of sugar (sucrose) and water, which has an index of refraction of 1.49, will not change direction appreciably on entering a colorless, transparent piece of quartz submersed in the solution because the quartz has an almost identical index of 1.51. The match in indexes makes the quartz nearly invisible in the sugar-water solution.

Another interesting phenomenon, the *Doppler effect,* accounts for the shift in the frequency of a wave when a wave source and an observer are in motion relative to each other compared with when they are at relative rest. This effect is most easily understood when the source is at rest in some medium and the observer is approaching the source at constant speed. The interval in time between each successive wave crest is shorter than it would be if the observer were at rest, and so the frequency observed is larger. The general rule, for observers moving at velocities much less than the velocity of the wave in its medium, is that the change in frequency depends only on the velocity of the observer relative to the source. Therefore, the shriek of an ambulance siren has a higher pitch when the source approaches and a lower pitch when the source recedes. For an observer following the ambulance at the same speed, the siren would sound normal. Similar shifts are observed for visible light.

Polarization is a property of light and of other transverse waves. *Transverse waves* are those in which the displacement of a test particle is always perpendicular to the direction in which the wave travels. When that displacement is always parallel to a particular direction, the wave is said to be *(linearly) polarized.* A ray of light emitted from a hot object, like a lamp filament or the sun, is unpolarized; such a ray consists of many component waves overlapped so that there is no special direction perpendicular to the ray in which a test particle is favored to move. The components of an unpolarized ray can be sorted to select such a special direction and so make one or more polarized rays. An unpolarized ray that is partly reflected and partly transmitted by an angled sheet of glass is split into rays that are polarized; an unpolarized ray can become polarized by going through a material that allows only waves corresponding to one special direction to pass through. Polarized sunglasses and stretched cellophane wrap are examples of polarizing materials.

STANDARD SET 5. Electric and Magnetic Phenomena

The electromagnetic force is one of only four fundamental forces; the others are the gravitational force and the forces that govern the strong and weak nuclear interactions. Electric and magnetic phenomena are well understood by scientists, and the unifying theory of the electromagnetic force is one of the great suc-cesses of science. The electromagnetic force accounts for the structure and for the unique chemical and physical properties of atoms and molecules. This force binds atoms and molecules and largely accounts for the properties of matter. Photons convey this force and electromagnetic energy.

Using electromagnetism for practical technological applications is taken for granted in modern society. Many devices of daily life, such as household appliances, computers, and equipment for communication, entertainment, and transportation, were developed from electromagnetic phenomena. Understanding the fundamental ideas of electricity and magnetism is basic to achieving success in a vast array of endeavors, from auto mechanics to nuclear physics.

Electricity and magnetism are now known to be two manifestations of a single phenomenon, the electromagnetic force. The originally separate theories explaining electricity and magnetism have been combined into a single theory of electromagnetism, whose predictive power is greater than that of either of the two previous, separate theories. The joining of these theories into a common mathematical framework is an example of how seemingly disparate phenomena can sometimes be unified in physics.

Studies of electric and magnetic phenomena build directly on the high school physics standards presented earlier and require a thorough understanding of the concepts of motion, forces, and conservation of energy. The subject of energy transport by waves is also important. Students in the lower grade levels are introduced to electricity as they learn that electric current can carry energy from one place to another. They also learn about light and the relationship between electricity and magnetism. To understand the concepts in Standard Set 5, students will need a strong grasp of beginning algebra and geometry. Basic trigonometry is also required for some of the advanced topics. Several topics covered in the lower grade levels may need to be reviewed as a part of teaching this standard set, particularly during the transition to standards-based education. In particular, the following facts are pertinent: (1) charge occurs in definite, discrete amounts; (2) charge comes in two varieties: positive and negative; and (3) the smallest amount of observable charge is the charge on an electron (or a proton).

Students should be acquainted with Newton's law of gravitation from standards studied previously (see Standard 1.e for grade two and Standard 4.c for grade five in Chapter 3 and standards 2.g and 4.e for grade eight in Chapter 4). Both Newton's law and Coulomb's law describe forces that diminish as the square of distance, and it may be helpful to compare those forces as a part of teaching some of the standards (see standards 1.e and 1.m* in this section). However, the comparison should be done with attention to the fundamental differences between the two types of forces, and certain points must be clearly understood to avoid sowing misconceptions. For example:

- Only the difference in electric or gravitational potential between two points has physical significance; the value of the potential at a particular point can be defined only relative to some reference point.
- The direction of an electric current is defined as the same as the direction of motion of charge carriers, conventionally assumed to be positive, although the charge carriers (the electrons) in wires are in fact negative. Therefore the direction of the electric current in wires is opposite to the direction of motion of the charge carriers.
- A *direct current* (DC) flows in one direction only, and an *alternating current* (AC) reverses at regular intervals.
- Ohm's law applies to conducting material under the assumption that resistance is independent of the magnitude and polarity of the potential difference (or of the applied electric field) across the material. The formulas used in Ohm's law to calculate an unknown amount of current, voltage, or resistance are $I = V/R$, $V = IR$, and $R = V/I$.

It may be helpful to describe *electric potential* as a measure of the tendency of a charged body to move from one point to another in an electrostatic field in the same way that *gravitational potential* is a measure of a body with mass to move from one point to another in a gravitational field. In both fields the work done to move the body does not depend on the path taken between the points but can be computed from the difference in the potential at the points.

As students solve simple circuit problems for this standard, they will also need to know the schematic representations of the various circuit elements, including a battery, a resistor, and a capacitor.

5. Electric and magnetic phenomena are related and have many practical applications. As a basis for understanding this concept:

a. *Students know* how to predict the voltage or current in simple direct current (DC) electric circuits constructed from batteries, wires, resistors, and capacitors.

Electric current I is the flow of net charge, and a complete, continuous path of current is called an *electric circuit.* If the charge carriers are positive, the electric current flows in the direction the carriers move; but if the carriers are negative, as they are in ordinary wires, the electric current flows in the opposite direction. Wires that carry currents are usually made of highly conducting metals, such as copper. If net charge q passes by a point a in a conducting wire in time t, the current I_a at that point is

$$I_a = q/t \,. \qquad \text{(eq. 32)}$$

In the case of uniform current I, the rate of charge flow is the same through the entire length of the wire. Current is measured in units of amperes (A), which are equal to coulombs/second (A = C/s), the logical consequence of equation (32).

A particle with a charge q placed in an electric field will be subject to electrostatic forces and will have a potential energy. Moving the charge will change its potential energy from some value PE_a to PE_b, reflecting the work W_{ba} done by the electric field (see Standard 2.a in this section). Potential energy depends also on the magnitude of the charge being transported. A more convenient quantity is the potential energy per unit charge, which has a unique value at any point, independent of the actual charge of the particle in the electric field. This quantity is called *electric potential,* or just *potential,* and the difference V_{ab} between the potentials at two points a and b is the *voltage.* By this definition, voltage provides a measure of the work per unit charge required to move the charge between two points a and b in the field; alternatively, it represents the corresponding difference in potential energy per unit charge. This principle is expressed as

$$V_{ab} = V_a - V_b = W_{ba}/q = PE_a/q - PE_b/q \,. \qquad \text{(eq. 33)}$$

Electric potential and voltage are measured in units of volt (V), which, as required by the preceding definition, is equal to joules per coulomb (J/C).

For a current-carrying wire, the potential difference between two points along the wire causes the current to flow in that segment.

5. b. *Students know* how to solve problems involving Ohm's law.

Resistance, measured in ohms, of a conducting medium (conductor) is the opposition offered by the conductor to the flow of electric charge. A potential difference V is required to cause electrons to move continuously. Ohm's law gives the relationship between the current I that results when a voltage V is applied across a wire with resistance R. This law is expressed as

$$I = V/R \,. \qquad \text{(eq. 34)}$$

Capacitors, which are devices for storing electrical charge, generally consist of two conductors with a potential difference that are separated by an insulator. A typical capacitor consists of two parallel metal plates insulated from each other by a *dielectric,* a material that does not conduct electricity. Capacitance *C,* the ability of a capacitor to store electric charge, can be measured in units of farads. The capacitance can be found from the following relation:

$$C = q/V, \qquad \text{(eq. 35)}$$

where q is the charge stored ($+q$ on one plate and $-q$ on the other) and V is the potential difference between the conducting surfaces. Based on equation (35), the unit of farad is defined as coulomb/volt (C/V).

5. c. *Students know* any resistive element in a DC circuit dissipates energy, which heats the resistor. Students can calculate the power (rate of energy dissipation) in any resistive circuit element by using the formula Power = IR (potential difference) × I (current) = I^2R.

Electric power P is defined as the rate of dissipation of electric energy, or the rate of production of heat energy, in a resistor and is given by Joule's law, in which

$$P = IV. \qquad \text{(eq. 36)}$$

Through the use of Ohm's law, this equation can also be written as $P = I^2R$ or $P = V^2/R$. Power is measured in watts, where 1 watt = 1 ampere-volt (W = A-V) = 1 joule/second.

Dissipation of energy as heat is a consequence of electrical resistance. In other words *electric power* is equivalent to the work per second that must be done to maintain an electric current. Alternatively, *power* is the rate at which electrical energy is transferred from the source to other parts of the circuit. The unit of kilowatt hour (kWH) is sometimes used commercially to represent energy production and consumption, where 1 kWH = 3.6×10^6 J.

5. d. *Students know* the properties of transistors and the role of transistors in electric circuits.

Semiconductors are materials with an energy barrier such that only electrons with energy above a certain amount can "flow." As the temperature rises, more electrons are free to move through these materials. A transistor is made of a combination of differently "doped" materials arranged in a special way. Transistors can be used to control large current output with a small bias voltage. A common role of transistors in electric circuits is that of amplifiers. In that role transistors have almost entirely replaced vacuum tubes that were widely used in early radios, television sets, and computers.

5. e. *Students know* charged particles are sources of electric fields and are subject to the forces of the electric fields from other charges.

Electrostatic force represents an interaction across space between two charged bodies. The magnitude of the force is expressed by a relationship similar to that for the gravitational force between two bodies with mass. For both gravity and electricity, the force varies inversely as the square of the distance between the two bodies. For two charges q_1 and q_2 separated by a distance r, the relationship is called Coulomb's law,

$$F = kq_1q_2/r^2 \,, \qquad \text{(eq. 37)}$$

where k is a constant. Customary units for charge are coulombs (C), in which case $k = 9 \times 10^9 \text{Nm}^2/\text{C}^2$.

An electric field is a condition produced in space by the presence of charges. A field is said to exist in a region of space if a force can be measured on a test charge in the region. Many different and complicated distributions of electric charge can produce the same simple motion of a test charge and therefore the same simple field; for that reason it is usually easier to study first the effect of a model field on a test charge and to consider only later what distribution of other charges might produce that field.

5. f. *Students know* magnetic materials and electric currents (moving electric charges) are sources of magnetic fields and are subject to forces arising from the magnetic fields of other sources.

A magnetic force exists between magnets or current-carrying conductors or both. A stationary charge does not produce magnetic forces. Furthermore, no evidence for the existence of magnetic monopoles, which would be the magnetic equivalent of electric charges, has yet been found. Iron and other materials that can be magnetized have domains in which the combined motion of electrons produces the equivalent of small magnets in the metal. When many of these domains are aligned, the entire metal object becomes a strong magnet. Therefore, to the best of scientific knowledge, all magnetic effects result from the motion of electrical charges.

The concept of a field applies to magnetism just as it does to electricity (see Standard 5.e in this section). Magnetic fields are generated either by magnetic materials or by electric currents caused by the motion of charged particles. A standard unit for the magnetic field strength is the Tesla (T). Electric charges moving through a magnetic field experience a magnetic force. The direction of the magnetic force is always perpendicular to the line of motion of the electric charges. The force is at maximum when the direction of motion of the electric charges (their velocity vector) is perpendicular to the magnetic field and at zero when the two are parallel.

5. g. *Students know* how to determine the direction of a magnetic field produced by a current flowing in a straight wire or in a coil.

The direction of a magnetic field is by convention taken to be outward from a north pole and inward from a south pole. The right-hand rule finds the direction of the magnetic field produced by a current flowing in a wire or coil. To find the direction in a wire, a student wraps the fingers of the right hand around the wire with the thumb pointing in the direction in which the electric current flows (in a wire electrons and electric current move in opposite directions). The fingers encircling the wire then point in the direction of the magnetic field outside the wire. The same rule will find the direction of the magnetic field inside a coil if one imagines that the right hand wraps around a wire that forms one of the loops that make up the coil. A different rule using the right hand also works for coils. The coil is held in the palm of the right hand with the fingers wrapped around the coil and pointing in the direction in which the electric current flows through the loops. The thumb then points in the direction of the magnetic field inside the coil.

5. h. *Students know* changing magnetic fields produce electric fields, thereby inducing currents in nearby conductors.

The concept of electromagnetic induction is based on the observation that changing magnetic fields create electric fields, just as changing electric fields are sources of magnetic fields. In a conductor these induced electric fields can drive a current. The direction of the induced current is always such as to oppose the changing magnetic field that caused it. This principle is called Lenz's law.

5. i. *Students know* plasmas, the fourth state of matter, contain ions or free electrons or both and conduct electricity.

A *plasma* is a mixture of positive ions and free electrons that is electrically neutral on the whole but that can conduct electricity. A plasma can be created by very high temperatures when molecules disassociate and their constituent atoms further break up into positively charged ions and negatively charged electrons. Much of the matter in the universe is in stars in the form of plasma, a mixture of electrified fragments of atoms. Plasma is considered a fourth state of matter, as fundamental as solid, liquid, and gas.

5. j.* *Students know* electric and magnetic fields contain energy and act as vector force fields.

Both the electric field **E** and the magnetic field **B** are vector fields; therefore, they have a magnitude and a direction. The fields from matter whose distributions in space and in velocity do not change with time are easy to visualize; for example, charges fixed in space, steady electric currents in wires, or permanent magnets. Electric fields from matter like this are generally represented by "lines of force" that start on positive charges and end on negative charges but never form closed loops (see Standard 5.m*, which appears later in this section). In contrast, the lines for magnetic fields always form closed loops; they never start and end—magnetic field lines do not have terminal points. Even the magnetic field lines around simple bar magnets, which are typically drawn as emanating from the north pole and entering the south pole, in fact continue through the body of the magnet to form closed loops.

The reason magnetic fields form loops while electric fields do not has to do with their different sources in matter at rest. Electric fields come from point charges, and magnetic fields come from point dipoles, which are more complicated; no sources of magnetic field with the simple properties of charge—that is, no magnetic monopoles—are known to exist. The direction in which an electric field points along a line of force is away from positive charge and toward negative charge; the direction in which a magnetic field (that is due to a current) points along a closed loop can be found by the right-hand rule (see Standard 5.g, which appears earlier in this section).

Electric and magnetic fields are associated with the existence of potential energy. The fields are usually said to *contain* energy. For example, the potential energy of a system of two charges q_1 and q_2 located a distance r apart, is given by

$$PE = kq_1q_2/r\,. \qquad \text{(eq. 38)}$$

In general, the potential energy of a system of fixed-point charges is defined as the work required to assemble the system bringing each charge in from an infinite distance.

5. k.* *Students know* the force on a charged particle in an electric field is $q\mathbf{E}$, where $\mathbf{E}$ is the electric field at the position of the particle and q is the charge of the particle.

The electric field strength $\mathbf{E}$ at a given point is defined as the force experienced by a unit positive charge, $\mathbf{E} = \mathbf{F}/q$. The units of $\mathbf{E}$ are newton/coulomb (N/C). By this definition the force experienced by a charged particle is

$$\mathbf{F} = q\mathbf{E}\,, \qquad \text{(eq. 39)}$$

where q is the magnitude of the particle's charge in coulombs and $\mathbf{E}$ is the electric field at the position of the charged particle.

5. l.* *Students know* how to calculate the electric field resulting from a point charge.

Coulomb's law is used in calculating the electric field caused by a point charge. According to equation (39), $\mathbf{E} = \mathbf{F}/q$, the magnitude of the field produced by a point charge q_1 is found by substituting equation (37) for $\mathbf{F}$ and dividing by the magnitude of the positive test charge q_2, which gives

$$E = kq_1/r^2. \qquad \text{(eq. 40)}$$

The direction of **E** is determined by the type of the source charge q_1, so that the vector is away from the positive charge (+) and toward the negative charge (–). (Remember that by definition the *field strength* is the force per unit of positive test charge.)

5. m.* *Students know* static electric fields have as their source some arrangement of electric charges.

The existence of a static electric field in a region of space implies a distribution of charges as the source. Conversely, any set of charges or charged surfaces sets up an electric field in the space around the charge. The customary first step in visualizing an electric field is to draw smooth curves, each of which contains only points of equal electric potential. Electric field lines ("lines of force") can then be drawn as curves that are everywhere perpendicular to the curves of equal potential. Electric field lines are assigned a direction that runs from regions of high potential to low and, therefore, from positive point charges to negative ones. The lines of force represent the path a particle with a small positive charge would take if released in the field.

The method used in deriving equation (40) can be used, in principle, to determine the field produced from any distribution of charges. At each point a net vector **E** is obtained by summing the vector contributions from each charge. This process can be readily done for a two-charge system in which the geometry is relatively simple. For more complicated distributions the methods of calculus are generally required to obtain the field.

5. n.* *Students know* the magnitude of the force on a moving particle (with charge *q*) in a magnetic field is *qvB* sin(*a*), where *a* is the angle between ***v*** and ***B*** (*v* and *B* are the magnitudes of vectors ***v*** and ***B***, respectively), and students use the right-hand rule to find the direction of this force.

The force on a moving particle of charge q traveling at velocity v in a magnetic field B is given by

$$F = qvB \sin(a) , \qquad \text{(eq. 41)}$$

where a is the angle between the direction of the motion of the charged particle and the direction of the magnetic field. (If $a = 0$, then the particle is traveling parallel to the direction of the field and the magnetic force on it is zero.) The maximum force is obtained when the particle is traveling perpendicular to the magnetic field. Students can determine the direction of the magnetic force through the use of the right-hand rule. The magnetic force is perpendicular to both the direction of motion of the charge and to the direction of the magnetic field. Equation (41) shows that Tesla, a standard unit for the magnetic field mentioned previously, is equal to 1 N-s/C-m (see the discussion for Standard 5.f, which appears previously in this section).

5. o.* *Students know* how to apply the concepts of electrical and gravitational potential energy to solve problems involving conservation of energy.

In standards 2.a and 2.b in this section, students learned that if a stone is raised from Earth's surface, the work done against Earth's gravitational attraction is stored as potential energy in the system of stone plus Earth. If the stone is released, the stored potential energy is transformed into kinetic energy, which steadily increases as the stone moves faster toward Earth. Once the stone comes to rest, this kinetic energy will ultimately be transformed into thermal energy. A similar situation exists in electrostatics. If the separation between two opposite charges is increased, work must be performed. The work is positive if the charges are opposite and negative. The energy represented by this work can be thought of as stored in the system of charges as electric potential energy (see also Standard 5.j* in this section) and, like gravitational potential energy, may be transformed into other forms, such as kinetic and thermal energy.

A simple example is a charge q moving freely between point a and point b, with a potential difference V_{ab} between the two points. If q is positive, the change in electric potential energy can be found from equation (35) and is

$$\Delta PE = qV_{ab}\,. \qquad \text{(eq. 42)}$$

By conservation of energy a corresponding amount of the kinetic energy is acquired, or released, by the charge at point b such that

$$\Delta KE = \Delta PE = qV_{ab}\,. \qquad \text{(eq. 43)}$$

Through substitution of the standard expression $\frac{1}{2}mv^2$ for the kinetic energy, a variety of predictions can be made, assuming the accelerating potential does not result in velocities approaching the velocity of light. The final velocity v can be found if the charge q, the mass m, and the potential V *are known. This method of imparting energy to charged particles is applied in such devices as television sets and in accelerators*

Notes

1. *Science Content Standards for California Public Schools, Kindergarten Through Grade Twelve.* Sacramento: California Department of Education, 2000.
2. *Science Safety Handbook for California Public Schools.* Sacramento: California Department of Education, 1999.